Appendix 13

Dredging and spoil disposal modelling

HR Wallingford
Working with water

EX 6219

Ichthys Gas Field Development Project
Dredging and Spoil Disposal Modelling

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Summary

Ichthys Gas Field Development Project

Dredging and Spoil Disposal Modelling

Report EX 6219
February 2010

INPEX Browse Ltd. (INPEX) is working towards the development of the Ichthys Gas Field, located in the Browse Basin, approximately 850 kilometres south-west of Darwin off the north-western coast of Australia.

Ichthys Project has requested HR Wallingford to conduct numerical modelling of the dredging and disposal associated with the proposed dredging activities within Darwin Harbour. This also required development of the proposed dredge plan and associated inputs to the numerical modelling.

Detailed numerical modelling of the fine-grained and coarse-grained material released during the proposed dredging methodology was undertaken, including sensitivities to material type, disaggregation, variations in dredge plant methodology and changes to the prevailing hydrodynamic conditions. The simulations completed suggest approximately 500,000 tonnes of fine-grained material and a similar quantity of coarse-grained material will be released within the Darwin Harbour during the proposed dredge schedule. The material removed during the dredging will be placed at an offshore disposal ground.

Through diffusion and advection by tidal currents the fine-grained material released by the dredging will be transported around the East Arm; a proportion of this material will accrete on the upper subtidal and low intertidal areas and may then be subject to agitation and resuspension by wind-waves; providing a mechanism for transport of fine material onto the higher intertidal area (Mangrove habitat). The simulations indicate that approximately 850 ha of Mangrove habitat will experience accretion of up to 10mm in depth, with approximately 2 ha experiencing up to 100mm of accretion over the proposed 4 year dredge program.

Within the subtidal areas of the East Arm the mass of coarse material released by the dredging activity is expected to migrate away from the point of release over the longer term. The mean depth of coarse-grained sediment generated over the proposed dredge area during the dredging activity is estimated to be 0.1m; this depth is relatively small when compared to the size of existing sand waves and bed features. Much of this sand will be retained within the dredged footprint.

Material, both coarse and fine-grained will be transported from the offshore disposal ground. It has been simulated that fine-grained material will show a net drift to the north-east of the disposal ground, whilst the magnitude and direction of the coarse-grained transport is likely to be dependant upon the prevailing tidal and wave energy with transport in both the south-west and north-east directions away from the disposal ground.

This report describes the inputs, methodology and modelling results for the dispersion and settling patterns of the dredge material arising from the proposed dredging of Darwin Harbour.

Contents

Contents continued

Contents continued

Figures

Contents continued

Contents continued

Contents continued

Contents continued

Contents continued

Contents continued

1. Introduction

1.1 BACKGROUND

INPEX Browse, Ltd. (INPEX) proposes to develop the natural gas and associated condensate contained in the Ichthys Field situated about 220 km off Western Australia's Kimberley coast and about 820 km west-south-west of Darwin. The field encompasses an area of 800 km^2 in water depths ranging from 235 to 275 m.

The two reservoirs which make up the field are estimated to contain 12.8 tcf (trillion cubic feet) of sales gas and 527 MMbbl (million barrels) of condensate. INPEX proposes to process the reservoir fluids to produce liquefied natural gas (LNG), liquefied petroleum gases (LPGs) and condensate for export to overseas markets.

For the Ichthys Project, the company plans to install offshore extraction facilities at the field and a subsea gas pipeline from the field to onshore facilities at Blaydin Point in Darwin Harbour. A two-train LNG plant, an LPG fractionation plant, a condensate stabilisation plant and a product loading jetty will be constructed at a site on Blaydin Point. Around 85% of the condensate will be extracted and exported directly from the offshore facilities while the remaining 15% will be processed at and exported from Blaydin Point.

In May 2008 INPEX referred its proposal to develop the Ichthys Field to the Commonwealth's Department of the Environment, Water, Heritage and the Arts and the Northern Territory's Department of Natural Resources, Environment and the Arts. The Commonwealth and Northern Territory ministers responsible for environmental matters both determined that the Project should be formally assessed at the environmental impact statement (EIS) level to ensure that potential impacts associated with the Project are identified and appropriately addressed.

Assessment will be undertaken in accordance with the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth) and the *Environmental Assessment Act* (NT). It was agreed that INPEX should submit a single EIS document to the two responsible government departments in the Northern Territory and the Commonwealth for assessment.

HR Wallingford Limited was commissioned to carry out modelling work associated with INPEX's preparation of the EIS and this technical report, *Dredging and Spoil Disposal Modelling*, was prepared in part fulfilment of that commission.

1.2 PROPOSED DREDGING

Ichthys Project has requested HR Wallingford to conduct numerical modelling of the dredging and disposal associated with the proposed dredging activities within Darwin Harbour. This also required development of the proposed dredge plan and associated inputs to the numerical modelling.

The dredging for the Ichthys Project consists of 3 components,

(1) shipping channel/ approach area / turning basin / berthing area;
(2) module offloading facility area,
(3) Inshore pipeline route.

The material removed during these dredging activities will be transported to an offshore disposal ground. The zones of proposed dredging, including the offshore disposal ground are shown in Figure 1 and Figure 2.

Various methodologies relating to the dredging of these different components have been developed in order to refine the overall dredge process and minimise environmental impact. The dredge plan arising from this process is referred to as the Dredging Case Study.

A proposed Dredging Case Study is presented in this document. This document details the methods and numerical models adopted to define inputs and represent the transport of both fine and coarse sediment during the proposed dredging. It includes the processed model outputs, in the form of, but not limited to, coloured surface plots, vector plots, graphs and tables.

1.3 APPROACH TO STUDY

To complete the required sediment transport modelling for the Environmental Impact Statement a comprehensive understanding of the existing environment at Darwin, and the requirements of the proposed Ichthys development is necessary. To build this picture, investigations into various environmental parameters and project requirements were undertaken. These parameters and requirements were used as a framework to plan and develop the sequential methodology used to complete the modelling studies:

1. The project scope – details of the civil engineering and construction tasks required, including location of channels and berthing pockets. This was used to focus attention to specific areas of interest and relevance.
2. Geotechnical conditions – information relating to the type and properties of the prevailing ground conditions was collected by Coffey Geotechnical. Some of this information (strength and grain size classification) formed inputs to the Dredging Research Simulation (DRS) models. However, the geotechnical information provided was limited in spatial extent so assumptions on the location, volume and specific grading of the material to be dredged have been made.
3. Dredge Plan Schedule – once the types of material to be dredged had been defined the most appropriate dredging equipment type and size, considering minimal loss of material to the environment, whilst meeting specification and production requirements were chosen. Using the production rate estimates and loss rate estimates from the DRS models a schedule of works was developed. In parallel to this a TELEMAC-2D area flow model of Darwin Harbour and the surrounding offshore area was set up, calibrated and validated against data provided to HR Wallingford by INPEX. The outputs from this hydrodynamic model were used to drive the sediment transport models.
4. Sediment transport modelling; fine sediment – using the dredge plan schedule and the estimated loss rates a schematisation of the dredge program was made; this schematisation is based upon the combination of dredging plant working within different parts of the area to be dredged (zones) for defined periods of time. The schematisations (referred to as ‘phases’) form the direct inputs to the plume modelling. This modelling used releases (defined in the phases) of fine material occurring in the different zones of the proposed dredge area within East Arm and also at the proposed offshore disposal ground. As well as using the hydrodynamic inputs from the TELEMAC-2D area model, additional inputs from a locally

generated wind wave model were included. The inclusion of wind waves as well as tidal currents is an important feature within the modelling; it allows the modelling of the agitation and the potential for redistribution of deposited fine-grained material over the intertidal area generated by the dredging activity.

5. Sediment transport modelling; coarse material – the processes of erosion, transport and deposition of non-cohesive sediment under the action of tidal currents is significantly different to that of cohesive sediment. Thus a different modelling suite and modelling methodology was used. The dredging activity will release coarse-grained material that will be dispersed locally to the location of the dredge activity, for example within the footprint of the proposed approach area and footprint of the proposed offshore disposal ground. This material will then be available for transport and redistribution by the prevailing hydrodynamics (provided by the TELEMAC-2D model) and consideration of the offshore wave conditions; simulated by the inclusion of additional shear stress at the seabed.

6. Presentation of results - following completion of the required model simulations, the results have been presented within this report in the form of coloured surface plots, time-series, and exceedance tables of suspended sediment concentrations and depth of deposits at specific receptors within and over the wider area of Darwin Harbour and its offshore environment.

1.4 REPORT STRUCTURE

This report describes the inputs, methodology and modelling results for the dispersion and settling patterns of the dredge material arising from the proposed dredging of Darwin Harbour.

This report is structured as follows:

Section 1 – Introduction
Section 2 – Materials to be dredged
Section 3 – Dredging Method
Section 4 – Sediment transport modelling (fine material)
Section 5 – Sediment transport modelling (coarse material)
Section 6 – Conclusions

This report draws upon information found in the following documents:

Document Reference	Synopsis
EX6218	HR Wallingford - Hydrodynamic and wave modelling – setup, calibration and validation of flow model of Darwin Harbour.
S-383-13M0-050 Rev A	JKC - Dredging Strategy Report – Detailing proposed method and plant to be used in the dredging of various areas within the East Arm.
GEOTPARA07036AB	Coffey - Geotechnical investigations, analysis and summary of geotechnical tests and investigations.
C036-AH-REP-0044_2	URS – Mangrove and mud sampling report characterisation of sediment type and properties found within mangrove areas in Darwin Harbour
L036-AC-REP-0001_0	BMT-WBM – Metocean data collection detailing data collection methods and results of wave conditions experienced in and around Darwin Harbour
L440AU0001.01_0	Fugro Seismic refraction report – detailing geophysical properties of surface and subsurface sediments found in and around Darwin Harbour.

2. Materials to be dredged

2.1 IN-SITU VOLUME

The dredging strategy Report (Ref 1) undertook a thorough assessment of the available geotechnical information, including historic data and project specific investigations. From this assessment, a preliminary geological model of the dredging footprint was developed and indicative volumes for the identified material types were calculated. These calculations indicate that the total dredge volume for the marine facilities is approximately 16.9 Mm^3 and consists of approximately 14.2 Mm^3 of weak material and a further 2.7 Mm^3 of strong material. The majority of this material will be removed from the approach area; the location of the zones discussed below is shown in Figure 3.

Table 1 below describes the volumes of material to be dredged by region defined in Figure 3.

Table 1 Summary volumes of materials to be dredged for marine facilities

Material	Volume (Mm^3)	Dredge zone(s)
Weak	8.964	shipping channel/ berthing area/ turning basin
Weak	3.5	shipping channel/ berthing area
Weak	1.17	module offloading facility
Weak	0.574	Inshore pipeline route
Medium	1.925	turning basin/ berthing area
Medium	0.45	shipping channel (Midway)
Medium	0.124	shipping channel (Walker Shoal)
Strong	0.12	shipping channel (Walker Shoal)
Strong	0.047	berthing area

Total **16.874Mm^3**

2.2 SOIL TYPE (PARTICLE SIZE DISTRIBUTION)

For the determination of the dredging plan, production rates and losses from the various dredging operations, it was first necessary to establish characteristics of the materials to be dredged. For unconsolidated materials it is the particle size distribution (PSD) and in-situ dry density which are important. For stronger material (weak to strong rocks) it is knowledge of the strength of the material in-situ that is required along with an estimate of the nature of the material after dredging. These strengths, densities and PSDs are required as inputs to the DRL in-house Dredger Models.

The soil laboratory test results given in the Nearshore Geotechnical Investigation Laboratory Testing Report (Ref 2) were reviewed to ascertain the characteristics of the soils down to the required dredge level of -14 m LAT in the approach area.

The analysis highlighted the presence of five different material types within the areas to be dredged. Table 2 below shows the PSDs for the four weak material types, the most common of which are PSD Types 2 and 3. The table includes the assumed in-situ bulk and dry densities and fines content (<75 µm).

Table 2 In Situ particle size distributions for weak soils to be dredged

Particle size (µm)	PSD TYPE 1	PSD TYPE 2	PSD TYPE 3	PSD TYPE 4
< 20	21.1	6.6	26.5	51
20-60	6.4	7.15	18.75	13.6
60-80	6.4	7.15	18.75	13.6
80-100	5.36	24	8.1	5.7
100-150	5.36	24	8.1	5.7
150-200	5.36	24	8.1	5.7
200-300	17	4	7	3
300-400	16	2.8	3	1
400-600	12	0.3	1	0.7
600-1000	4	0	0.7	0
1000-2000	1	0	0	0
2000-4000	0.02	0	0	0
> 4000	0	0	0	0
Sum	100	100	100	100
Fines (%)	32.30	19.11	59.31	74.80
Bulk Density (T/m^3)	2.05	1.95	1.7	1.56
Dry Density (T/m^3)	1.67	1.51	1.1	0.87

A significant proportion of the material to be dredged is rock of a variable strength and nature; as noted above rock does not have an in-situ PSD but, following dredging the product will have a PSD. However, this material will be removed by use of backhoe dredger for the lower strengths (UCS[1] 0 to 10 MPa), cutter-suction dredger for material with medium strength (UCS 10 MPa to 30 MPa) and Drilling and Blasting for higher strength material (UCS >30 MPa).

On the basis of the laboratory testing it has been estimated that about 80% (2 Mm^3) of the rock material has a strength of <10 MPa and will therefore be dredged using a backhoe dredger. Much of this material will retain its in-situ properties after being loaded by backhoe dredger into a barge (see Sections 3.1.1 and 3.1.2).

It is further estimated that about 0.5 Mm^3 of the rock will be in the strength range 10-30 MPa and that this will be dredged with a cutter-suction dredger. The information in the core logs is insufficient to determine whether any weaker rock lies within the medium strength rock. However, if this were the case then this weaker material is also likely to be dredged by cutter-suction dredger. The rock itself is mostly phyllite, with some conglomerate. Phyllite is a mudstone and consequently when subjected to the fracturing and abrasion processes associated with the cutter-suction dredger operation there is an expectation of some breakdown of the rock into fines.

Seven sediment samples supplied to HR Wallingford from the Phase 1 Geotechnical Investigations have undergone laboratory testing to assess their susceptibility to breakdown when subject to dredging by cutter-suction dredger (Ref 3). Six of the samples were phyllite (covering a UCS[1] range from 0.8 to 23.4 MPa) and one was conglomerate (UCS 20.8). Five of the samples had UCSs in the range 9.0 to 23.4 MPa (four of phyllite and one of conglomerate) and are therefore of relevance to the

[1] *UCS (Unconfined Compressive Strength) can be defined as the measure of force required to crush a sample of sediment in the vertical direction without lateral restraint.

Dredging Case Study under consideration where the cutter-suction dredger is planned to dredge material in the strength range 10-30 MPa.

All of the five samples with strength in the range of interest yielded virtually no fines (material <75 μm in diameter) when subject to the fracturing tests. The maximum percentage of fines generated was 0.3. This implies that the action of the teeth of the cutter-suction dredger itself would generate negligible fines.

The fracturing process occurs within a turbulent flow regime created by the rotation of the cutterhead; this turbulent flow will also generate disaggregation of the fractured material. Two of the five samples had UCSs of 9.0 and 11.5 MPa. Abrasion testing of clasts of these materials revealed that they were capable of breakdown into fine particles yielding up to ~35% fines in tests to simulate the action of the cutter head.

In the tests undertaken, harder materials (UCSs of 20.8 and 23.4) generated virtually no fines, (<0.1%). Therefore very low fines releases might be expected at a cutter head when such materials are dredged.

On the basis that the cutter-suction dredger is anticipated to encounter a range of different strength material when dredging the medium strength phyllite (10 to 30 MPa) the product at the cutter-head of the cutter-suction dredger dredging was assumed conservatively to contain an average of 30% fines.

The differing extraction methods will generate a disaggregated form of the in-situ material, a representative disaggregated PSD is shown for each one in Table 3.

Table 3 Assumed PSDs of weak rock (phyllite) after being cut by cutter-suction dredger (PSD 5) and Drill and Blast (PSD 6)

Particle size (μm)	**cutter-suction dredger (10-30 MPa)**	**Drill and Blast (>30 MPa)**
	PSD	**PSD**
	TYPE 5	**TYPE 6**
< 20	16	2
20 to 60	13	1
60 to 80	1.5	1
80 to 100	0.5	1
100 to 150	1	3
150 to 200	1	5
200 to 300	1	7
300 to 400	0.5	8
400 to 600	0.5	10
600 to 1000	2	18
1000 to 2000	1	22
2000 to 4000	4	16
4000 to 6000	1	4
>6000	57	2
Sum	100	100
Fines (%)	30	3.75
Bulk Density (T/m^3)	2.4	2.3
Dry Density (T/m^3)	2.24	2.08

When the material cut by the cutter-suction dredger is drawn up through the pipe and pump of the dredger prior to discharge back to the seabed from a mid point on the cutter arm there will be further abrasion of the dredged material. The laboratory abrasion tests indicated that such abrasion might be as much as a total of 65% in the medium strength material. Again conservatively the assumption has been made that the fines content of this discharge product will be about 60%.

There is insufficient detail within the geotechnical information to draw conclusions regarding the spatial and vertical extent of the differing weak soil types. As PSD Types 2 and 3 are the most commonly occurring types, an assumption has been made to linearly average the properties of these 2 soil types. This generates a combined PSD Type (for PSD 2 and 3) shown in Table 4.

Table 4 Assumed average PSD of combined Type 2 and 3 material

Particle size (µm)	TYPE
	PSD 2/3
< 20	16.55
20 to 60	12.95
60 to 80	12.95
80 to 100	16.05
100 to 150	16.05
150 to 200	16.05
200 to 300	5.5
300 to 400	2.9
400 to 600	0.65
600 to 1000	0.35
1000 to 2000	0
2000 to 4000	0
4000 to 6000	0
>6000	0
Sum	100
Fines (%)	39.21
Bulk Density (T/m^3)	1.825
Dry Density (T/m^3)	1,305

2.3 MASS AND VOLUME BY TYPE

Table 5 below describes the type, mass and volume of the material to be dredged and by which dredging plant. The volumes of material of PSD Type 1 material are expected to be insignificant; in addition the proportion of fines contained within the material (32%) is expected to be of a similar magnitude to that off the average of the predominantly occurring weak material (39%).

Table 5 Dry mass of material to be dredged by sediment type and region

Sediment Type	Dry Density (T/M^3)	Material Type	Volume (Mm^3)	Mass (Mt)	Dredge zone(s)	Plant
Average 2/3	1.305	Weak	8.964	11.698	shipping channel/ berthing area/ turning basin	trailing suction hopper dredger
Average 2/3	1.305	Weak	3.500	4.568	shipping channel/ berthing area	backhoe Dredger
4	0.870	Weak	1.170	1.018	Module offloading facility	backhoe Dredger
5*	2.240	Weak Rock (<10 MPa)	1.925	4.312	turning basin/berthing area	backhoe Dredger
5*	2.240	Weak Rock (10-30 MPa)	0.450	1.008	shipping channel (Midway)	Cutter suction dredger
5*	2.240	Weak Rock (10-30 MPa)	0.124	0.278	shipping channel (Walker Shoal)	Cutter suction dredger
6*	2.080	Strong Rock (>30 MPa)	0.120	0.250	shipping channel (Walker Shoal)	Drill and blasting
6*	2.080	Strong Rock (>30 MPa)	0.047	0.098	approach area	Drill and blasting
		Channel Total:	16.300	23.229		
4	0.870	Weak	0.278	0.242	Pipeline	backhoe dredger
Average 2/3	1.305	Weak	0.296	0.386	Pipeline	backhoe dredger
		Pipeline Total:	0.574	0.628		
		Grand Total:	**16.874**	**23.857**		

* PSD after dredging

The respective sediment fractions contained within each representative sediment type are given by PSD Types 1-6. Using this information the mass of each component size fraction of the material arising from the dredging has been calculated.

The sediment fractions have been defined into 3 classification bands covering ‘fines’ (<75 µm), ‘fine sand’ (75 µm-200 µm) and ‘medium sand’ or coarser (>200 µm). The masses arising are quoted in units of Million Dry Tonnes and as a percentage of the total material to be dredged of that sediment type. This information is presented in Table 6.

Table 6 Dry Mass of fines by PSD type (Including pipeline approach)

Sediment type	Mass (Mt)	% Mass Fines <75 µm	Mass Fines <75 µm (Mt)	% Mass Fraction 75-200 µm	Mass of Fraction 75-200 µm (Mt)	% Mass Greater than 200 µm	Mass greater than 200 µm (Mt)
PSD Average of 2/3	16.652	39.2%	6.529	51.4%	8.557	9.4%	1.567
PSD 4	1.260	74.8%	0.942	20.5%	0.258	4.7%	0.059
PSD 5	5.598	20.4%	1.142	2.6%	0.146	77.0%	4.310
PSD 6	0.347	3.8%	0.013	9.3%	0.032	87.0%	0.302
	Total	**~36.0%**	**8.626**	**~38%**	**8.993**	**~26%**	**6.238**

Grand Total: 23.857

3. Dredging Method

3.1 SCHEDULING OF DREDGE OPERATIONS

The Schedule for the Dredging Case Study is shown in Figure 4. The dredging plant, production rates and assumptions for the different aspects of the Dredging Case Study are outlined below.

The Project calls for the installation of a module offloading facility and shipping channel, approach area, turning basin and berthing area within the East Arm of Darwin Harbour. In addition to this there is a requirement to dredge a trench for the installation of a pipeline.

3.1.1 Pipeline trench

For the purposes of this modelling study, dredging for the pipeline trench is included at the beginning of the proposed scheme of works, using backhoe dredger plant and barges. The volume of material to be removed is of order 0.57 Mm^3 and the construction of the trench is expected to take approximately 10 weeks to complete. For this activity there will be losses from the bucket of the backhoe dredger whilst excavating material and from the barge during placement at the offshore disposal ground. The dredging of the proposed pipeline trench is an activity that is independent of the dredging requirements in East Arm, and could be undertaken in advance of, or in parallel to, works in East Arm.

3.1.2 Dredging in East Arm

Dredging of the Module offloading facility

Dredging of the module offloading facility involves the removal of about 1.2 Mm^3 of weak material; this will be undertaken by a backhoe dredger. Excavated material will be loaded to 3,000 m^3 barges and transported to the offshore disposal ground. Three, 3,000 m^3 hopper barges will be required for this activity assuming a maximum round trip distance to the placement site and back of 80 km and a sailing speed of about 8 knots.

Dredging of weak materials

A backhoe dredger with a 15 m^3 bucket capacity will be used to dredge 3.5 Mm^3 of weak materials to -6.0 m LAT within the East Arm. The backhoe dredger will load directly to 3,000 m^3 hopper barges; the hopper barges will transport material to the offshore disposal ground and place material on the bed. Three, 3,000 m^3 hopper barges will be required for this activity to be undertaken on a continuous basis assuming a maximum round trip distance to placement and back of 80 km and a transit speed for the barges of about 8 knots. This part of the dredging with backhoe dredger will take approximately 15 months. For this activity there will be losses from the bucket whilst excavating material and from the barge during placement at the offshore disposal ground.

All other weak materials from -6.0 m LAT to the final dredge level of -14 m LAT will be removed using a medium sized trailing suction hopper dredger (for the Dredging Case Study it is assumed to be approximately 12,000 m^3 in capacity) and placed at the offshore disposal area. The volume of material to be dredged by trailing suction hopper dredger is about 8.9 Mm^3. This is expected to take approximately 23 months. For this activity there will be losses from the draghead and propeller/vessel wash only during dredging, as it is assumed for the Dredging Case Study no overflow of the hopper will occur. Losses will also occur when the material is placed at the offshore disposal ground.

Dredging of weak rock

A further 1.9 Mm^3 of weak rock (phyllite with UCS<10MPa) in the turning and berth areas will be removed by backhoe dredger; this will be transported and placed at the offshore disposal ground by barges. It is expected this process will take approximately 26 months. Note that the production rate for the backhoe dredger working in the phyllite will be reduced compared to when it is working in the weak materials. Losses will occur from the bucket and placement of material at the offshore disposal ground by barges.

Dredging of strong rock

The stronger phyllite and conglomerate (UCS 10 to 30MPa) below -6.0 m LAT will be pre-cut using a cutter-suction dredger and discharged back to the seabed through the underwater pump in the ladder (a very short transport distance). Table 5 indicates that there is approximately 450,000 m^3 of such material in the Midway section of the shipping channel and 124,000 m^3 in the Walker Shoal area. After cutting and discharge back to the seabed this material will be re-dredged using a trailing suction hopper dredger and transported to the offshore disposal ground; this process is expected to take approximately 2 months. There will be losses from several stages of this dredge phase; losses will occur from the cutter-head and from placement back to the seabed from the cutter-suction dredger, losses from the drag-head and propeller/vessel wash for the trailing suction hopper dredger will also occur during redredging. There will then be losses from the placement of material at the offshore disposal ground.

Drilling and blasting

Approximately 120,000 m^3 of very strong rock will be drilled and blasted in the Walker Shoal and provisional volume estimates suggest that there may be a further 47,000 m^3 of high strength material to be blasted in the approach area/berthing area. The drill and blast operation is anticipated to take approximately 14 months; a backhoe dredger will be used to load this material to 3,000 m^3 barges that will transport the blasted rock to the offshore disposal ground. The removal and transportation of this material is expected to take approximately 1 month to complete. Again a total of three 3,000 m^3 barges will be required to support this activity assuming a maximum round trip distance to the placement site and back of 80 km and a sailing speed of about 8 knots.

3.2 PLANT TYPE AND PRODUCTION RATE

The production rates and loss of material rates from the dredging plant are based upon the following plant type:

1. backhoe dredger - Nominal 15 m^3 bucket capacity
2. trailing suction hopper dredger – Hopper capacity of about 12,000 m^3
3. cutter-suction dredger – Cutter head power of 3,500 Kw

It is anticipated that the backhoe dredger will load hopper barges with a nominal capacity of 3,000 m^3. It is assumed that the average round trip to the offshore disposal ground is approximately 80 km from the area of dredging. Three barges will be required for continuous operations when the backhoe dredger is working in weak materials. When working in weak rock the production rate of the backhoe dredger will be reduced and only two barges would be required for continuous operations.

The production rate of the dredging will vary dependant upon the plant being used and the type of material encountered. The types of material that are to be dredged are defined in Table 2 and Table 3. The production rates for the different plant working in the different materials are summarised in the Table 7 below. It should be noted that some plant do not encounter all PSD types.

As defined in the Dredge Schedule (Figure 4) the material dredged by the cutter-suction dredger will be placed back to the bed immediately after being cut from its in-situ location. This will then be re-dredged by trailing suction hopper dredger; similarly the material arising from the drill and blast operations will be redredged by backhoe dredger. The production rates for this re-dredged material are shown in italics in Table 7.

Table 7 Production rate for plant in differing material types

Plant Type	PSD type	Material Description	Production Rate (m^3/wk)
backhoe dredger	PSD 2/3	A very fine to medium sand containing a significant fines/mud proportion.	60,000
	PSD 4	A very fine to fine sand containing a dominant proportion of fines/mud.	60,000
	PSD 5	Weak insitu phyllite (USC <10MPa)	19,000
	PSD 6	Coarse material comprising dominantly of cobble and pebble sized material with a very low fines content arising from the drill and blast process	*60,000*
trailing suction hopper dredger	PSD 2/3	A very fine to medium sand containing a significant fines/mud proportion.	100,000 no overflow
	PSD 5	Very coarse material comprising dominantly of cobble size material with a proportion of fine material arising from cutter-suction dredger dredging of medium strength phyllite	*100,000* no overflow
cutter-suction	PSD 5	Medium strength in-situ phyllite (UCS	95,000

Plant Type	PSD type	Material Description	Production Rate (m^3/wk)
dredger		10-30MPa) Breaks down upon cutting to form very coarse material comprising dominantly of cobble size material with a proportion of fine material	

3.3 PLANT TYPE AND LOSS RATE

As with the simulated production rate of the plant, the rate of loss of material from the plant and barge equipment will vary dependant upon the material type that is being dredged.

3.3.1 Loss from backhoe dredger and barges

The backhoe dredger selected for the Dredging Case Study is assumed to have a 15 m^3 capacity bucket, with an assumed production rate of 60,000 m^3/wk. Hourly production is thus, 400 m^3/hr assuming a 150 hr working week.

Very few measurements of re-suspension of dredge material around backhoes have been made. Kirby and Land, 1991 (Ref 4), suggest an "S" factor of 12 kg/m^3 for the larger backhoes. In this case this would give a loss rate of 1.33 kg/s. However, it is likely that this factor was experienced in more benign hydrodynamic conditions than Darwin Harbour, so the loss rate is likely to be somewhat higher.

A more similar operation may be the grab dredging that was undertaken in the River Tees, in the UK in May, 2000 (Ref 5), in an area of strong currents. Measurements made during the work indicated a loss rate of some 3.35% of the total dredged. Taking account of the larger bucket size proposed here and the fact that a backhoe dredger is to be used, a loss of 3% is considered to be conservative. Based on the PSDs given in Table 2, Table 3 and Table 4 the loss rates for the dredging with backhoe dredger for the different soils are shown in Table 8.

Table 8 Loss rates from 15m^3 backhoe dredger dredging in weak materials

Soil	PSD 2	PSD 3	PSD2/3	PSD 4	PSD5	PSD6
Total loss (kg/s)	5.03	3.67	4.35	2.91	2.36	6.90
Fines fraction (%)	19.11	59.31	39.2	74.80	35.0	3.75
Fines lost (kg/s)	0.96	2.18	1.6	2.18	0.83	0.26

It is assumed that the above losses will occur throughout the water column and may adopt a bi-modal distribution focused near bed and towards the water surface.

For the purpose of modelling the impacts of losses from backhoe dredger operations in weak materials an average of the loss rate for materials PSD 2 and PSD 3 can be assumed to be representative, i.e. 4.35 kg/s total loss and 1.6 kg/s for fines material loss rate.

It is assumed that the barges can be loaded with no overflow. Weak material will be excavated from the bed in what is considered close to its in-situ state; therefore it is assumed for purposes of the Dredging Case Study that 90% of the mass dredged by backhoe dredger retains the in situ properties after placement into the barge whilst the remainder is in the hopper as low density slurry.

The most commonly occurring soils in this area are PSD 2 and PSD 3; it is, therefore assumed a linear average of these two PSD's will characterise the material that is likely to arise on the seabed after placement at the offshore disposal ground; this PSD is presented in Table 2.

Losses during placement are calculated on the basis that the fines fraction of 5% of the placed quantity is assumed to be lost into the water column over a period of 5 minutes. The assumed loaded capacity of the hopper barge is 2250 m^3, and 3 barges are required to complete the cycle without delay to the backhoe dredger. The production rate is easily met with 3 barges working efficiently; specifically each barge will, on average, only need to be loaded to bulked volume of 1800 m^3. Table 9 below defines the total mass per barge load (assuming loaded to 1800 m^3 bulked), mass of fines per barge load and equivalent loss to suspension of fine material per second based on the above assumption.

Table 9 Masses released by barge placement for differing PSD type

PSD Type	Total Dry Mass released per barge load (T)	Rate of release of Dry Mass per barge load (kg/s)	Total Dry Mass of Fines released per barge load (T)	Rate of release of Dry Mass of Fines per barge load (kg/s)
PSD 2/3	1709	5697	670	2233
PSD 4	1139	3797	876	2920
PSD 5	2736	9120	958	3193
PSD 6	2540	8467	92	306

3.3.2 Loss from cutter-suction dredger

The particle size distribution for the disaggregated weak rock to be dredged by cutter-suction dredger (PSD 5) is presented in Table 3. Assuming a productivity of 95,000 m^3/wk then the associated rate of fines spilt (assuming 110 hrs working per week, 864 m^3/hr, *in situ* bulk density of 2.4 T/m^3 and a dredging efficiency of 70%) would be 370 m^3/hr.

The fines fraction for PSD 5 when working in medium strength material is 20% and thus the amount available for re-suspension is 72 kg/s. However, in practice some of the material is bound together in lump form and thus the amount available for re-suspension will be less than this. In addition, in the dynamic conditions pertaining to Darwin, the loss at the top of the cut may well be considerable, whilst the loss at the bottom of the cut could be very small because of the confinement provided by the dredged cut itself. Hence, a conservative figure would be some 50% of this loss rate i.e. about 36 kg/s.

The cutter-suction dredger will place the cut material back to the seabed to be re-dredged by a trailing suction hopper dredger. The passage up the pipe and through the dredge pump will lead to further abrasion of the cut material. Additional losses will be generated from this placement process, which are assumed to comprise a fines content of 5% of the mass that is placed to the bed. This is equivalent to 8.5 kg/s assuming the fines content of the cut and pumped material is about 60%.

3.3.3 Loss from trailing suction hopper dredger

The losses from the trailing suction hopper dredger will occur at two stages through the dredging program, at the time of dredging and at the time of placement of the material in the hopper at the offshore disposal ground. In the Dredging Case Study it is assumed that the trailing suction hopper dredger is not permitted to overflow during the dredging as this will significantly reduce the potential mass of material that is released. However, the trailing suction hopper dredger will release some material through the process of propeller wash and the drag-head on the seabed. How the magnitude of the losses from these processes is calculated is described below.

In the case where a trailing suction hopper dredger is permitted to overflow it is known that a large proportion of the material discharged from trailing suction hopper dredgers falls to the seabed as a density current and remains close to the footprint of the dredging. Subsequently, this material may be re-mobilised by ship passage and/or prevailing hydrodynamics. Measurements carried out in the vicinity of a working sand dredger (8,225 m^3 capacity trailing suction hopper dredger) in Hong Kong (Ref 6) in the 1990s 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 agitation and suspension caused by the action of the drag head and propeller wash over the seabed is generally accepted to be 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) noting that this will occur throughout the total loading cycle.

This approach scales losses due to re-suspension at the drag head proportionately according to how much sediment is available for resuspension within the system. An example of the proportion of losses due to overflow, drag head and propeller wash is described in Table 10 below.

Table 10 Typical loss rates from a trailing suction hopper dredger working in PSD2/3 with overflow

Losses from trailing suction hopper dredger	Loss Rate (kg/s)
Potential Total Fines Loss from overflow (kg/s)	624
Probable re-suspended residual loss (at 15% of total)	94
Re-suspension due to draghead (at 1/3rd of residual or 5% of total)	31
Accumulation on bed for potential resuspension by currents and waves	499

Thus, if the trailing suction hopper dredger was used in overflow mode, losses at the drag-head could be expected to be of order 30 kg/s; however this takes into consideration the resuspension of material generated by the drag-head moving through material released to the bed by overflow. As overflow is not used during the proposed dredge schedule it is likely the loss from the draghead and propeller wash will be significantly lower as there will be less fines available on the bed as a source for resuspension.

For the Dredging Case Study where *no overflow* from the trailing suction hopper dredger is assumed it is conservatively assumed that drag-head and propeller wash effects resuspend about 50% of the mass of fines from the bed that would have occurred if overflow were to be permitted (i.e 50% of 30 kg/s). In the simulations a release rate of 15 kg/s is used.

Losses from placement of the material at the offshore disposal area will occur in a similar fashion to those generated by the barges. Table 11 below defines the total mass per trailing suction hopper dredger cycle assuming a loaded hopper capacity of 3,200 m^3 by total mass, and mass of fines per hopper load and equivalent mass of fine material placed per second based on the above assumption. It is assumed that the trailing suction hopper dredger discharges its load uniformly over a 10 minute period.

Table 11 Masses released by trailing suction hopper dredger placement for differing PSD type

PSD Type	Total Dry Mass Placed per trailing suction hopper dredger load (T)	Rate of release of dry mass per trailing suction hopper dredger load (Kg/s)	Total Dry Mass of Fines release per trailing suction hopper dredger load (T)	Rate of release of Dry Mass of fines per trailing suction hopper dredger load (Kg/s)
PSD 2/3	4176	6960	1639	2729
PSD 5	7168	11947	1434	2389

4. Sediment Transport Modelling – Fine material

The modelling of dispersion and settling patterns of the fine (<75μm) material released from the dredging activities was undertaken using the coupled TELEMAC-2D flow model and DELFT-3D Water Quality Module (DELWAQ).

The set-up, calibration and validation of the TELEMAC-2D model is described in HR Wallingford Report EX6218 (Ref 7).

4.1 DELWAQ MODEL

DELWAQ has been developed by Deltares and is a 2D or 3D water quality modelling framework. It solves the advection-diffusion-reaction equations on a model grid and can be used for a wide range of model substances including suspended fine sediments. DELWAQ is part of the Delft3D modelling suite, and was further developed by a joint effort between Deltares and EDF-LNHE to take as input (flow) files generated by the TELEMAC-2D and 3D flow models. In the present study a 2D model has been used. The erosion formulation used was the standard formulation usually attributed to Partheniades. Deposition was calculated using Krones equation. The specific threshold for erosion was set at 0.2 N/m^2 and the threshold for deposition was set at 0.1 N/m^2. These values have been defined in accordance with observed measurements and accepted values (Ref 8), which have been observed to range between 0.02 N/m^2 and 5.0 N/m^2 for erosion and 0.06 N/m^2 and 0.1 N/m^2 for deposition.

Darwin Harbour experiences a typical Tropical climate, with pronounced wet and dry seasons. The accompanying variation in persistent wind direction affects the water levels and wind waves generated within the Harbour. The TELEMAC-2D modelling has accounted for the wind induced set-up and set-down generated within the Harbour by the seasonal variation. The variation in locally generated waves within the Harbour, which have a significant role in the resuspension and distribution of fine sediment over the intertidal and mangrove areas, has been included in the DELWAQ model.

The NOAA Wavewatch model wind data at location 12°S and 130°E was used as input wind speed and direction data for a complete year (April 2005 – April 2006). Other locations were considered (e.g Darwin Airport) but only incomplete and poor resolution data was available. The input data is shown in Figure 5.

4.2 APPROACH TO MODELLING

The Dredging Case Study can be considered in three separate sections:

- Pipeline trench dredge
- approach area and module offloading facility dredge
- Offshore disposal.

The three components of the dredging activity have been simulated individually and also in combination in the necessary way to simulate their overall effect. Sensitivity tests have also been performed for the three sections. There is not a requirement within the dredge schedule for the Pipeline trench dredge to be undertaken simultaneously with the dredging program for the East Arm; however sensitivity tests to the simultaneous and independent dredging of these sections of the dredge schedule has been conducted.

Specifically in the East Arm sensitivity tests have been conducted through the refinement of the proposed dredge schedule. The Dredging Case Study presented here is the final iteration; where use of different plant, different modes of operation of plant and environmentally conservative assumptions about the type of material that is likely to be encountered are the most appropriate to minimise, the release of fines to the system. The key parameter within these sensitivity tests has been the exclusion of overflowing by the trailing suction hopper dredger and the use of backhoe dredger plant to remove a significant proportion of the rock material. By using these methods of operation the trailing suction hopper dredger does not release a relatively large mass of fine material; the fine material is captured in the hopper and transported offshore. The backhoe dredger releases a relatively lower mass of fines into the system than the cutter-suction dredger dredging the same material; however the penalty for this is the significantly lower production rate. How these releases for the 3 sections are represented in the modelling are described in the tables below.

The sensitivity assumptions made for the East Arm dredging hold true for the proposed pipeline dredge; particularly in view of the relatively small volume to be removed and the restrictions on plant choice available to complete the dredging due to the geometry of the dredge trench. The fines released by the proposed pipeline dredge are anticipated to be a few percent of the total fines mass released within the East Arm.

The material that is dredged within the East Arm will be transported to the offshore disposal ground; here it will be placed to the bed by hopper barges or by trailing suction hopper dredger dumping. Some of the material will immediately go into suspension as it falls through the water column; a proportion of the remainder (dependant upon the trapping by coarser material) will go to the seabed where it is then available for resuspension.

In the model simulations the fine material is released into the specific area (defined in Figure 3) that the dredging activity is scheduled to occur. For the modelling conducted within the East Arm the material is distributed evenly over the area and throughout the water column; the exact location of the dredge plant has not been assumed and therefore the initial concentration field will be spread over the whole zone in which the plant will ultimately work. This will lead to the under prediction of concentrations at the specific location that the dredger may be working (the near-field), but has the advantage of representing a release of fines over the whole zone that is to be dredged simultaneously; this ensures that transport pathways and dispersion effects over the entire area of dredging activity (the mid- and far-fields) are included in the modelling without the penalty of very complex set-up procedures to represent the full detail of the spatial distribution of the dredging process itself.

A different approach has been used for the offshore disposal ground because here it is practical to represent the individual disposal of each load of placed material over a relatively small area within the simulations; here the material is released at a (random) point within the area allocated for the offshore disposal ground, the material is released over an area approximately 200 m in diameter (simulating a single release from a barge or the trailing suction hopper dredger). Consequently the simulations here will be representative of the local concentration in the near-, mid- and far-field generated when the material is placed to the bed, and will allow for the potential accumulation of material on the bed that is then subjected to the processes of erosion and transportation. This is a more appropriate technique for the offshore disposal ground than used within the East Arm; if the material was placed over the whole disposal ground equally (as per the methodology for the East Arm) very low concentrations would be expected and complete dispersion of the fines might be anticipated, it would also not allow for the potential accumulation of material to the bed.

Sensitivity tests simulating varying amounts of how much of this material goes into suspension have been performed. For the Dredging case Study the assumption is that 7% of the mass placed immediately enters suspension, with 43% of the mass placed available for resuspension by the prevailing hydrodynamics. The remaining 50% of the mass placed is assumed to be immobile as a result of burial by other placed material or by armouring of the surface of the placed material.

In this report near-field, mid-field and far-field may be considered as:

- Near-field – The zone of immediate impact of the dredging plant; specifically within 500 m down stream of the operational plant.
- Mid-field – The zone of impact that is within 1 tidal excursion of the material released during the dredge operation.
- Far-field – The remaining zone of impact (in excess of 1 tidal excursion).

4.3 PIPELINE

4.3.1 Inputs and assumptions for pipeline dredge plume modelling

In addition to the dredging for the Module offloading facility, approach area and berth INPEX propose to excavate a trench for the sub-marine pipeline. This dredge will have a total volume of 574,000 m^3. The pipeline approach area is shown in Figure 6.

Table 12 below gives the volumes of material to be dredged for the trench broken down into different zones along the pipeline approach. The table also indicates the proposed dredge and disposal method.

Table 12 Volumes and disposal route for pipeline approach area dredge material

Area	Volume (m^3)	Material type assumption	Mass (T)	Disposal method
Shore crossing	225,000	PSD 4	195,750	backhoe dredger/Barge/Offshore
Zone A	53,000	PSD 4	46,110	backhoe dredger/Barge/Offshore
Zone B	73,000	PSD2/3	95,265	backhoe dredger/Barge/Offshore
Zone C	34,000	PSD2/3	44,370	backhoe dredger/Barge/Offshore
Zone D	127,000	PSD2/3	165,735	backhoe dredger/Barge/Offshore
Zone E (rock dumping only)	0	n/a	0	n/a
Zone F	62,000	PSD2/3	80,910	backhoe dredger/Barge/Offshore
Total	**574,000 m^3**		**628,140 t**	

Coffey Geotechnical (2009) undertook a program of boreholes along the proposed pipeline route. From this information the nature of the seabed material to be dredged has been characterised. For the Shore Crossing Zone and Zone A, with dredge volumes of 225,000 m^3 and 53,000 m^3 respectively the borehole analysis (PLBH01) shows significant fines content in the range 50-96%, hence PSD Type 4 (Table 2) with a fines content of 74.8% was chosen to represent this zone. For the other dredge zones, the borehole analysis (PLBH02-05) showed fines contents in the range of 15-40%; consequently the average PSD Type 2/3 of 39.2% was chosen for conservatism.

The plant specified to conduct the works is a backhoe dredger, with nominal bucket capacity of 15 m^3. This plant is similar to that used to dredge areas such as the module offloading facility as detailed in Section 3.2 of this document. The production rate, working in the material types defined in Table 2 with adequate tendering by barges is 60,000 m^3. From this it is possible to estimate the duration of dredging and the rate and total of fines losses from the dredging activity in each zone for the pipeline approach; this is presented in Table 13 below. The specific release included in the plume modelling is defined in Table 14. The releases are also included on Figure 7. In the modelling results presented the simulated release of fines from the pipeline trench dredge occurs simultaneously with the release from the module offloading facility dredging as this is expected to be conservative with respect to the rate of mass of fines released within Darwin Harbour; and illustrates the combined effect of the dredging activities. However, dredge plant availability may restrict the possibility of conducting the dredging simultaneously.

Table 13 Fines released and duration of dredging activity for pipeline channel approach

Zone	Volume to be dredge (m3)	Time Taken (Wks)	Loss Rate (Kg/s)	Mass of fine material lost (T)
Shore Crossing Zone	225,000	3.75	2.18	4,944
Zone A	53,000	0.88	2.18	1,165
Zone B	73,000	1.22	1.60	1,177
Zone C	34,000	0.57	1.60	548
Zone D	127,000	2.12	1.60	2,048
Zone E	0	0.00	1.60	0
Zone F	62,000	1.03	1.60	1,000
Total for pipeline approach:	**574,000**	**Approx 10**		**Approx 11,000**

Table 14 Inputs to fine sediment transport modelling for the pipeline trench dredge

Phase	Description	Duration	Bathymetry at start of dredging	Season	Releases to system
1a	backhoe dredger Shore Crossing Zone and Zone A	1.25 months	Existing	WET	A = backhoe dredger 2.18kg/s into suspension continuous release
1b	backhoe dredger in Zone B - F	1.25 months	Existing	WET	A = backhoe dredger 1.6kg/s into suspension continuous release

4.4 EAST ARM

4.4.1 Inputs and assumptions for East Arm dredge plume modelling

The approach to the sediment plume dispersion modelling in the East Arm has been to simulate the entire dredging operation via a number of representative phases. A typical dredge phase represents a time period of 1 to 11 months. The hydrodynamics for that period are represented by a number of repeating spring-neap cycles of tides representative of the wet or dry season. The TELEMAC-2D flow model provides this input (Ref 7). Wave effects, which are of importance over the intertidal areas in terms of periodically preventing deposition and causing erosion are represented in the DELWAQ model using a time-series of wind data from which to generate wind waves over the model domain.

The bathymetry for the modelling is selected to be representative of conditions during the phase and thus over time as the simulation runs through one phase into the next the evolution of the dredged footprint is included. The Dredging Case Study in the East Arm is represented by 10 Phases; with Phases 1 to 9 containing dredge activity and Phase 10 representing a period of 6 months after the cessation of dredging activities. The sediment plume dispersion modelling in this manner entails a continuous simulation of the whole dredging activity moving through one phase then the next until the whole of the dredging operation has been simulated.

Table 15 below summarises the 9 different phases that make up the overall Dredging Case Study indicating the dredging plant operating, the length of time the plant is operating, a representation of the bathymetry within the East Arm (also taking into account the progress of the dredging), the predominant season that occurs during the proposed dredging and the rate of release of mass of fine material by the plant operating in the East Arm.

Table 15 Description of schematisation and plume model inputs for the proposed dredge schedule in East Arm

Phase	Description	Duration	Bathymetry at start of dredging	Season	Releases to system
1	backhoe dredger in Module offloading facility.	5 months	Existing	WET	A = backhoe dredger 2.18 kg/s into suspension continuous release ***Note additional release for pipeline dredge work included (Defined in Table 14)***
2	backhoe dredger in berthing area, trailing suction hopper dredger in approach area area	8.5 months (backhoe dredger) 1.5 months starting at 7 months (trailing suction hopper dredger)	module offloading facility -4 m LAT	DRY	A = backhoe dredger 1.6 kg/s into suspension continuous release B = trailing suction hopper dredger 15 kg/s into suspension for 52 minutes every 311 minutes
3	backhoe dredger in turning basin, trailing suction hopper dredger in approach area	3 months	module offloading facility -4 m LAT berthing area -6 m LAT	WET	A = backhoe dredger 0.83 kg/s into suspension continuous release B = trailing suction hopper dredger 15 kg/s into suspension for 52 minutes every 311 minutes
4	trailing suction hopper dredger in berthing area, backhoe dredger in turning basin	6.5 months	module offloading facility -4 m LAT berthing area -6 m LAT approach area -7.8 m LAT	WET	A = trailing suction hopper dredger 15 kg/s into suspension for 52 minutes every 311 minutes B = backhoe dredger 1.6 kg/s into suspension continuous release
5	trailing suction hopper dredger in berthing area, backhoe dredger in Turning Basin,	2.5 months	module offloading facility -4 m LAT berthing area -10 m LAT turning basin -6 m LAT approach area -11 m LAT	DRY	A = trailing suction hopper dredger 15 kg/s into suspension for 52 minutes every 311 minutes B = backhoe dredger 0.83 kg/s into suspension continuous release

Phase	Description	Duration	Bathymetry at start of dredging	Season	Releases to system
6	1 x backhoe dredger in berthing area Area 1 x trailing suction hopper dredger in turning basin(part 1) 1 x trailing suction hopper dredger in berthing area Area (part 2) 1 x trailing suction hopper dredger in turning basin(part 3) 1 x cutter-suction dredger in berthing area Area	10.5 months (backhoe dredger) 4.5 months (trailing suction hopper dredger Part 1) 1 month (trailing suction hopper dredger Berth) 5 months (trailing suction hopper dredger Part 2) 1.5 month (cutter-suction dredger)	module offloading facility -4 m LAT berthing area -10 m LAT turning basin -6 m LAT approach area -11 m LAT	WET	A = backhoe dredger 0.83 kg/s into suspension continuous release B = 15 kg/s into suspension for 52 minutes every 311 minutes for both Part 1, Part 2 & 3 C = cutter-suction dredger 36 kg/s into suspension continuous release D = cutter-suction dredger 8.5 kg/s on to the bed continuous release
7	backhoe dredger in turning basin	5.5 months	module offloading facility -4 m LAT berthing area -14. 5m LAT turning basin-10 m LAT approach area -11 m LAT	WET	A = backhoe dredger 0.83 kg/s into suspension continuous release
8	backhoe dredger in approach area	4.5 months	module offloading facility -4 m LAT berthing area -14.5 m LAT turning basin-14.5 m LAT approach area -11 m LAT	WET	A = backhoe dredger 0.83 kg/s into suspension continuous release
9	Drill and Blast clear-up	1 months	module offloading facility -4 m LAT berthing area -14.5 m LAT turning basin -14.5 m LAT approach area -14.5 m LAT	DRY	A = backhoe dredger 0.26 kg/s into suspension continuous release
10	None	6 months	Installed depths	DRY	None

The proposed dredging activity will release fines into the local water column that can be advected and dispersed by the prevailing hydrodynamics, and or provide a source of fine material at the seabed (for example through cutter-suction dredger placement) that may then be resuspended by prevailing hydrodynamic action (i.e. peak currents over spring tide periods).

The rate of generation of fine material during the dredging activities is covered in Section 3.2; however it is also prudent to consider the total mass released during the dredging program as this will have a direct impact upon the total level of accretion within the vicinity of the dredging activity.

Table 16 below shows the total fines released in East Arm per dredging phase during the Dredging Case Study. The total mass of fines released simulated over the total dredging period (47 months) is of order 472,000 tonnes. This table includes the additional 11,000 tonnes generated during the proposed pipeline trench dredge. In the model simulations this additional mass of fines is released during the first 2.5 months of Phase 1. Note however, that the pipeline trench dredge may take place independently of the East Arm dredging.

Figure 7 also shows the relative magnitudes of the masses of fines released by the respective plant during the proposed dredge schedule within the East Arm (this also includes the pipeline dredge described in Section 4.3 above which has a total release of about 11,000 tonnes of fine material.)

Table 16 Mass of fines released during each phase of the proposed dredge plan

Phase	Length of simulation (Months)	Mass of fines released per phase (t)	Cumulative Mass of fines released (t)
1	5	38,400	38,400
2	8.5	43,600	82,000
3	3	25,100	107,100
4	6.5	67,000	174,100
5	2.5	21,000	195,100
6	10.5	255,600	450,700
7	5.5	11,500	462,200
8	4.5	9,400	471,600
9	1	700	472,300
Total	**47.0**	**472,300**	**472,300**

The total mass released during the modelled phases for each of the dredging plans has assumed the same loss rates as defined in Section 3.2. However, although these are the most appropriate loss terms to use in the numerical modelling and are considered to be a conservative estimate of the loss generated by the specified plant; variations in the material type to be dredged will affect the amounts of fines released at any one time.

The material is released evenly over the area where the dredging is taking place in the phase (by region defined in Figure 2). In this Dredging Case Study the releases are primarily straight into suspension, with the exception of the cutter-suction dredger where part of the release is made directly to the seabed and moves into suspension from the seabed. The material is released through the water depth at a constant rate defined within Table 14 and Table 15. This method of introducing mass to the model domain will underestimate local peak concentrations within and close to the footprint of the dredging activity, but is the most appropriate way of dispersing material to the far-field. Given that the key receptors of interest in the East Arm and Darwin Harbour are outside the dredging footprint this approach to simulating the dredging source was considered most appropriate in terms of computational efficiency and ease of examining a variety of dredge phases and sensitivity tests.

Figure 7 demonstrates that within the Dredging Case Study the greatest mass released to the system is generated by the use of the cutter-suction dredger, in Phase 6 about 2.5 years into the dredging program.

A dry density value of 700 kg/m^3 has been used to convert mass deposited on the seabed to depth of deposit on the seabed. This assumption is consistent with URS's field observations of the in-situ density of the surface material present over the mangrove areas (Ref 9). It is anticipated that there will be some vertical structure to the density of newly deposited material and that any rapid deposition in the subtidal areas may give rise to lower in-situ dry densities.

The model outputs for the East Arm modelling are discussed in Section 4.6.2

4.5 OFFSHORE DISPOSAL GROUND

4.5.1 Inputs and assumptions for offshore disposal ground dredge plume modelling

The modelling of fine sediment transport at the offshore disposal ground arising from placement activities has also been schematised. The input data for the mass of material delivered to the offshore disposal ground are defined in Table 9 and Table 11. The periods of placement at the offshore disposal ground match those of the dredging activity in the East Arm and the Pipeline trench dredge defined in Table 14 and Table 15. The schematisation is summarised in Table 17 below.

Table 17 Schematisation of fine material placed at the offshore disposal ground

Phase	Plant	Plant type	Load in Hopper (Tonnes)	Placement period (Months)	Frequency of Release	Mass fines released (Tons)
1	A	Barge	1,566	5.0	5 min every 592 min	997,800
1	*B*	*Barge*	*1,566*	*1.2*	*5 min every 592 min*	*222,600*
1	*B*	*Barge*	*2,358*	*1.2*	*5 min every 592 min*	*187,400*
2	A	Barge	2,358	8.5	5 min every 592 min	1,338,900
2	B	trailing suction hopper dredger	4,176	1.5	10 min every 311 min	181,600
3	A	Barge	3,730	3.0	5 min every 592 min	182,100
3	B	trailing suction hopper dredger	4,176	3.0	10 min every 311 min	367,500
4	A	Barge	2,358	6.5	5 min every 1020 min	929,300
4	B	trailing suction hopper dredger	4,176	6.5	10 min every 311 min	791,300
5	A	Barge	3,730	2.5	5 min every 1020 min	203,200
5	C	trailing suction hopper dredger	4,176	2.5	10 min every 311 min	306,900
6	A	Barge	3,730	10.5	5 min every 1020 min	844,600
6	B – Part 1	trailing suction hopper dredger	4,176	4.5	10 min every 311 min	549,100
6	B – Part 2	trailing suction hopper dredger	7,168	1.0	10 min every 311 min	192,900
6	B – Part 3	trailing suction hopper dredger	4,176	5.0	10 min every 311 min	605,500
7	A	Barge	3,730	5.5	5 min every 1020 min	443,700
8	A	Barge	3,730	4.5	5 min every 1020 min	363,500
9	A	Barge	3,614	1.0	5 min every 592 min	23,900
					Totals:	**8,731,800**

The cycle time for dredge plant operating at the offshore disposal ground are defined below.

A typical cycle for 3,000 m^3 barge loaded with weak materials is as follows:

- Loading – 220 minutes
- Sail to offshore disposal ground – 181 minutes
- Place material – 10 minutes
- Sail back to site – 181 minutes
- Total cycle – 592 minutes

Three barges required for continuous operations.

A typical cycle for 3,000 m^3 barge loaded with weak rock material from a backhoe dredger is as follows:

- Loading – 648 minutes
- Sail to offshore disposal ground – 181 minutes
- Place material – 10 minutes
- Sail back to site – 181 minutes
- Total cycle – 1020 minutes

Two barges required for continuous operations.

A typical cycle for 12,000 m^3 trailing suction hopper dredger is as follows:

- Loading
  - Pre overflow – 52 minutes
  - Overflow – 0 minutes
- Sail to offshore disposal ground – 122 minutes
- Place material – 15 minutes
- Sail back to site – 122 minutes
- Total cycle – 311 minutes

Table 17 suggests that approximately 8.7 Million Tonnes of fine (less than 75 μm) material will be placed at the offshore disposal ground, the remainder of the placed material being coarse.

Some of the fine material placed offshore (a proportion of the 8.7 Million Tonnes) will be available for transportation by the prevailing hydrodynamics. The proportion of this material that will be available is variable, although a mass will be immediately entrained into suspension that can be advected from the location of disposal it is also dependant upon the level of cohesion and trapping generated by the coarse material fractions when placed to the bed. Sensitivity tests to this process have been conducted.

The modelling tests conducted have assumed that a total of 50% of the fine material placed is available for diffusion and advection from the offshore disposal ground. Thus the total mass available for transport during the simulations is approximately 4.35 Million Tonnes. This assumed proportion takes into account the availability of sediment for transport as it is dropped from the barge (some will immediately enter suspension and be transported by prevailing hydrodynamics) whereas the majority will come to rest on the seabed at the location of placement. This material will contain a mixture of mud, silt, sand and coarse fractions (fractured rock from drill and blast activities) and consequently some of the finer fractions may be trapped, or protected from potential transport energies by armouring of the surface of the placed material.

The rate of placement of the dredge material at the offshore disposal ground will vary, and is dependant upon the material type dredged and type of plant operating. A time series of the cumulative simulated mass released at the offshore disposal ground is shown in Figure 151. This figure includes the material dredged and placed at the disposal site for the pipeline trench dredge.

In contrast to the dredging within East Arm the precise location of disposal in the offshore disposal ground has been represented in the simulations. Placement is represented in the model as occurring randomly within the entirety of the proposed disposal site; a single placement being distributed over an area of approximately 200 m in diameter. This means that local peak concentrations within the disposal area are represented unlike the situation in East Arm where peak concentrations will be underestimated. The model outputs for the offshore disposal ground are discussed in Section 4.6.3.

4.6 PLUME MODELLING RESULTS

4.6.1 Pipeline

The dredging of the pipeline trench is completed by using a single backhoe dredger loading three hopper barges. The material is taken to the offshore disposal ground. In the simulation the dredging commences at the shore end of the pipeline and moves progressively further offshore as material is removed. The releases from the backhoe dredger are relatively low magnitude; from the borehole data it is anticipated that the material located within the shoreline crossing zone will contain the highest fines content. This will lead to the highest levels of fines release when dredging this material. Of specific relevance are the suspended sediment concentration and deposition levels of fines material generated by this dredging activity at the Channel Island coral area. Time-series of concentration is shown for this location in Figure 8 with time-series of deposition shown in Figure 9, Figure 8 to Figure 15 shows the time-series concentration and deposition at Channel Island coral, north east Wickham Point, South Shell Island and Weed Reef for the completed 47 month long Dredging Case Study (including the 6 months post-dredge), this also includes the effects of placing material to the offshore disposal ground. The various phases of the Dredging Case Study are also marked on the Figures.

In reference to the Channel Island coral site the relatively short time scale of the proposed pipeline trench dredging is apparent; with concentrations peaking at approximately 18 mg/L above background at approximately Day 30 into the dredge program when the combination of tidal currents, dredge plant location and release rates combine to generate the highest suspended concentrations A secondary peak in the suspended sediment concentrations is also apparent approximately 900 Days into the dredge program; this can be attributed to the high intensity of dredge activity in the East Arm during Phase 6. Concentrations at this time peak at around 10 mg/L above background at this location; however more significant increases, of up to 70 mg/L, are evident at north-east Wickham Point and South Shell Island. Peak suspended sediment concentrations do not exceed 6mg/L at Weed Reef for the simulations conducted. The levels of simulated accumulation at all the coral sites remain less than 1mm throughout the whole of the dredge program.

In the sensitivity tests conducted the effect of the module offloading facility dredging, will increase the background suspended sediment concentration levels at the Channel Island corals by a relatively insignificant amount. The increase in magnitude is low, of the order of 5% of the levels generated by the dredging of the pipeline trench. This is demonstrated by the low levels of increased concentration at the Channel Island corals occurring from Day 100 to 140. Due to the low level of fine material release and short duration of the pipeline dredge, the pipeline dredge is not predicted to affect suspended sediment concentrations significantly within the East Arm. Concentration levels of less than 5 mg/L above background may potentially occur in the western end of the East Arm.

Figure 16 shows a coloured surface plot of the peak levels of suspended sediment concentration above background during the proposed pipeline dredge. They occur during the approach to the second series of spring tides at approximately Day 30 in the dredge schedule. The peak levels are generated at this time due to the accumulation of fine material on the seabed within the vicinity of the dredge activity during the neap phase of the spring to neap cycle. Once the tidal flows obtain sufficient energy this material is then resuspended generating a plume of material that leads to this concentration level.

Once the dredging activity moves offshore, the increase in background concentration levels generated by the pipeline trench dredging at the Channel Island Coral site steadily reduces. However, consideration should be given to the increase in background concentration levels generated by dredging in the East Arm.

The level of accretion in the intertidal zone is low during this dredge activity; levels of accretion of less than 100 mm are expected at the end of the proposed pipeline trench dredge, shown in Figure 17. These levels of accretion are expected to occur generally within the dredge footprint of the pipeline trench and only within the shore crossing zone.

4.6.2 East Arm

The dredging of the proposed approach area and module offloading facilitywill be completed using a combination of plant, including backhoe dredger, trailing suction hopper dredger and cutter-suction dredger, the releases from the individual plant being variable in magnitude. Some drilling and blasting of hard rock material will also be required. The excavated material will be transported to the offshore disposal ground by barges and trailing suction hopper dredger.

The results presented in Figure 18 to Figure 93 consider the fate of the fine material released in the East Arm, but also give consideration to interaction of additional fine sediment sources from the pipeline trench dredge and placement at the offshore disposal ground. The results are presented on a phase by phase basis with an additional figure representing the 1.5 month period of most intense dredging activity as defined in Table 15, with an additional phase (Phase 10) being a 6 month period after the cessation of dredging. The plots show the median concentration, the 95th percentile concentration and depth of accumulated fine sediment at the end of each phase.

Figure 18 to Figure 28 show the simulated median concentration values within the East Arm for each dredging phase during the Dredging Case Study. The median, which is the most frequently occurring concentration value experienced throughout the dredge phase, is shown in colour bands, with concentrations of less than 3 mg/L above background not shown. The footprint of the proposed approach area is also shown. The mean water level within the Harbour is represented as a black line; this delineates the approximate extent of the mangrove area. Figure 29 to Figure 39 show the 95th percentile concentration value using the same format and colour scale. The 95th percentile values represent the suspended sediment concentration value which is likely to be exceeded for only 5% of the time per phase of dredging.

Looking through the figures sequentially it is apparent that the concentration fields gradually increase in extent and magnitude towards Phase 6; following Phase 6 they reduce significantly. The greatest median suspended sediment concentrations occur at the time of the dredging activity that releases the most fines (Phase 6); this pattern is repeated in the 95th percentile figures. For all phases within the Dredging Case Study peak median suspended sediment concentration levels do not exceed 100 mg/L within the zone of dredging and over 200 mg/L locally high on the intertidal zones; this level may be attributed to shallow water depth and temporary 'ponding' effects within the model bathymetry. For the 95th percentile figures, peak concentrations within the dredge area remain below 200 mg/L with similar values occurring over the high intertidal areas. Looking at Figure 35, which represents the most intensive period of dredging (middle section of Phase 6), the zone of elevated concentrations generally remains within the East Arm, even during the period of activity that includes use of the cutter-suction dredger. The 95th percentile concentration field extends less than 5km seaward of Mandorah at a value of 3 mg/L. In context, the concentration field may exceed this extent and magnitude for approximately 2 days over the 1.5 month period of cutter-suction dredger dredging within the 4 year dredge program. Table 18 below provides the equivalent length of time (days) that 95th percentile concentrations are simulated to be exceeded for each scenario.

Table 18 Time equivalent of 95th percentile concentration exceedances

Phase	Length of simulation (Months)	Length of time in excess of 95th percentile (nearest 0.25 days)
1	5	7.25
2	8.5	12.25
3	3	4.25
4	6.5	9.5
5	2.5	3.75
6	10.5	15.25
7	5.5	8
8	4.5	6.5
9	1	1.5
10	6	8.75
All	**53**	**77**

The concentration field also migrates into Cossack and Lightening Creeks to the south of the proposed approach area, and out of the East Arm to Channel Island; however, the 95th percentile concentration in this area is around 3 mg/L.

Figure 40 to Figure 83 show the dynamic nature of the plume arising from the dredging activities. The figures show the extent of the plume at peak flood current and ebb tide current during a neap tide and a spring tide respectively. These figures represent the period within the tide when current velocities are at their maximum, this will typically generate the greatest potential for dispersion of the dredge plume. The most apparent difference between the concentration fields during typical spring and neap tides is the larger area of the plume on both the flood and ebb during a spring tide. The plume is significantly more dispersed during the flood tide, with the concentration field extending onto the intertidals. Peak levels during the spring flood tide vary dependant upon the operational plant; backhoe dredger plant typically generate concentrations fields in the range of 5-20 mg/L; whilst the period of peak activity in Phase 6, which includes the trailing suction hopper dredger and cutter-suction dredger generates values of up to 200 mg/L.

Figure 68 to Figure 79 demonstrate that instantaneous suspended sediment concentrations at various stages through the tidal cycle for Phases 7 to 9 are low; specifically they remain below the 3 mg/L. This can be attributed to the relatively low release rates of the backhoe dredge and the modelled releases are spread over the proposed area of dredged activity to accurately represent the mid and far-field dispersion of the released material.

Figure 84 to Figure 93 show the simulated levels of accretion of fine material within the East Arm for each dredging phase during the Dredging Case Study. The depth of accretion of fine material is represented by varying colours. The locations of marine wrecks and heritage sites (including the Catalina wreck locations) are represented by black triangles.

Approximately 472,000 dry tonnes of fine material is released by the Dredging Case Study within East Arm. Some of this material is transported by the prevailing hydrodynamics out of Darwin Harbour; however the majority remains within the East Arm and is deposited onto the intertidal areas where wave action assists in transferring the fines higher into the mangrove areas of the intertidal areas where wave action and tidal currents are reduced. This fine material accumulates over the intertidals at a rate that is proportional to the releases occurring within the East Arm. This is apparent in Figure 84 and Figure 85 where the releases are predominately from backhoe dredger plant. The levels of accretion are generally less than 20 mm and the majority occurs over the low intertidal areas, with higher intertidal areas experiencing accretion up to 10 mm in depth.

As more plant (trailing suction hopper dredger) becomes engaged in the dredging activity, through Phases 3, 4 and 5 more fine material begins to accrete over the low intertidal area so that by the end of Phase 5 (Figure 88) levels of accretion of up to 50 mm are simulated on the north side of Darwin Port with similar, localised values found in the low intertidal between Preston and Wickham Point. During Phase 6 there is a significant increase in dredge activity and release of fines with the introduction of the cutter-suction dredger. The cutter-suction dredger will be working in the berthing area area, with a significant mass of material placed to the bed for re-dredging by trailing suction hopper dredger. This work leads to an accretion of fines within the dredge pocket of up to 500 mm. However, the peak levels of accretion over the intertidal areas have not increased significantly. Levels of up to 100mm are simulated in some of the low intertidal areas between Preston Point and Wickham Point; with the majority of areas experiencing accretion remaining below 20mm.

During Phases 7, 8 and 9 only backhoe dredger plant is working and there is little additional fine material accumulating within East Arm. Phase 10, which shows the areas of deposition 6 months after dredging has stopped, with some slight erosion of the accumulated areas as the prevailing hydrodynamics begin to erode and redistribute some of the deposited material.

The figures also show that fine-grained sediment is not simulated to accumulate over the wreck sites during the dredge program; additionally the plots highlight that the accumulation patterns between Phase 6 and Phase 10 are dominated by redistribution rather than additional accumulation, consistent with the reduced fines release rate. This is demonstrated by the localised zones of accumulation and erosion.

For the Dredging Case Study time-series of suspended sediment concentrations and deposition above background rates at the locations of the corals in Darwin Harbour have been extracted from the model results. These are presented in Figure 8 and Figure 9 and discussed in the context of the pipeline dredging in Section 4.6.1

The cutter-suction dredger activity (which occurs for 1.5 months during Phase 6 – see Table 15) is noticeable on Figure 8 at all locations; with suspended sediment concentrations peaking at Wickham Point at approximately 70 mg/L above background at around Day 900. Typically, concentrations at Wickham Point and South Shell Island are in the range of 7-15 mg/L above background with concentrations of around 3 mg/L experienced at Weed Reef. Peak values for South Shell Island are similar to Wickham Point, whilst those at Weed Reef remain below 10 mg/L for all dredging phases.

Another form of presenting these results is to tabulate the exceedance of different concentration thresholds at different locations for different phases during the Dredging Case Study; these are shown in Table 19 to Table 29. Table 30 presents a summary; detailing the exceedance values for the whole Dredging Case Study

Table 19 Percentage exceedances of concentration thresholds at locations around Darwin Harbour - Phase 1

Concentration (mg/L)	Percentage Exceedance at location for Phase 1			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	99.84	99.73	99.82	67.03
5	<0.01	0.01	<0.01	0.37
10	0.00	<0.01	0.00	0.03
20	0.00	0.00	0.00	<0.01
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 20 Percentage exceedances of concentration thresholds at locations around Darwin Harbour - Phase 2

Concentration (mg/L)	Percentage Exceedance at location for Phase 2			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	100.00	100.00	100.00	66.59
5	0.51	<0.01	<0.01	<0.01
10	<0.01	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 21 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 3

Concentration (mg/L)	Percentage Exceedance at location for Phase 3			
	south Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	100.00	100.00	100.00	67.17
5	0.61	<0.01	<0.01	<0.01
10	<0.01	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 22 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 4

Concentration (mg/L)	Percentage Exceedance at location for Phase 4			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	100.00	100.00	100.00	67.16
5	2.03	<0.01	<0.01	<0.01
10	<0.01	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 23 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 5

Concentration (mg/L)	Percentage Exceedance at location for Phase 5			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	100.00	100.00	100.00	66.58
5	1.16	<0.01	<0.01	<0.01
10	<0.01	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 24 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 6

Concentration (mg/L)	Percentage Exceedance at location for Phase 6			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	100.00	100.00	100.00	67.17
5	9.60	5.60	<0.01	0.03
10	5.49	2.75	0.00	<0.01
20	2.50	0.83	0.00	0.00
50	0.19	0.05	0.00	0.00
100	<0.01	<0.01	0.00	0.00

Table 25 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 7

Concentration (mg/L)	Percentage Exceedance at location for Phase 7			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	100.00	100.00	100.00	67.17
5	0.06	<0.01	<0.01	<0.01
10	<0.01	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 26 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 8

Concentration (mg/L)	Percentage Exceedance at location for Phase 8			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	100.00	100.00	100.00	67.16
5	<0.01	<0.01	<0.01	<0.01
10	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 27 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 9

Concentration (mg/L)	Percentage Exceedance at location for Phase 9			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	99.96	99.96	99.96	66.59
5	<0.01	<0.01	<0.01	<0.01
10	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 28 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – Phase 10

Concentration (mg/L)	Percentage Exceedance at location for Phase 10			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	99.98	99.99	100.00	67.12
5	<0.01	<0.01	<0.01	<0.01
10	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
50	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00

Table 29 Percentage exceedances of concentration thresholds at locations around Darwin Harbour – all phases during Dredging Case Study

Concentration (mg/L)	Percentage Exceedance at location for Dredging program			
	South Shell Island	NE Wickham Point	Weed Reef	Channel Island Coral
0	99.98	99.97	99.98	67.02
5	2.33	1.11	<0.01	0.04
10	1.09	0.55	0.00	<0.01
20	0.50	0.16	0.00	0.00
50	0.04	0.01	0.00	0.00
100	<0.01	<0.01	0.00	0.00

The accumulation of fines over the mangrove areas has been investigated in detail; for the purposes of this modelling study mangrove habitat occurs within the intertidal zone. The area of accretion above different depth thresholds in these areas have been established and are provided in Table 30

Table 30 Depth of accumulation during Dredging Case Study over all Mangrove zones

Deposit thickness greater than (mm)	Area covered in all mangrove zones (ha)
10	846.2
20	356.0
50	30.0
60	13.3
80	4.5
100	2.1
200	0.0

Table 30 shows that approximately 850 ha of the intertidals will experience accretion of 10 mm, with approximately 2 ha experiencing accretion in excess of 100 mm.

4.6.3 Additional sensitive locations within East Arm

Within East Arm six additional locations have been identified as potential sensitive receivers to accumulation of fine material. The locations are defined as the following (see Figure 2):

Talc Head

The simulations conducted show that sediment is not simulated to accumulate at this location; in addition, the concentration field is not apparent at 3 mg/L for the 95th percentile analysis. However, the proposed pipeline trench dredge will pass within 3km of this location and thus brief periods of a small increase in suspended concentrations should be expected as the releases from the backhoe dredger are relatively low.

Channel Island Intake

Time series analysis of the simulations has been conducted; they demonstrate that fine material is not simulated to accumulate at the Channel Island location other than local to the proposed pipeline dredge trench. However, concentrations at the Channel Island coral location are simulated to peak at approximately 20 mg/L; this concentration field will encompass the island during part of the pipeline shore approach dredge. Concentrations at the Channel Island intake are simulated to reach up to 10 mg/L above background. (Figure 16)

Hudson Creek Export Facility

The model has simulated that an accumulation of fine material may occur within Hudson Creek; this will reach a maximum of up to 100 mm during Phase 6. However, the model shows that the areas of accumulation will be patchy and are likely to be influenced by the local variations in bathymetry and water depth; consequently, some areas within Hudson Creek do not experience accumulations of fine material. This pattern is reflected within the concentration field. Maximum 95th percentile values reach 200 mg/L in a localised area with values ranging between 20-50 mg/L being typical.

East Arm Boat Ramp and Landing

The simulations conducted indicate that some accretion of fine material will occur at these locations in the order of 5-20 mm during the Dredge Case Study. 95th percentile concentrations in this area are in the range of 20-50 mg/L.

Port Corporation Berth

The tests conducted show local deposition on the upstream (south-eastern) end of the East Arm Port Berth of the order (20-50 mm), but deposition is not simulated to occur further west along the East Arm Wharf.

Fort Point

Several berths exist on the south-eastern flank of Fort Point. The test conducted simulated that some accumulation of fine material is to be expected within these berths. Levels of up to 50 mm are simulated to occur; with peak 95th percentile concentrations in the range of 10-20 mg/L.

Its should be acknowledged that the model has limited resolution in the areas of question; it is not detailed enough to represent all the features of the various Darwin waterfront developments (various marina basins, jetties, ramps and basins running from Frances Bay around to Emery Point). By virtue of there design, marine berths generate quiescent areas of water and given that the model predicts small increases in background concentrations in most of these areas it is reasonable to assume that most of these basins will be subjected to a degree of enhanced siltation.

In context, the additional accumulation of this fine material will augment the existing maintenance dredge requirements. Using the Fort Point Berths as an example; the modelling has simulated that approximately 1500 m^3 of fine material may accumulate within the berth area over the course of the dredging. This emphasises the potential of these features as sediment sinks within Darwin Harbour. However, the pattern and levels of accumulation within the basin will vary considerably; consequently, this value should be considered against existing maintenance requirements.

4.7 OFFSHORE DISPOSAL PLUME MODELLING RESULTS

Coarse and fine material will be placed at the offshore disposal ground throughout the duration of the Dredging Case Study by barge and trailing suction hopper dredger. Again the results are presented on a phase by phase basis, and are centred on the median concentration and depth of accumulated fine sediment at the end of each phase.

Figure 94 to Figure 104 show the simulated median concentration values at the offshore disposal ground for each dredging phase during the Dredging Case Study. Figure 105 to Figure 115 show the simulated 95th percentile concentration values at the offshore disposal ground, in the same format and colour scale as Figure 94 to Figure 104.

Looking sequentially at the figures it is apparent there is no interaction of the East Arm and offshore disposal area plume discernable at median concentrations of greater than 3 mg/L. For most phases the median concentration value does not exceed 3 mg/L; specifically only within Phase 5 is an area represented on the figure. A small zone at the western extremity of Shoal Bay is apparent with median concentrations up to 5 mg/L.

Figure 105 to Figure 115 demonstrates that at 95th percentile levels the concentration fields are not simulated to interact; however, the plume from the offshore disposal ground is significantly better defined. The plume is simulated to cover a relatively large area; with the concentration field reaching into Shoal Bay and to the Vernon Islands – albeit at relatively low levels of concentration (up to 10 mg/L). At the 95th percentile level a few zones of high concentration exist; specifically the Howard River mouth and the offshore disposal ground. Here the concentration values are around 20-50 mg/L. The higher concentrations within the river mouth can be attributed to the shallow water depths (as with the intertidal areas in East Arm); whilst those at the offshore disposal ground may be related to the intensity of releases.

Figure 116 to Figure 125 show the level of fine material accumulation in the vicinity of Darwin Harbour. Sequentially, the figures show a gradual trend of accumulation in the high subtidal and low intertidal areas along the coastline between Mandorah and the Adelaide River mouth. The areas of accumulation are limited in size and do not become apparent until the end of Phase 3. Some very local accumulation is present at the offshore disposal ground; however, the pattern and level of this will be dependant upon the placement by the operational plant.

The fine material continues to accumulate through Phase 4 to 6, with levels of up to 20 mm occurring within Shoal Bay, to the East of Lee Point. No material is simulated to occur in the Howard River mouth at this time. Levels of up to 20 mm are simulated to occur within the Adelaide River mouth; and very locally this may reach 50 mm. It is worth noting that the model does not fully represent the tidal prism of the Howard and Adelaide Rivers nor simulate the effects of fresh water outflow; this may affect the pattern and levels of accretion within these areas.

Figure 126 shows the location of the representative points within the model domain used and Figure 127 to Figure 129 shows the simulated time-series of suspended sediment concentration at representative points for the Howard River, Gunn Point and Adelaide River. It shows that background suspended sediment concentrations are not simulated to exceed 15 mg/L throughout the Dredging Case Study. In general suspended sediment concentrations build through the dredge schedule and reduce after Day 750. The suspended sediment concentrations are highest at the Howard River location; this is to be expected due to its proximity to the offshore disposal ground, with appreciable spikes occurring (Day 375 and Day 750) when the combination of placement frequency and hopper material containing a higher proportion of fines occurs, and temporary accumulation of fine material on the seabed during neap tides generate elevated suspended sediment concentrations. This pattern is less obvious as the distance is increased from the offshore disposal ground. Clearly defined peaks are apparent with the variation in tidal range (moving from spring to neap and back to spring range at all sites.) The time-series of elevated concentrations extends further at the Adelaide River location than Gunn Point; this can be attributed to the accumulation and subsequent resuspension of fine material at this location. Table 31 shows the exceedance of various suspended sediment concentration thresholds at the Howard River Mouth, Gunn Point and Adelaide River.

Table 31 Percentage exceedances of concentration thresholds at various locations outside of Darwin Harbour

Concentration (mg/L)	Percentage exceedance at location for all phases		
	Mouth of Howard River	Mouth of Adelaide River	Gunn Point
0	99.89	98.83	99.95
5	0.74	0.19	0.44
10	0.05	<0.01	<0.01
20	<0.01	0.00	0.00
50	0.00	0.00	0.00
100	0.00	0.00	0.00

Fine material is not simulated to accumulate at the offshore disposal ground during the length of the simulated Dredging Case Study. However, the underlying assumption that 50% of the placed mass of fines is trapped within the seabed at the disposal ground is not inconsistent with observations of the seabed (Ref 11). These observations indicate that over the disposal ground the seabed sediments comprise a varying mix of fines and sands.

5. *Sediment Transport Modelling – Coarse material*

5.1 INTRODUCTION

The TELEMAC-2D flow model tool used to drive the fine sediment plume modelling work within Darwin Harbour has also been used to model the potential sand transport pathways in the East Arm and around the proposed offshore disposal ground. The rate of release of sand-sized material associated with the pipeline trench is considered to be insignificant and therefore sand dispersion from this element of the dredging activity has not been simulated.

The HR Wallingford sand transport model, SANDFLOW has been used to simulate the sand transport. SANDFLOW is a dynamic non-cohesive sediment transport model that simulates the process of entrainment, transport and settling. The SANDFLOW model has been developed in-house at HR Wallingford.

The approach to the sand transport modelling has been developed with the following in mind:

- Identification of the existing sand transport pathways from the offshore disposal ground and within the East Arm.
- Consideration of the distribution of sand within the model domain based on seabed sediment data.
- Identification of the effects on existing sand transport patterns of bathymetric modification at the offshore disposal ground and within East Arm.

5.2 TEST CONDUCTED

The following tests are presented sequentially through this section of the report and are designed to reflect the areas of investigation defined above:

1. Sand transport in the East Arm

a. Identification of existing sand transport pathways where the model has a mobile bed over the whole model domain with the exception of the area above -2 m LAT. This is designed to reflect the existing in-situ sediment types experienced. The seabed sediment type above this relative water level throughout East Arm is likely to be mud and silt due to the presence of mangroves over much of the intertidal area. The plume modelling results have shown some accretion of fine material in the high subtidal areas.
b. Identification of the potential transport pathways with mobile bed as above but with the bathymetry changed to represent the completion of the dredging works in East Arm. This simulation will highlight the modification to the existing sand transport pathways generated by the modification to the seabed by the dredge activity.
c. Identification of the potential transport pathways generated by placement of the sandy material to the bed within then footprint of proposed dredging based on the existing bathymetry within the East Arm. This simulation will detail how the material will move when placed to the bed and its potential migration to and potential accumulation on historic marine wreck sites at the beginning of the dredge program.

2. Sand Transport at the offshore disposal ground
   a. Identification of the existing sand transport pathways where the model has a mobile bed over the whole model domain with the exception of the area through the Clarence Straits. This assumption is consistent with the high tidal flow velocities that are likely to occur in this area preventing the natural accumulation of sand on the seabed. HR Wallingford has received some qualitative information relating to the seabed sediment types located towards the north end of Shoal Bay that suggests the presence of gravel material. This is consistent with the high flow velocities experienced at this location. This simulation will represent the potential transport pathways in the offshore area prior to disposal activities commencing. It is also representative of the first months of offshore disposal when no significant morphological change to the seabed occurs. It is noted that the material type being placed at the offshore disposal site is broadly similar (silty-sand) to that found in-situ based on a drop camera survey (Ref 11).
   b. Identification of the potential transport pathways generated after placement of the sandy material to the bed; this material is then assumed to accumulate to a depth of 1.0 m above the baseline bathymetry. The model has a mobile bed over the whole model domain as above. This simulation will identify the effects on the potential sand transport magnitudes from the site generated by modifications to the tidal flow by the reduction in water depth. This simulation will represent potential transport pathways under the maximum simulated level that the seabed is to be locally raised by material placed there.

An important influencing factor in the rates and patterns of potential sand transport is the inclusion of wave effects. Specifically, the transmission of energy through the water column by sea waves generates a stress at the seabed that can be represented as an oscillatory current. The magnitude of the current is directly linked to the energy of a wave and is defined by the combination of wave height, wave period and water depth. For the offshore disposal ground, which is relatively exposed, wave action is likely to contribute significantly to the potential transport of sandy material at the seabed. In view of this, additional simulations have been undertaken including the effect of a constant wave height and period over the whole model domain to represent the effect of wave-stirring at the seabed.

Additional sensitivity tests have been conducted relating to the location of the placement of material within the proposed offshore disposal area and to varying the size of the material placed there. Specifically, a test of larger sized material (350 µm) was undertaken for both the East Arm and offshore disposal ground. The results showed that the potential sediment transport patterns remained effectively identical to those of smaller sized material. However, the magnitude of the sediment transport rate was significantly reduced; by order a half the rate of 150 µm material. This magnitude in reduction of transport rate is consistent with the analysis of observed threshold of motion velocities and potential transport rates of varying sized material under taken by Van Rijn (Ref 12) and Soulsby (Ref 13). 150 µm sized sand material is representative of the finer sand fractions of the silty sand and gravel type material to be placed at the offshore disposal site and will therefore serve to be conservative in the representation of the extent and magnitude of potential sediment transport.

Sand transport is strongly linked to the strength and direction of the peak current flows in the areas of interest. It should be noted that within East Arm and Darwin Harbour the flow model is well calibrated (Ref 7) and hence there is a strong degree of confidence in the sand transport model predictions in this area. In the vicinity of the offshore disposal site the flow model is less well validated. Accordingly it has not been considered appropriate to simulate sand transport processes to the same level of detail as for the fine sediment. The sand transport modelling has not considered different phases or the full extent of the dredge program. A period of six months of uniform release of sand at the dredge site in East Arm or at the disposal site has been used as the basis for the simulations. These simulations have then been scaled up to account for the total release of sands during the dredging (or disposal) process.

5.3 INPUT WAVE CONDITIONS

As previously discussed, the rate of transport of coarse material at the offshore disposal area is greatly influenced by the inclusion of wave effects. A uniform wave condition of 1.25 metre significant wave height (Hs) and 8 second peak period (Tp) was used as input to the sensitivity testing of sand transport under the action of waves.

These representative values are consistent with the modelled range in values for offshore wave conditions described in EX6218. These parameters are also consistent with the available data collected by BMT from February to April 2009 using a Seabird Pressure transducer; therefore waves of this magnitude may be more common during the wet-season but also have the potential to occur during the dry season. However, this is a very short period of time to analyse and deduce a typical wave climate for a given location, especially given that the period that was measured covers a transition between seasons.

5.4 SAND DISPERSION – EAST ARM

5.4.1 Material put on the bed by dredging activity in the East Arm

During the dredging within the East Arm a mass of coarse material will be released by the dredge plant. The sandy material released will quite rapidly descend to the seabed because of the relatively high settling velocities of the sand particles. As a starting point for considering the fate of material released into East Arm from the dredging activity the assumption is made that the released sands initially accumulate within the footprint of the approach area. The net mass of coarse material released during the course of the dredging in this area is expected to be in the order of 0.4 Mt. Assuming this material forms a deposit on the bed with a dry density of 1.6 t/m^3 and it is released evenly over the entire approach area footprint, this is equivalent to a depth of deposit of 0.1 m. As with the disposal activity this release will take place over several years and accordingly the amounts present on the seabed will vary over time with some accumulating in the footprint and some sand being transported away from the area of the dredging. Because the mass of sand released into East Arm during the dredging is relatively small the subsequent impacts of sand migrating away from the dredge area are also expected to be small.

5.4.2 Sand transport predictions

Figure 130 and Figure 131 show the results of the sand transport predictions for Test 1a described above, the location of historic marine wrecks including Catalina sites being shown as purple dots on all figures. Figure 130 shows the transport vectors for sand and illustrates a residual transport into East Arm. Areas of potential accretion (red) and erosion (blue) are illustrated in Figure 131. The flow field has been applied to the seabed for a spring-neap cycle (approximately 14 days) and the simulations show that the seabed below -2 m LAT within the East Arm is potentially mobile under existing conditions if it is comprised of 150 µm material, with the area covered by the approach area indicating a net flood-dominant transport pattern into the East Arm. The seabed demonstrates that zones of erosion and deposition exist under the existing conditions.

This simulation suggests that, where the existing seabed is comprised of fine sand, most of the seabed in the vicinity of the historic wreck sites is exposed to the potential for erosion and deposition under the existing hydrodynamics; specifically, the seabed around the wrecks located at the to the western end of the approach area show areas of potential erosion and deposition of up 0.02 m during a spring-neap cycle. The seabed around the wreck sites located further into the East Arm and on the south side of the approach area is subject to lower levels of potential erosion and deposition.

Figure 132 and Figure 133 display the results of the sand transport prediction for Test 1b described above. The images are comparable to Figure 130 and Figure 131. The figures illustrate that the potential sand transport pattern is still one of flood tide dominance, particularly in the outer section of the approach area as the proposed dredging has made little modification to the magnitude and direction of the tidal currents in this area of Darwin Harbour. The westernmost wreck site is still in a zone of high potential sand transport, and is subject to the same potential magnitudes of erosion and deposition as indicated in the pre-dredge simulation.

An appreciable change has occurred within the eastern half (east of 706000 mE) of the proposed dredge area. The potential sand transport rates have reduced significantly as a result of the currents reducing in the deepened area; specifically within the Turning Area, rates have reduced from a magnitude of over 20,000 kg/m/cycle to less than a few hundred. The potential sand transport rates at the locations of all the wreck sites (with the exception of the westernmost) have reduced appreciably. An increase in the intensity of the net ebb tide current on the north-east slope of the approach area has generated a local zone of erosion that is not apparent in the pre-dredge simulation, and may be attributed to an acceleration of the local flow field in this area.

The reduction in the potential sand transport rate is mirrored in the potential zones of erosion and deposition. In the western section of the approach area, the patterns of potential erosion and deposition remain broadly similar to those generated during the pre-dredge. In the eastern section of the approach area, there has been a significant modification to patterns of potential erosion and deposition, with a large area of the dredge basin now experiencing accretion. This is generated by a significant reduction in tidal flow velocity caused by the increase in water depth coupled with the net flood-dominant transport pattern of the outer approach area.

At all the wreck locations the potential levels of deposition and erosion have been reduced; an appreciable change is noted at the sites along the southern side of the approach area. The intensity of the erosion and deposition pattern to the north side of the approach area has also reduced in magnitude; this may impact upon the rate of migration of the existing bed forms in this area, shown in Figure 134

Figure 135 and Figure 136 display the results from Test 1c. This simulation differs in approach to Tests 1a and 1b in that sand has only been placed within the dredge footprint of the approach area. This is in order to simulate the fate of sandy material placed to the bed during the dredge activities in the East Arm. The simulation represents a 'worst case' scenario as it uses the pre-dredge bathymetry, as Test 1b highlighted the presence of the dredged feature generates a potential sediment trap for sandy material in the eastern area. Thus, as the dredging operation continues, the depth of the dredge pocket will increase and its ability to trap sediment will also increase. At the beginning of the proposed dredging, there will be the greatest potential for material to migrate from the point of origin and not become potentially trapped within the created dredge pocket.

Note that based on these results the total accretion estimated to occur outside of the footprint of dredging is likely to be less than a few centimetres because of the magnitude of the initial losses of sand-sized material during the dredging. The release of sands and patterns of accumulation will not be uniform as illustrated by the model but will represent variability at a scale below that of the grid resolution in the model. A uniform initial deposit of 100 mm is assumed.

Figure 135 demonstrates that the net flood tide transport pathway is apparent over the approach area and material will tend to migrate along the approach area into the eastern section of this area under the residual current. Potential transport pathways exist for material to migrate out of the east end towards the north-east of the approach area; this material may feed existing bed-forms. This pattern is consistent with the alignment and migration of well formed sand waves in this area (Ref 14) shown in Figure 134.

Figure 135 indicates that all the wreck sites are on the fringe of a potential sand transport pathway for sandy material released by the dredging activity; this is confirmed by the potential zones of deposition and erosion. The simulation conducted shows that sediment is not expected to accrete over the seabed in the vicinity of most of the wrecks as a result of dispersion from the dredge site over a single spring-neap tide cycle. Only 2 wreck sites (midway along the southern edge and to the north-east of the approach area) are simulated to experience deposition over a spring-neap cycle. The magnitude of this accretion is relatively low in the context of existing patterns.

When Figure 131 and Figure 136 are compared, the potential depth of deposition generated by the dredging activity in the East Arm over the wreck sites is placed in context. The magnitude and area that is simulated to be mobile under existing seabed and hydrodynamic conditions by virtue is simulated to be larger; however, it is apparent that the material released during the dredge activities does not significantly enhance the deposition at the wreck sites.

It is likely that the levels of potential deposition generated at the wreck sites by tidal reworking of the sand deposited within the proposed approach area over the longer term will be relatively low. Consideration should also be given to the natural migration of the sand waves present to the north of the proposed approach area; as migration of these features may potentially generate sedimentation around wrecks within these locations that is more significant than that generated by the release of sand material by dredging inside the proposed approach area footprint.

The amounts of sand released during the Dredging Case Study are small because it is assumed there is no overflow of the trailing suction hopper dredger. Accordingly, the risk of associated sedimentation in the vicinity of the wreck sites is also small. It should be noted, however, that the resolution of the flow model in East Arm is insufficient to represent the detail of morphology around the wrecks; hence, the assumption from the modelling that deposition of a few centimetres might occur uniformly over areas of the seabed does not fully represent the small scale interaction around wreck sites. Such interaction is likely to locally trap proportionately more of the sandy material that migrates towards the wreck sites from the dredge footprint.

The influence of waves on the potential sand transport pathways has not been simulated for the East Arm; the predominantly occurring wave height and period recorded within the East Arm is unlikely to increase the magnitude of the sand transport pathways, although such waves are important for the transport of fines in shallower waters.

5.5 OFFSHORE DISPOSAL GROUND

5.5.1 Grading of material placed at the offshore site

The assumed breakdown of fractions of coarse material to be placed offshore that are greater than 75 µm is given in Table 32 below. This breakdown is the assumed particle size distribution following dredging. Material which is granular in-situ will retain its in-situ size distribution. Soft, medium and hard rock will break up into coarser and smaller fractions.

Table 32 Assumed particle size distribution of coarse and fine material placed at the offshore disposal site by size fraction

Size fraction (µm)	Percentage of total
Fine material (<75 um)	33%
75 - 80	2%
80 -100	11%
100 -150	13%
150 - 200	14%
200 - 300	6%
300 - 400	3%
400 - 600	1%
600 - 1000	1%
1000 - 2000	0%
2000 - 4000	1%
> 4000	15%
Total	**100%**

The mass distribution of the coarser material takes a bi-modal distribution, with a significant proportion of the material placed (40%) having a grain size of between 75 to 200 µm, and 16% having a grain size over 2000 µm.

Table 33 below gives the threshold of motion (U_{crit}) for the median grain size of each class, calculated by the method given by Soulsby (1997).

Table 33 U_{crit} values for various sand fractions present in the dredge material

Size (µm)	U_{crit} (m/s)
78	0.467
90	0.470
125	0.473
175	0.474
250	0.477
350	0.485
500	0.508
800	0.573
1,500	0.754
3,000	1.099

Coarse material released into the East Arm will tend to be in the finer sand fractions. Offshore disposal will release all sizes of material. The peak spring tidal currents experienced at the offshore disposal area are predicted to be of the order 0.9 m/s. This flow magnitude is not sufficient alone to generate transport for the coarsest fractions of the material placed offshore which represent some 16% of the mass placed. Whilst much of the placed material is likely to be mobile at the placement site the action of the currents will tend to sort and armour the placed material effectively trapping some of the more mobile fractions (both fines and fine sands) in the bed. Additionally, burial of some of the finer material within individual placements will reduce the availability of the finer material for transport. It has been assumed that, of the fines fraction placed, about 50% is available for dispersion away from the site as detailed in Section 4 of this report, the remainder being trapped by armouring or buried as described above.

Transport of this larger sized material (a few millimeters in diameter) is possible under combined wave and tidal flow action. Assuming the coarse material has a dry density of 1.6 t/m^3 after placement onto the seabed and it were all spread evenly over the footprint of the offshore disposal area, the coarse material would equate to an average depth of deposit of approximately 1.0 m; however, if only the southern half of the disposal area were used this would increase to 2.0 m. The placement activity will occur over a period of years. The rate of placement combined with the rate of dispersion of the finer material from the site will lead to reduced levels of average accumulation.

5.5.2 Sand transport predictions

Simulations of sand transport from the offshore disposal ground have been undertaken as detailed above. Figure 137 and Figure 138 display the results for Test 2a; they show the sand transport patterns (flux magnitude and direction) and zones of potential erosion and deposition for 150 µm sand over a spring-neap cycle at the offshore disposal area. They can be considered representative of the potential sand transport pathways at the start of the dredging program.

The initial condition for these runs is schematised as sand placed uniformly over the whole model domain, with the exception of the Clarence Straits. In this area the tidal currents are potentially too strong to allow a sandy seabed to exist. Seabed surface sediment investigations have shown that gravel sediments exists to the northern end of Shoal Bay; this is consistent with the higher tidal current velocities experienced in this area. The depth of sediment placed over the mobile bed area is equivalent to 1m; this in an arbitrary depth and will allow sufficient supply of sand should the prevailing hydrodynamics have a tendency to erode the seabed. The depth of sand available in the model is not represented in the morphology of the model and does not therefore have an impact on flow conditions; it is included in the model as a potential source.

Figure 137 indicates that some of the sands dispersing from the offshore disposal ground may follow a transport pathway towards the sand banks in the vicinity of the approach areas to Darwin Harbour. The figure also illustrates the presence of a flood-dominant potential transport pattern into Darwin Harbour under tide-only conditions.

Under tide-only conditions the predicted net sand transport pathway is to the south-west of the offshore disposal area during a spring-neap cycle. The potential sand transport pathway is dominated by the magnitude and duration of the prevailing tidal current above the critical velocity for transport. In the model peak-tidal currents are directed towards the south-west.

Under tide-only conditions the north-east edge of the site is most susceptible to deposition due to the gradually diminishing tidal current velocities across the proposed offshore disposal ground; this is shown in Figure 138. The remainder of the site is shown to be relatively immobile when considering sediment size of 150 μm.

In a repeat simulation of Test 2a including wave-stirring effects, the potential sand transport rate is augmented significantly (Figure 139). Also, the zone of peak deposition extends further into the disposal site as the oscillatory current generated by the wave condition augments the transport capacity of the tidal flow entering the site on both the flood and ebb tides. Localised areas of erosion may also occur across the site; this is demonstrated in Figure 140. The blue line on Figure 141 and Figure 142 indicates the potential transport magnitude to the south-west, whilst the red line shows potential transport to the north-east.

During tide-only conditions the peak potential transport rates coincide with the largest flow magnitudes, which are prevalent during spring tides (Days 3-5). However, during neap tides (Days 10-13) the current velocities generated are not sufficient to generate potential sand transport.

During the sensitivity tests to grain size the patterns of potential sand transport pathways for the smaller- and larger-grain-sized material were similar, with the exception that for the larger-grain-sized material the magnitudes of transport are significantly less because the critical velocity for transport is exceeded for shorter periods of time.

The addition of a uniform wave condition to the simulation increases and changes the potential sand transport pathways significantly. This is demonstrated by the change in predicted flux magnitude and vector directions and by the reduction in asymmetry of the through-tide transport magnitudes as shown in Figure 141 and Figure 142.

Figure 143 and Figure 144 display the results of Test 2b; they show the sand transport patterns (flux magnitude and direction) and zones of potential erosion and deposition for 150 μm sand over a spring-neap cycle at the offshore disposal area when the bathymetry has been raised at the offshore disposal ground by 1.0 m to simulate the placement of the dredge material; they are comparable to Figure 137 and Figure 138. It is unlikely that the increase in seabed level will reach this height as material will be lost into suspension and winnowed following placement; however, it represents the maximum level attained if all coarse material is retained there.

A local increase in the potential sediment transport rate is apparent in Figure 143, and is consistent with erosion and deposition patterns shown in Figure 144. The pattern of erosion and deposition from the offshore disposal sites is explained by the local increase and decrease in the flow velocities over the site generated by the reduction in water depth. The net south-westerly transport pathway means that the material eroded from the north-east edge of the site is transported over the site and deposited on the south-western edge where the water depth increases and the flow velocities reduce.

This pattern of erosion on the north-east edge with redistribution and deposition to the south-west of the site is somewhat reduced by the inclusion of wave-stirring effects. Figure 145 and Figure 146, comparable to Figure 143 and Figure 144 show the significantly enhanced potential transport rates generated by the wave-stirring effects. Figure 146 shows that the erosion of the top edge of the side slope and the deposition of material is experienced on all sides of the proposed disposal ground; it is most prevalent on the north-east and south-west flanks. This material is then redeposited just outside of the disposal ground at the toe of the slope. This process indicates that there will be agitation and local redistribution of the placed material within the offshore disposal ground and that over time the slopes of the disposal site will degrade.

Figure 147 shows the potential sand transport rate away from the site under tide-only conditions when the offshore disposal ground bed elevation is raised by 1.0m to simulate the material placed at the site. The pattern of potential sediment transport is broadly similar to Figure 141 and Figure 142, with an increase in magnitudes to both the south west and north east under both tidal currents alone and with wave-stirring effects (Figure 148). This may be attributed to the additional mobilisation of sand over the site due to the reduction in local water depth and higher local current speed.

In all simulations conducted, the sediment-stirring effect generated by the wave orbital velocity, combined with net north-eastward residual current, creates net transport to the north and east. This is a result of this combination being sufficiently strong to overpower the predicted peak-tidal, current-driven potential sand transport pathway to the south-west. From the simulations conducted this is likely to occur when wave energies exceed that capable of generating an orbital velocity at the seabed of order 0.35 m/s. This wave orbital velocity is representative of the input wave condition, but is also representative of a wave having 1.0 metre significant wave height and 12 second peak period . The wave orbital velocity magnitude can be generated by numerous combinations of wave height and wave period which are likely to occur at the offshore disposal ground.

Figure 149 and Figure 150 show the difference in deposition patterns under existing bathymetry and raised bathymetry at the offshore disposal ground. Figure 149 emphasises the net north-east to south-west migration of material from the top edge of the offshore disposal ground. The pattern of erosion at the north-east edges of the disposal site is also apparent in Figure 150 under wave action; however, it is distributed more evenly, indicating a removal of material from the top of the slopes to the toe of the slopes of the proposed offshore disposal ground. Both images show that, under tide-only and wave-stirring effects, no discernable change to the pattern of deposition and erosion is evident at the mouth of Darwin Harbour over the spring-neap cycle. Table 34 below summarises the transport tests undertaken with relative magnitudes of potential transport rates from the offshore disposal ground.

Table 34 Potential sand transport rates from the offshore disposal ground

Test	Description	Flux to south-west (Tons/spring-neap cycle)	Flux to north-east (Tons/spring-neap cycle)
1	Tide-only transport	90,796	29,642
2	Tide plus wave transport	646,645	723,345
3	Tide-only transport and offshore disposal ground raised +1.0m	99,128	32,985
4	Tide plus wave transport and offshore disposal ground raised +1.0m	666,580	740,610

Table 35 below summarises the relative change in potential transport rates from the offshore disposal ground with the bed levels raised by 1 m.

Table 35 Relative changes in the potential sand transport rates from the offshore disposal ground

Test	Comparison description	Percentage increase SW	Percentage increase NE
1	Tide plus wave transport vs tide-only transport	612%	2340%
2	Tide plus wave transport with offshore disposal ground raised +1.0m vs tide-only transport with offshore disposal ground raised +1.0 m	572%	2145%
3	tide-only transport with offshore disposal ground raised +1.0m vs tide-only transport	9%	11%
4	Tide plus wave transport with offshore disposal ground raised +1.0 m vs Tide plus wave transport	3%	2%

In summary, the simulations have shown:

1. In the East Arm
   a. Significant potential for sand transport exists, with potential of transport across the wreck sites. The simulations have shown that the locations of the wrecks are susceptible to erosion and deposition over a spring-neap cycle. The presence of seabed forms (such as sand waves, for example) indicates the presence of mobile sand.
   b. The additional sand material released into the dredge footprint may be potentially transported from the point of origin, inline with the existing flood-

dominant residual current. The additional deposition this may generate within the East Arm is simulated to affect only a limited number of wreck sites over a spring-neap cycle; the magnitude of the effect is relatively small against the context of the already potentially mobile bed.

c. Following completion of the proposed dredging, sediment transport patterns at the western end of the approach area are not simulated to be affected greatly. However, where the greatest and most widespread bathymetric changes have occurred (within the eastern end of the approach area), there is substantial potential for the accumulation of sandy material. This trapped material will not be available for transport over other areas of the East Arm; subsequently, the transport rates to the north-eastern and southern flanks of the proposed dredged area are reduced, with a corresponding reduction in potential for deposition over the wreck sites. It should be noted the simulations represent a spring-neap tidal cycle, and the smallest levels of accumulation generated over this time indicate that, over the longer term accumulation and migration of the sediment is to be expected.

2. At the offshore disposal ground

a. The surrounding seabed is potentially mobile, with strong transport pathways identified into Darwin Harbour. Under tide-only conditions, material placed to the bed at commencement of the dredge program will have a tendency to migrate to the southwest of the site, with some accumulation in the north-east corner. If wave-stirring effects are considered, the sand transport potential is augmented significantly (1-2 orders of magnitude) and the net potential sand transport direction reverses from the south-west to north-east if wave energies are sufficient. The entrance to Darwin Harbour is an active zone of potential erosion and deposition; this is consistent with observed presence of sand banks and subtidal bars.

b. The placement of sandy material to the seabed will have the effect of reducing the water depth locally; this has the potential to influence sand transport patterns. In the simulations conducted, the effect of placement of material and raising of the seabed is limited in extent, with local zones of erosion and deposition observed at the fringes of the offshore disposal ground; this is the case for both tide and tide plus wave effects. The effects do not spread far beyond this local zone.

c. The effect of wave-stirring over the sandy seabed offshore is a more significant effect on the potential sand transport pathways and rates of transport than the effect of placing sand material to the seabed. Variability in wave action from one year to the next and the additional effects of extreme events will be responsible for changes in transport processes across the wider offshore area and in the vicinity of the mouth of Darwin Harbour. The influence of the offshore disposal on this process will be small, albeit that some of the sands dispersed over time from the site will feed into the sand transport regime in the approaches to Darwin Harbour.

5.5.3 Rate of placement of coarse material at the offshore disposal ground

A time-series of the modelled rate of transport of coarse material from the offshore disposal ground under varying hydrodynamic conditions is shown in Figure 151. This has been calculated by scaling up the simulated spring-neap cycle transport magnitudes to cover the length of the proposed dredge schedule. Thus, a comparison of the results at 6 month intervals is shown in the table below.

Table 36 Comparison of sandy mass placed and potential flux of sandy material away from the offshore disposal ground

Time (Months)	Gross Flux for 150 µm material (Tons)	Gross Flux for 150 µm material with wave condition (Tons)	Gross Flux for 150 µm material offshore disposal ground elevation +1.0 m(Tons)	Gross Flux for 150 µm material with wave condition offshore disposal ground elevation +1.0 m (Tons)
0	0	0	0	0
6	1,512,732	17,207,379	1,659,364	17,674,609
12	3,025,464	34,414,757	3,318,728	35,349,218
18	4,538,196	51,622,136	4,978,093	53,023,827
24	6,050,929	68,829,515	6,637,457	70,698,436
30	7,563,661	86,036,894	8,296,821	88,373,045
36	9,076,393	103,244,272	9,956,185	106,047,654
42	10,589,125	120,451,651	11,615,549	123,722,263
48	12,101,857	137,659,030	13,274,913	141,396,872

Table 32 shows that approximately 37% of material placed offshore during the proposed dredge plan are between 75 µm and 150 µm. The potential transporting capacity of the tidal flows (without any wave-stirring) is approximately 12 to 13 Million Tonnes of 150 µm median diameter material. Hence, during placement, if this fine fraction is not buried or otherwise lost to transport through armouring processes, all of this fine sand might be dispersed from the site by tidal conditions alone. Naturally, as the grain size increases, the transporting potential of the hydrodynamics reduces. It is likely that most of the material removed will be below 250 µm as the critical velocity for the threshold of motion magnitude for this size of material is lower.

This analysis shows that the material placed at the offshore disposal ground is likely to accumulate at a more rapid rate than can be removed by the potential sediment transport flux generated by the prevailing hydrodynamics. However, it is likely that the vast majority of the small-sized coarse material that is available to be transported (up to approximately 250 µm) will be transported away from the offshore disposal ground as a result of periodic wave activity at the site. The pathways of dispersion are illustrated in Figure 137 and Figure 139.

The reduction in water depth brought about by the disposal of material at the offshore disposal ground will increase the rate of flux of sand material from the offshore disposal ground; this is due to the increase in flow velocity over the site. However, the increase is not substantial and does not match the rate of placement of material to the site.

As already shown, wave-stirring effects significantly enhance the potential sediment transport flux from the proposed offshore disposal ground. The effect is greatest for the finest sand fractions. The tests conducted show that the majority of the small diameter sandy material can be transported away from the offshore disposal ground under tide-only conditions, with wave-stirring effects adding significantly to the potential sand transport capacity. This will mean during times of significant wave energy a significant proportion of material placed at the offshore disposal ground has the potential to be mobile.

6. Conclusions

This report presents a description of the comprehensive and detailed development and analysis of a Dredging Case Study, which could be applied to the development of Darwin Harbour East Arm for the Ichthys Project in specific relation to the mass of material released during a defined program of dredging activity. The dredging program comprises three key elements:

- Pipeline approach;
- East Arm shipping channel, approach area, turning basin and tanker berthing area as well as module offloading facility;
- Offshore disposal ground.

In relation to the proposed dredging and disposal of the dredge material, specific consideration and subsequent definition has been given to the following topics:

1. Dredging methodology – the type of plant to be used, its length of operation and significantly the associated production rate and simulated release rates (both fines and coarse material)
2. Fate of fine material – the use of numerical models to accurately simulate key processes of erosion, suspension, advection, diffusion and deposition of fine material within the East Arm and a specified offshore disposal ground. Specific attention has been given to the agitation and resuspension of fine material over the low intertidal zone as this process is significant in estimating the distribution and magnitude of accretion over the upper intertidal mangrove area. Estimations of the suspended sediment concentrations for this Dredging Case Study at various locations through Darwin Harbour have also been provided; of key interest are the Channel Island coral areas.
3. Fate of coarse material – as with modelling of fine material the use of numerical models to identify potential sand transport pathways and simulated levels of potential erosion and accretion within the East Arm and the offshore disposal ground has been completed. Of specific focus has been the potential for migration of coarse material onto Catalina wreck sites and the potential for accumulation offshore of sands adjacent to the approaches to Darwin Harbour.

6.1 PIPELINE APPROACH

The dredging of the pipeline approach channel is estimated to take approximately 10 weeks using a backhoe dredger of nominal 15 m^3 bucket capacity. The releases from this plant are expected to be relatively low, consequently suspended sediment concentrations and associated levels of deposition will remain low. Peak concentrations of the order 20 mg/L above background may be associated with this work at the Channel Island coral site, and peak levels of deposition of the order 200 mm may be generated; however the deposition will be confined to a small area (generally within the dredge footprint).

The far-field effects of this work are expected to be relatively very low, with the increase on background concentrations reducing significantly outside of the immediate vicinity of the operational plant when the dredging of the shore crossing zone is complete; this is after approximately 4 weeks into the scheduled program of works.

The specific levels of increases above background can be alleviated by modifying the point within the spring-neap cycle that the dredging is conducted. Neap tides tend to allow the accumulation of fine material on the seabed in the vicinity of the working plant; when tidal energy increases leading towards spring tides, this material is resuspended leading to elevated suspended sediment concentrations. Spring tides will prevent this accumulation but have the potential to disperse material over a larger area in the short term. It is suggested that this phase of work is conducted during spring tides to prevent the accumulation of fine material on the seabed. Accumulated material may be remobilised, generating short-lived but significantly elevated periods of suspended sediment concentrations as the tidal range and thus currents grow from neap to spring tides.

The effect of the proposed pipeline trench dredging is anticipated to be relatively insignificant to the complete program of works scheduled for the East Arm; this is to be expected as the mass of material to be removed is more than an order of magnitude less.

The dredging simulated to occur within the East Arm will have a relatively insignificant impact upon suspended sediment concentrations at the Channel Island corals; an increase of approximately 5% of the peak levels associated with the pipeline dredging have been simulated. The dredging of the pipeline approach channel will have negligible effect upon suspended sediment concentrations.

6.2 EAST ARM APPROACH AREA AND MODULE OFFLOADING FACILITY

The dredging of the East Arm approach channel and associated areas is expected to take approximately 47 months and release of the order 472,000 tons of fine material and a similar quantity of coarse material into the East Arm.

The majority of the coarse material will fall through the water column and rest on the seabed close to its point of generation. However, this material will then potentially be available for transport under the prevailing hydrodynamic conditions. Numerical modelling suggests that potential transport pathways exist for material placed within the approach area footprint; this is confirmed by the presence and apparent migration of sand waves within the vicinity of the proposed dredging.

Some of the released coarse material has the potential to be transported out of the proposed dredge footprint, and zones of accretion outside of the approach area will occur over the longer term. It is expected that the Catalina wreck sites will not be exposed to significant levels of sedimentation from coarse-grained material in the short term (weeks to months); however as evidence exists for the migration of existing bed features in the long term (years) the same migration of the released coarse-grained material should be expected. The mass of material placed on the seabed distributed evenly is the equivalent to a depth of approximately 0.1 m over the whole dredged area. In context this is significantly smaller in magnitude than the existing bed features, whose migration may pose a more significant threat to accretion over some of the Catalina wreck sites than coarse material released during the proposed dredging activity.

The post-dredge bathymetry has been simulated; it shows that there is the potential for material to accumulate within the dredge footprint and significantly reduces the net flood-dominant transport pathways that presently exist within the East Arm. The most significant change is simulated to occur at the eastern end of the approach area.

The fine material released during the proposed dredging is far more dispersive than the coarse material; this is illustrated by the extent of the plume concentration field during flood and ebb for both spring and neap tides. Consequently, the area that is subject to accretion is more widespread and variable in magnitude. However, no intertidal areas are predicted to experience accretion of more than 200 mm over the dredge program, the rate of accumulation being related to the intensity of the dredging and release rate from the operational plant.

The simulations have shown that accumulations of fine material gradually build through Phases 1 to 3 (months 0 to 16.5) when the backhoe dredger is operational, and from Phases 3 to 6 (months 16.5 to 36) as successively more plant are utilised. Peak dredging activity occurs in a 1.5-month window of peak dredging activity approximately half way through Phase 6 (month 30-31) which features backhoe dredger, trailing suction hopper dredger and cutter-suction dredger. The rates of accumulation are predicted to be highest during Phases 3 to 6 (months 16.5 to 36).

The rate of fines released during the dredging program is varied; the most significant rate occurring approximately 30 months into the program and is associated with the use of a cutter-suction dredger to remove some of the stronger phyllite. The plume arising from the dredge activity extends over a significant area filling most of the East Arm. Typically, median concentrations throughout all of the dredging phases are in the order of 3-20 mg/L. In context, additional analysis on the simulated results indicates that 95^{th} percentile concentrations remain below 200 mg/L, even when all dredge plant are in operation in Phase 6. It should be noted that this is equivalent to approximately 2 days within the 4 year Dredging Case Study when concentrations are simulated to exceed this value; typically, the phased averaged median concentrations remain below 50 mg/L.

This trend is also reflected in the rate and magnitude of accretion over the intertidal areas; specifically, an accreting trend is observed through the first 36 months, with peak rates observed in months 30 and 31. The release rates of fines then significantly diminish and the depth of accretion remains approximately constant with some areas experiencing slight erosion through until the end of the dredging program.

Some of the material is expected to accumulate within the dredge footprint and other quiescent areas of the subtidal area. Notable areas are the north side of the Port of Darwin and between Preston and Wickham Points. The accumulation is simulated to occur up to and through Phase 6 (months 25.5 to 36) of the dredging program; after this phase, due to the relatively low rate of fines released to the system, the accumulation tends to be redistributed.

6.3 OFFSHORE DISPOSAL GROUND

Nearly all mass dredged within the East Arm is expected to be placed offshore. Of this, some 8.7 Mt will be in the fines fraction. The majority of the placed material is expected to be coarse-grained material.

The coarse-grained material placed offshore will be exposed to the prevailing tidal currents and wave energies. If representative wave energy is included, the potential sand transport rate increases significantly over tidal energy alone. This allows not only more material to be potentially transported from the site but also some of the larger fractions of the coarse material generated by the cutter-suction dredger and drilling and blasting techniques to become mobile. It is possible that over the longer term a significant proportion of the coarse material placed at the offshore disposal ground will migrate away from the site, mixing in with the surrounding seabed sediments.

The sand transport modelling at the offshore disposal ground suggests that there is an asymmetric transport of coarse-grained material to the south-west due to the dominant peak-tidal currents; this is neutralised and ultimately reversed when wave-stirring effects reach a specific magnitude. Consequently, some coarse-grained sediment has the potential to be transported towards the mouth of Darwin Harbour.

Coarse material also has the potential to be transported to the north-east of the disposal site when wave energies reach a sufficient magnitude; this material is likely to be moved towards the Vernon Islands. The Clarence Straits are a region of high tidal energy and the sandy material that is transported from the site towards this area is unlikely to accumulate on the seabed in the Straits; however, it may form a feed for existing relative quiescent areas where sand is already present on the seabed.

Tests have been conducted to simulate the potential coarse-grained sediment transport pathways following an accumulation of material at the offshore disposal ground. The test identified that neither the existing net south-west tidal transport pathway, nor the net north-east, wave-agitated tidal transport pathway is affected by the modification to the bathymetry by an accumulation of material. The change in bathymetry affects only the local hydrodynamics and consequently the effect upon erosion and deposition patterns at the offshore disposal ground is limited to within a few hundred metres of its boundaries.

Over the longer term, it may be reasonably expected for the material placed at the offshore disposal ground to move and spread across the seabed through the combined effects of regular agitation from waves and currents and the less frequent influences of extreme storm events.

The fine-grained material placed offshore will be subject to the same hydrodynamic processes as the coarse-grained material; however, the net transport pattern of this material is dominated by the residual tidal currents and shows net north-easterly transport. The median suspended sediment concentrations are generally less than 3 mg/L. The specific amount of fines released from the offshore disposal ground will be subject to the amount of trapping and cohesion in the sediment. The 95^{th} percentile plots represent the extent of the concentration field offshore; the peak values are up to 20 mg/L located at the offshore disposal site and within the shallow confines of the intertidal areas of the Howard River. In addition to these zones of elevated suspended sediment concentrations, there are simulated to be patches of fine material accumulation in the high subtidal and low intertidal areas along the coastline between Mandorah and the Adelaide River. The patches are relatively small in size and not simulated to exceed more than 20mm in depth; the model does not fully represent the tidal prism of the river systems or take into account any fresh water flow which may alter the magnitude and pattern of accumulations. Fine material is not simulated to accumulate at the offshore disposal site during the course of the Dredging Case Study.

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Glossary

Term	Definition
95th percentile	The value in a set where 5% of values are greater and 95% are lower.
accretion	The build-up of sediment on subtidal and intertidal zones; the opposite of erosion.
bathymetry; bathymetric	Refers to the seabed and its measured depth, normally relative to LAT.
BHD	The abbreviation for backhoe dredger—mechanical dredger used in substrate types such as firm clay, soft rock and blasted rock; essentially, this type of dredger can be viewed as a land-based excavator mounted on a floating, stationary platform which is anchored by three spud poles.
concentration threshold	A nominated value of the amount of suspended sediment held in the water column at any one time; normally measured in milligrams per litre (mg/L).
CSD	The abbreviation for cutter-suction dredger—a stationary hydraulic dredger equipped with a cutterhead which excavates the soil to allow it to be sucked into a pipeline by the flow of water created by the dredge pump(s). During operation, the dredger moves around a spud pole by pulling and slacking on the two fore side wires. This type of dredger is capable of dredging all kinds of material, but particularly stronger material, and is accurate due to its movement around the spud pole.
DELWAQ	A 2D or 3D water quality modelling framework developed by Deltares. It solves the advection-diffusion-reaction equations on a model grid for a wide range of model substances including suspended fine sediments.
Dredging Case Study	The dredging plan (i.e. equipment to be used and timing schedule) developed to minimise environmental impact by refining various methodologies relating to the dredging of the different components within the dredging footprint, and used as the basis for predictions of environmental impacts.
dredging footprint	The area of seabed delineated by the boundary between that part of the seabed to be disturbed by the dredging process and that part which will remain in its natural state.
DRL	Dredging Research Limited—HR Wallingford's dredging and reclamation group.
dry tonne	Material from the seabed in its natural state contains a high percentage of water. Dry weight (measured in tonnes) of the same mass value of material is measured after the material has been dried to a relatively low, consistent moisture level. If the material is in its natural, wet state, it is called a wet tonne.
far-field	The zone of impact of the dredging plant that is more than one tidal excursion of the material released during the dredge operation.
GD	The abbreviation for grab dredger—a mechanical dredger which uses a crane with a clamshell grab. Similar to BHDs, the crane is mounted on a floating, stationary platform which is anchored by three spud poles. Soil types are generally limited to sediments and soft clays.
hopper barge	A purpose-built vessel for transporting dredge spoil to a designated disposal site. It may be either self-propelled or pushed or towed by a tug. Once at the disposal site, the spoil is discharged through the keel by opening the hopper.
hydrodynamics	Refers to the characteristics of fluids in motion; the nature of the movement of fluids.
intertidal zone	The area of foreshore that is exposed to the air at low tide and underwater at high tide.

Term	Definition
kg/s	The symbol for kilograms per second—used in dredging to express the rate of release of fines.
LAT	Lowest Astronomical Tide—the lowest tide that can be expected to occur under average atmospheric conditions (i.e. calm wind; standard air pressure of 1016 millibars). It is used as the level from which water depths are measured. A negative value indicates a level below LAT.
median	The value in a set where 50% of values are greater and 50% are lower. Also known as 50th percentile.
micrometre (µm)	The SI derived unit of length equivalent to one-millionth of a metre, or one-thousandth of a millimetre.
mid-field	The zone of impact of the dredging plant that is within one tidal excursion of the material released during the dredge operation.
Mm^3	The symbol for million cubic metres.
morphology; morphological	Refers to the characteristics, configuration and evolution of seabed forms and shapes as they influence and are influenced by fluid motion.
MPa	The symbol for megapascal, which is a million pascals. The pascal is the SI derived unit of pressure, stress, Young's modulus and tensile strength, and is defined as a force per unit area of one newton per square metre.
N/m^2	The symbol for newtons per square metre—a measure of force per unit area.
neap tide	The tide which has the smallest range between low and high; occurs twice a month.
near-field	The zone of immediate impact of the dredging plant; specifically, within 500 m downstream of the operational plant.
nearshore geotechnical investigation	An investigation carried out in late 2008, involving the extraction of core samples from approximately 30 holes drilled into the seabed, to the proposed dredging depth, in and around the dredging footprint. The core samples were analysed in a laboratory to determine material type and characteristics such as UCS and PSD. This information was used to develop the dredge plan.
oscillatory current	A current that varies in speed and direction over a period of time; often in a reciprocal fashion.
percentage exceedance	The percentage of time for which an instantaneous measurement of a variable quantity exceeds a given value.
PSD	The abbreviation for particle size distribution—the amounts of the various soil size fractions in a soil or disintegrated rock sample, usually expressed as weight percentage (also known as grain size distribution).
sand flux	The rate of movement of sand grains over the seabed; varies with current speed.
SANDFLOW	A dynamic, non-cohesive sediment transport model that simulates the process of entrainment, transport and settling of sand and coarser-grained materials; developed in-house at HR Wallingford.
significant wave height (H_s)	The average wave height (trough to crest) of the largest one-third of waves passing a given point.
spring tide	The tide which has the greatest range between low and high; occurs twice a month.
subtidal zone	The zone in the ocean below the lowest water line (i.e. below LAT). It immediately adjoins the intertidal zone.
t; (Mt)	The symbol for tonne(s); (symbol for megatonne(s)—million tonnes).

Term	Definition
TELEMAC-2D	A state-of-the-art, free-surface flow suite of solvers developed by a kernel of European organisations including the Laboratoire National d'Hydraulique et Environnement, Electricité de France, the Federal Waterways Engineering and Research Institute of Germany and HR Wallingford in the UK.
tidal excursion	The net horizontal distance covered by a water molecule or particle during one complete tidal cycle of flood and ebb.
threshold of motion	The minimum current speed required to entrain particles into the water column; dependent on particle size.
TSHD	The abbreviation for trailing suction hopper dredger—a hydraulic dredger used for removal of unconsolidated marine sediments using suction pipes or "drag arms" that are hung from gantries or lowered from the hull of the vessel. The sediment material is pumped, using onboard centrifugal pumps, to the dredger's hopper where solids separate out and water may be discharged at keel level. When the hopper is full, the vessel can travel to the designated disposal site and discharge the spoil to the seabed through the keel by opening the hopper.
UCS	The abbreviation for unconfined compressive strength—defined as the measure of force required to crush a sample of sediment in the vertical direction without lateral restraint.
wave period (T_p)	The time interval (normally in seconds) for successive wave crests to pass a given point.

Figures

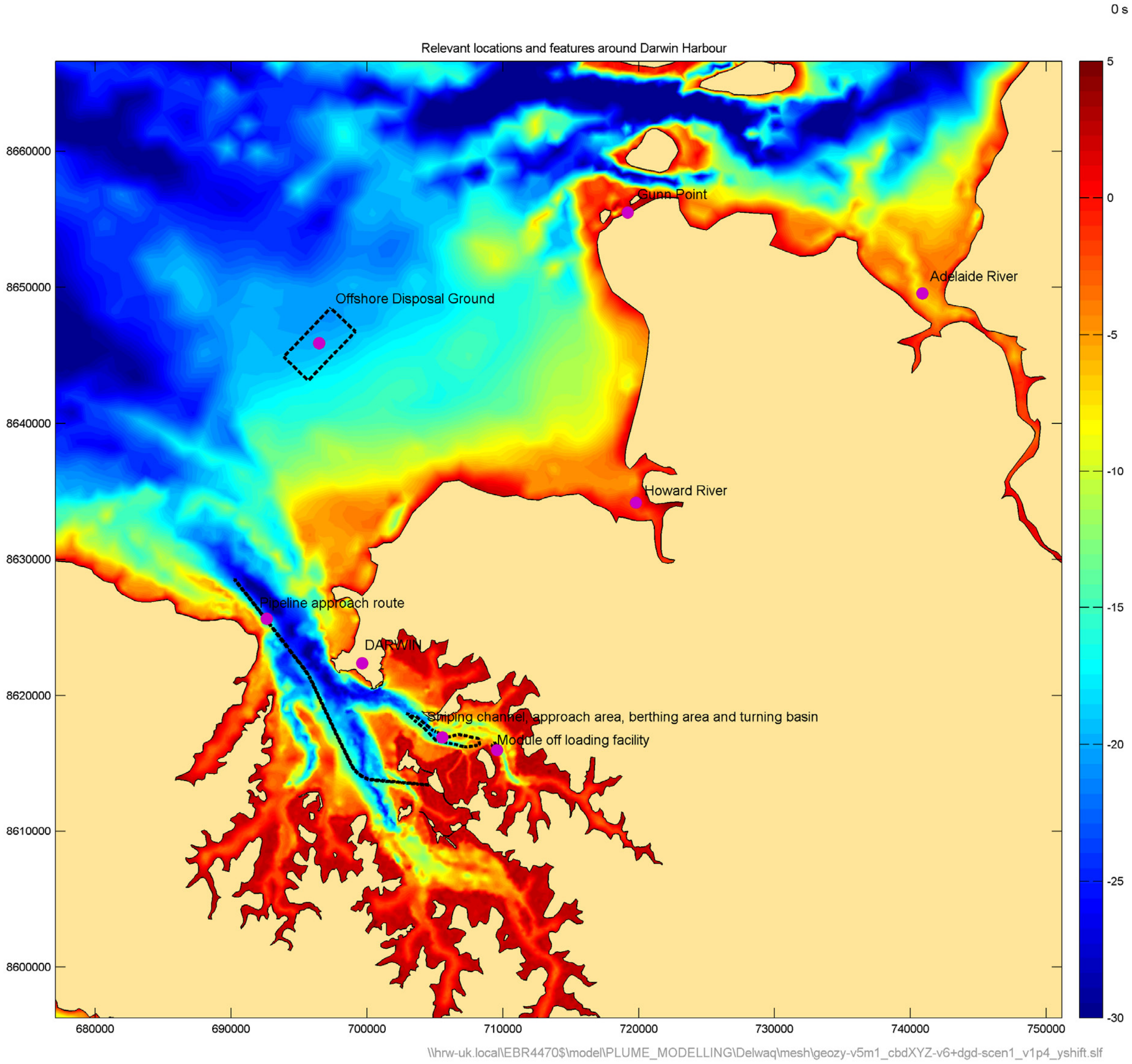


Figure 1 Location of relevant locations and project features in and around Darwin Harbour

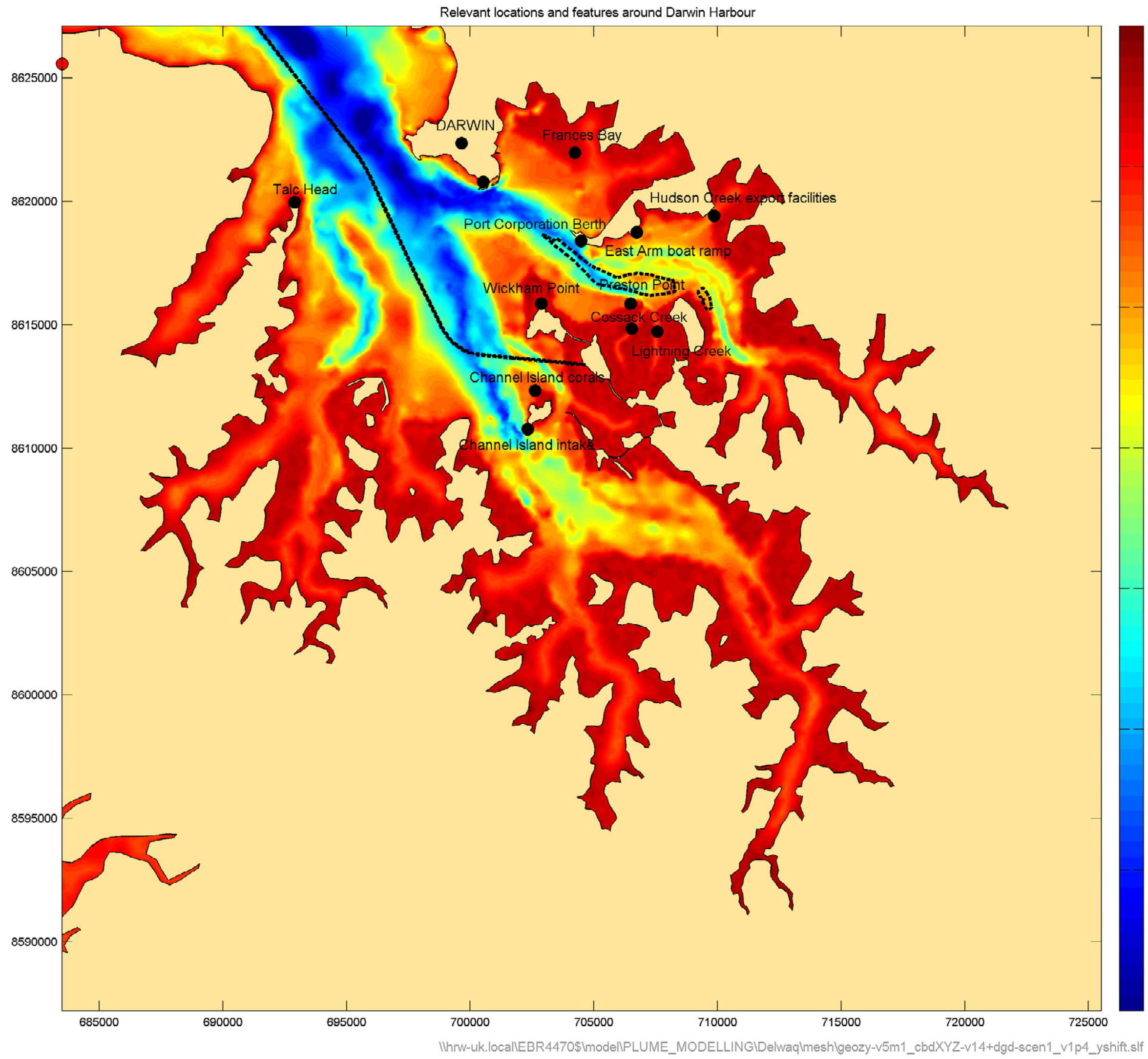


Figure 2 Location of relevant locations and features within Darwin Harbour

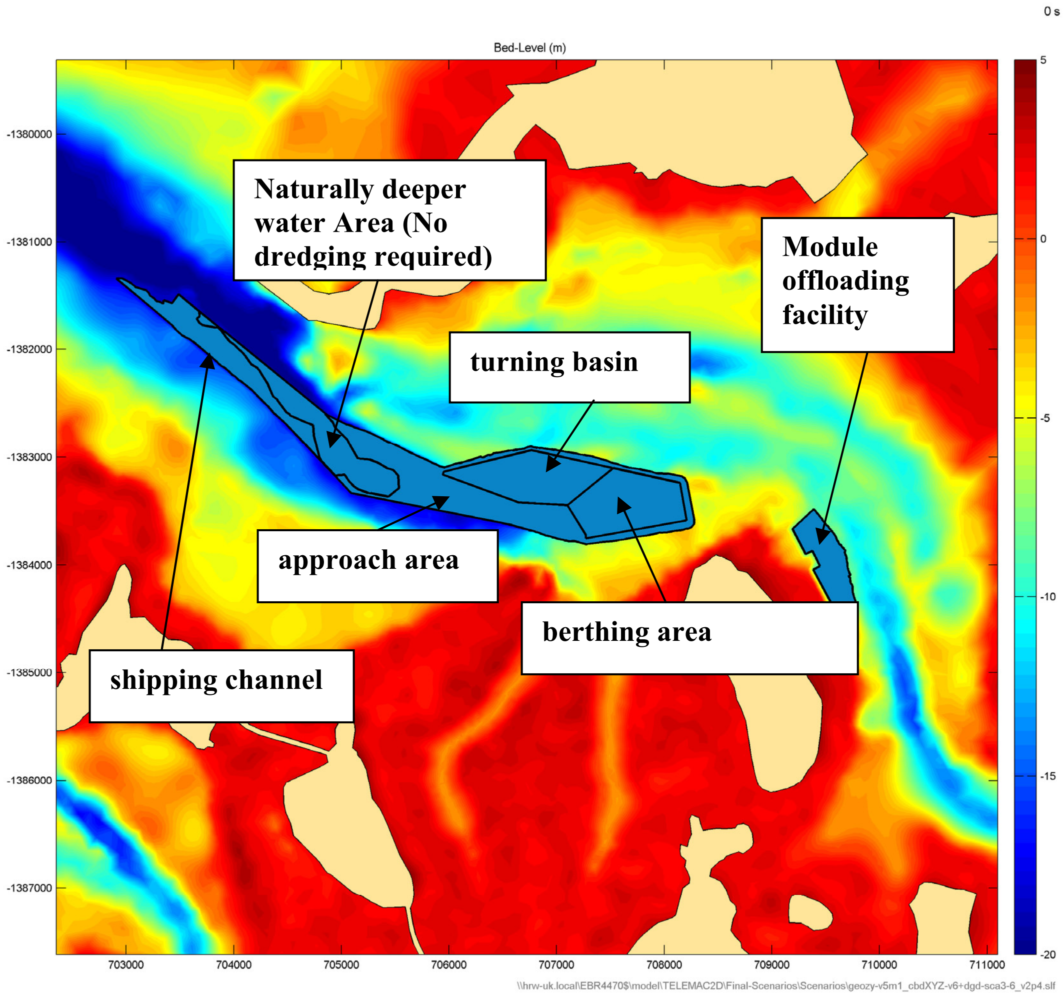


Figure 3 **Defined areas used to simulate fine material release in the sediment transport model within the East Arm**

INPEX - Outline dredge schedule
(Assumptions: Only 1xBHD & 3x3000m3 SHBs)

Schedule (EPC contract award = Month 0)

	Start (End of month)	Finish (End of month)
Dredging Contract 2 - Marine Facilities		
Simulated period of pipeline work		
1 x BHD and 3 x 3000m³ hopper barges		
Dredging Contract Award	4	
Mobilise 1 x BHD and 3 x 3000m³ hopper barges	4	6
MOF Apron	6	7
MOF Berth	7	11
Handover of MOF dredged areas		**29**
First delivery through MOF		**29**
Handover of LNG Berth for Jetty head piling		**29**
LNG Berth area with BHD	11	19.5
LNG Turning area with BHD	22.5	29
Mobilise 1x 12,000m³ TSHD	17	18
TSHD dredge material below -6.0m LAT		
Walker North/South	18	19
Midway	19	19.1
LNG Approach	19.1	23.35
LNG Berth	23.35	31.6
LNG Turning (part 1)	31.6	36
LNG Turning (part 2)	37	42
Demobilise 12,000m³ TSHD	42	43
BHD dredge weak rock below -6.0m LAT		
Overburden in walker shoal	32.5	33
LNG Berth (part 1) jetty area	19.5	22.5
LNG Berth (part 2) CSD access	33	35
LNG Berth (part 3) remainder	35	40
LNG Turning (part 1)	29	32.5
LNG Turning (part 2)	40	47.5
LNG Approach	47.5	52.25
Mobilise 1 x CSD	33	35
CSD pre-cut material to seabed for TSHD		0.5
LNG Turning	35	35.5
LNG Approach	35.5	35.75
Walker Shoal (inc Walker South)	35.75	35.95
LNG Berth	35.95	36.3
Demobilise 1 x CSD	36.3	38.3
TSHD dredge pre-cut CSD material		
LNG Turning	36.0	36.4
LNG Approach	36.4	36.6
Walker Shoal (inc Walker South)	36.6	36.8
LNG Berth	36.8	37.2
Completion of Drill and Blast activities		**34**
	37.0	51.25
Drill and Blast material	51.3	52.3
Demobilise 1 x BHD & 3 x 3,000m3 barges	52.3	54.3
Handover of PLF Dredged Areas		45

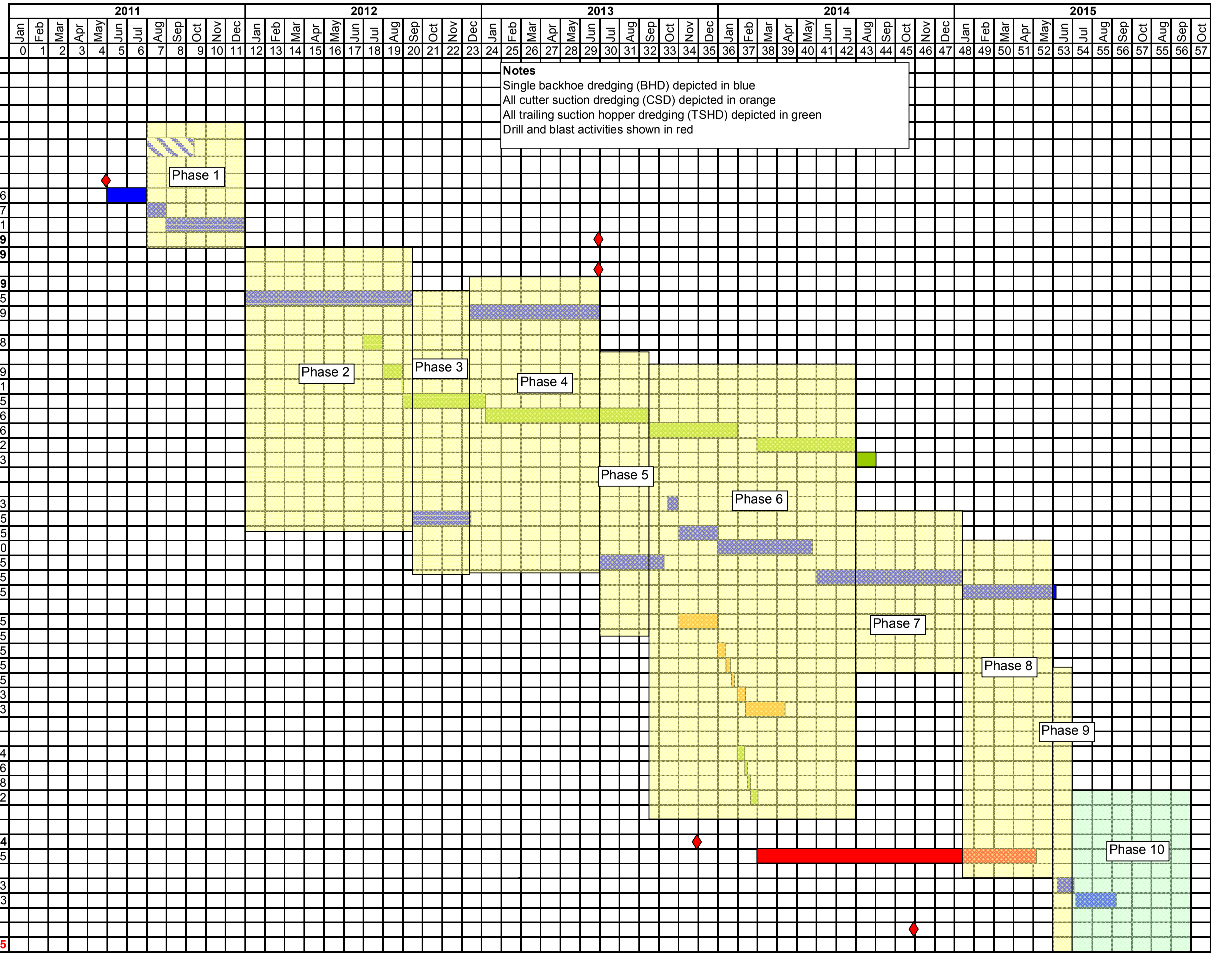


Figure 4 Dredge Schedule

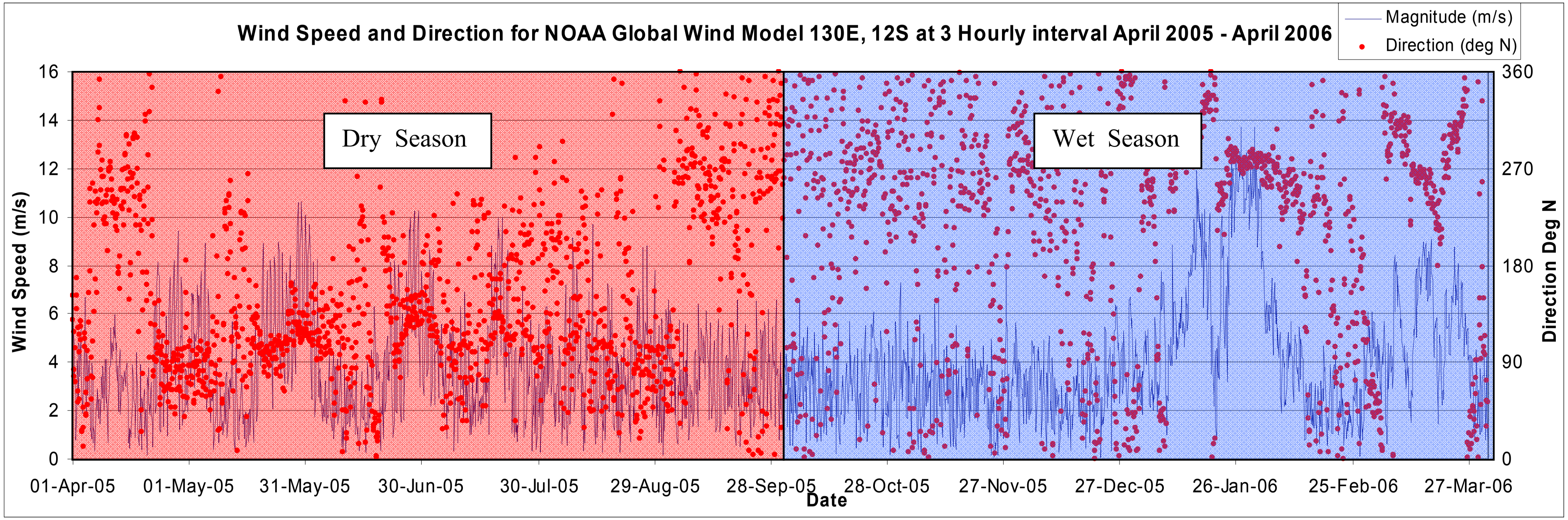


Figure 5 Wind speed and direction used as input to generate DELWAQ wind waves during wet and dry season

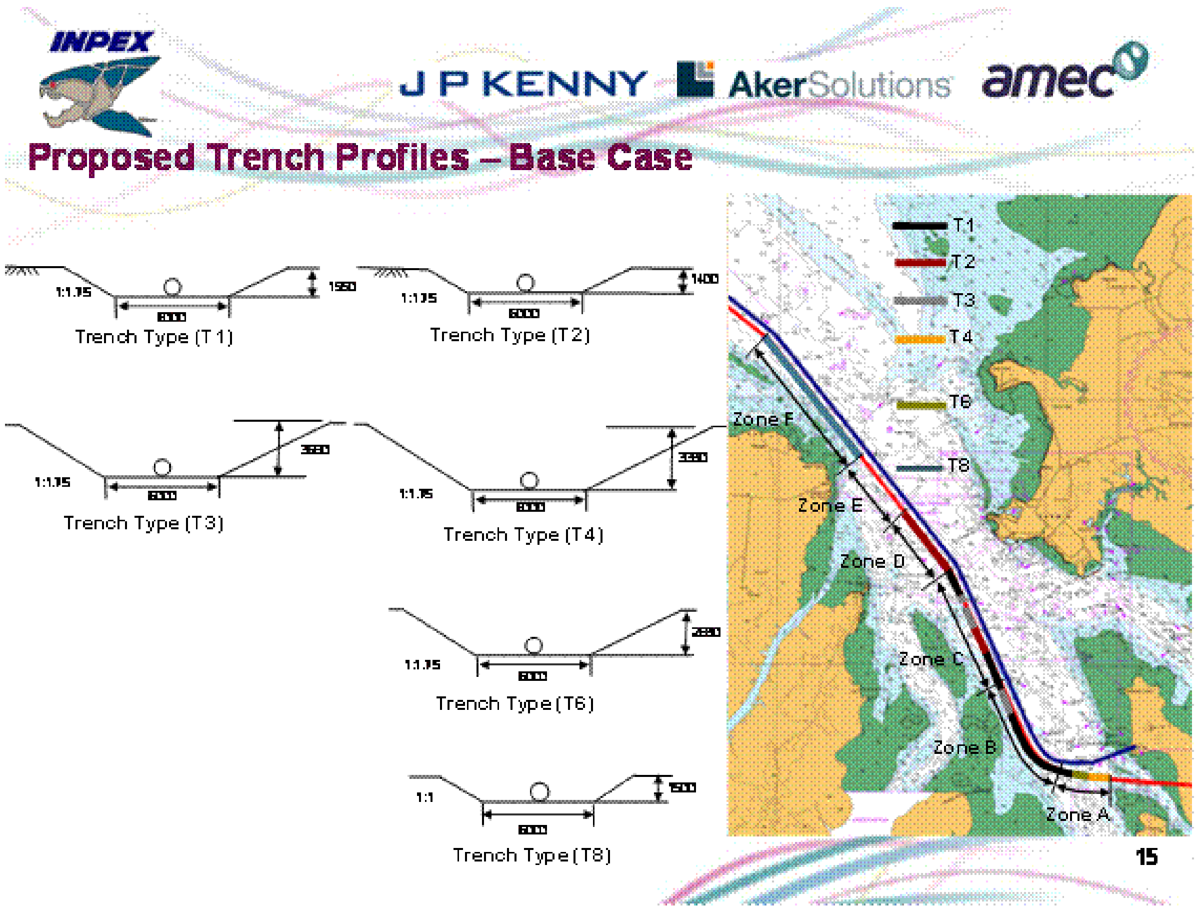
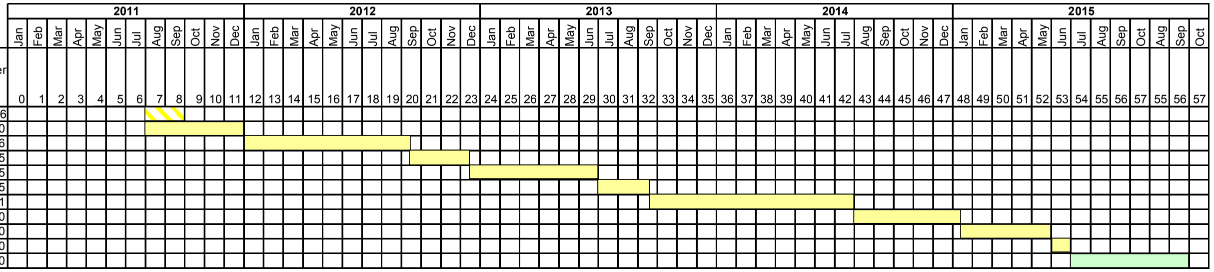


Figure 6 Proposed inshore pipeline approach route

Phase within Dredge Plan	Total Discharge (Kg)	Average Discharge Per Month (Kg)
Pipeline trench dredge	10,882,771	4,745,746
Phase 1	27,369,900	5,473,980
Phase 2	43,596,127	5,128,956
Phase 3	25,145,445	8,381,815
Phase 4	67,049,352	10,315,285
Phase 5	20,954,537	8,381,815
Phase 6	255,618,306	24,344,601
Phase 7	11,462,715	2,084,130
Phase 8	9,378,585	2,084,130
Phase 9	652,860	652,860
Phase 10	0	0



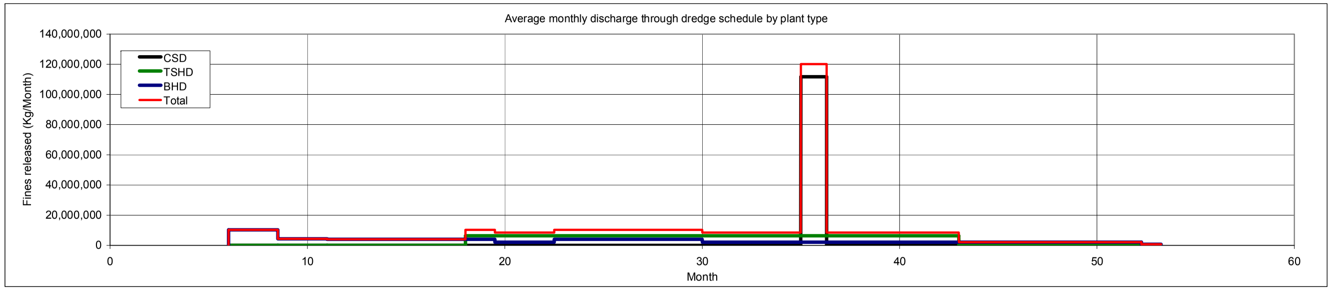


Figure 7 Average monthly discharge of fine material through dredge schedule by plant type for East Arm and Pipeline Dredging

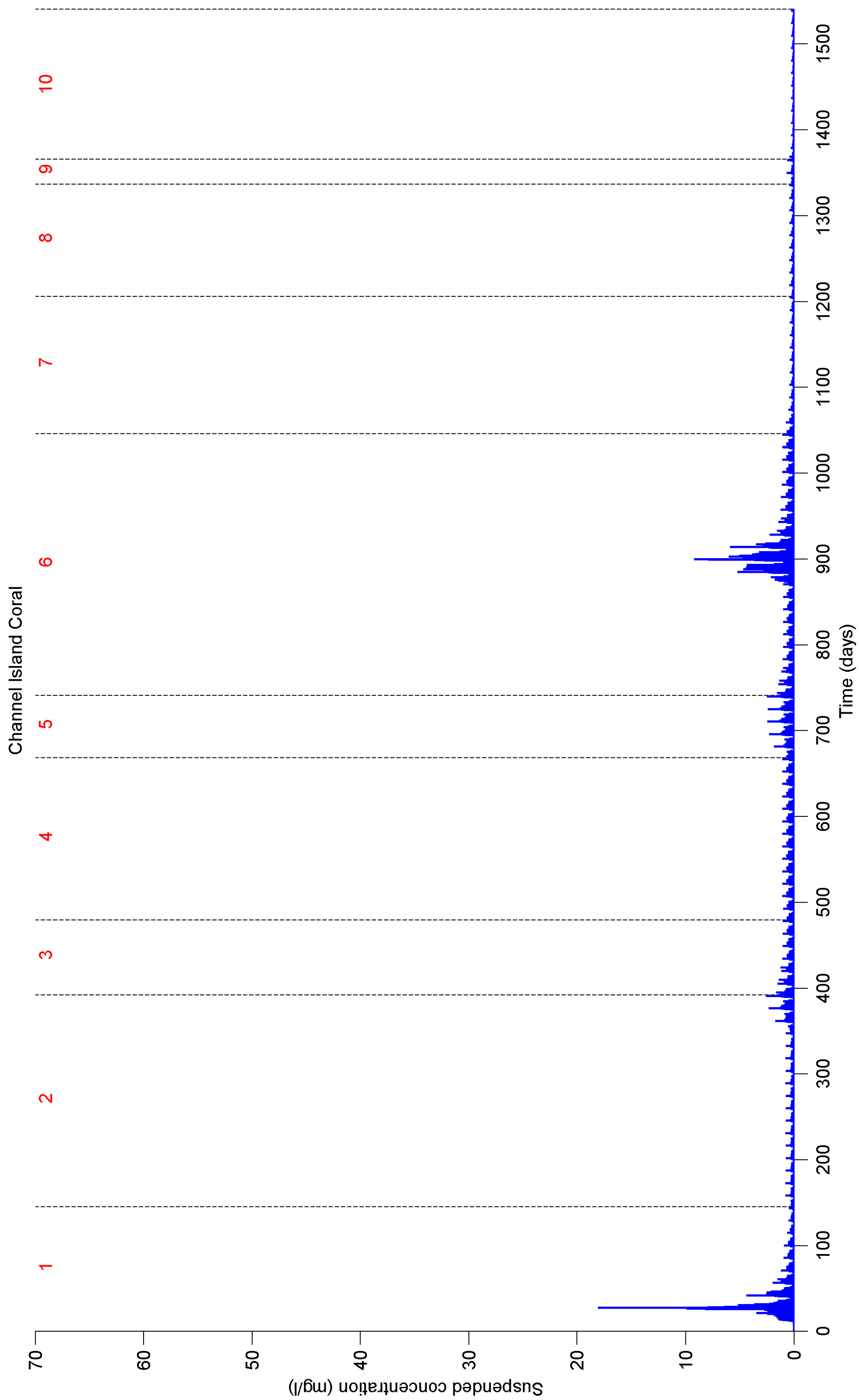


Figure 8 Time-series of suspended sediment concentrations at Channel Island coral location for the whole Dredging Case Study

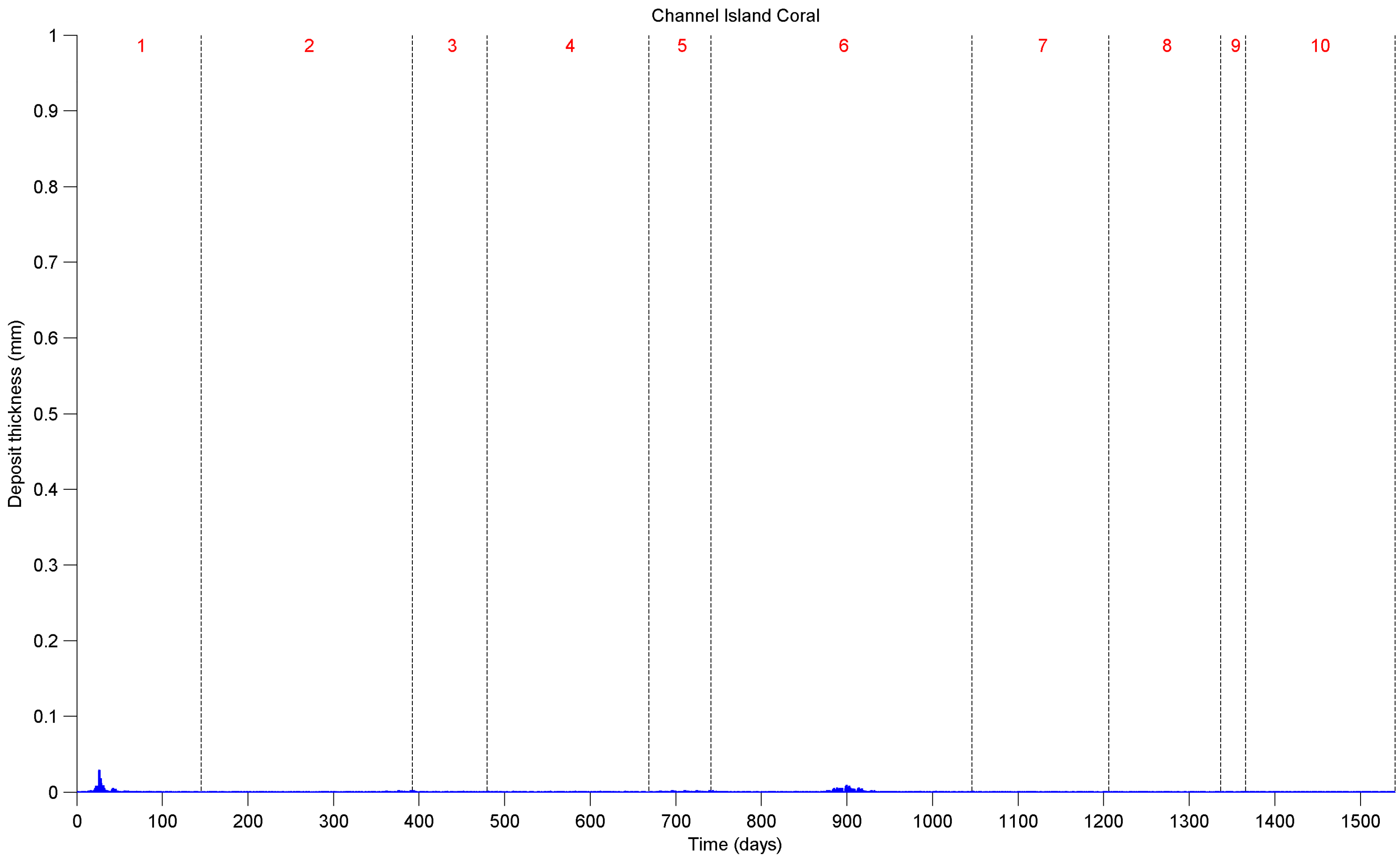


Figure 9 **Time-series of suspended sediment deposition at Channel Island coral location for the whole Dredging Case Study**

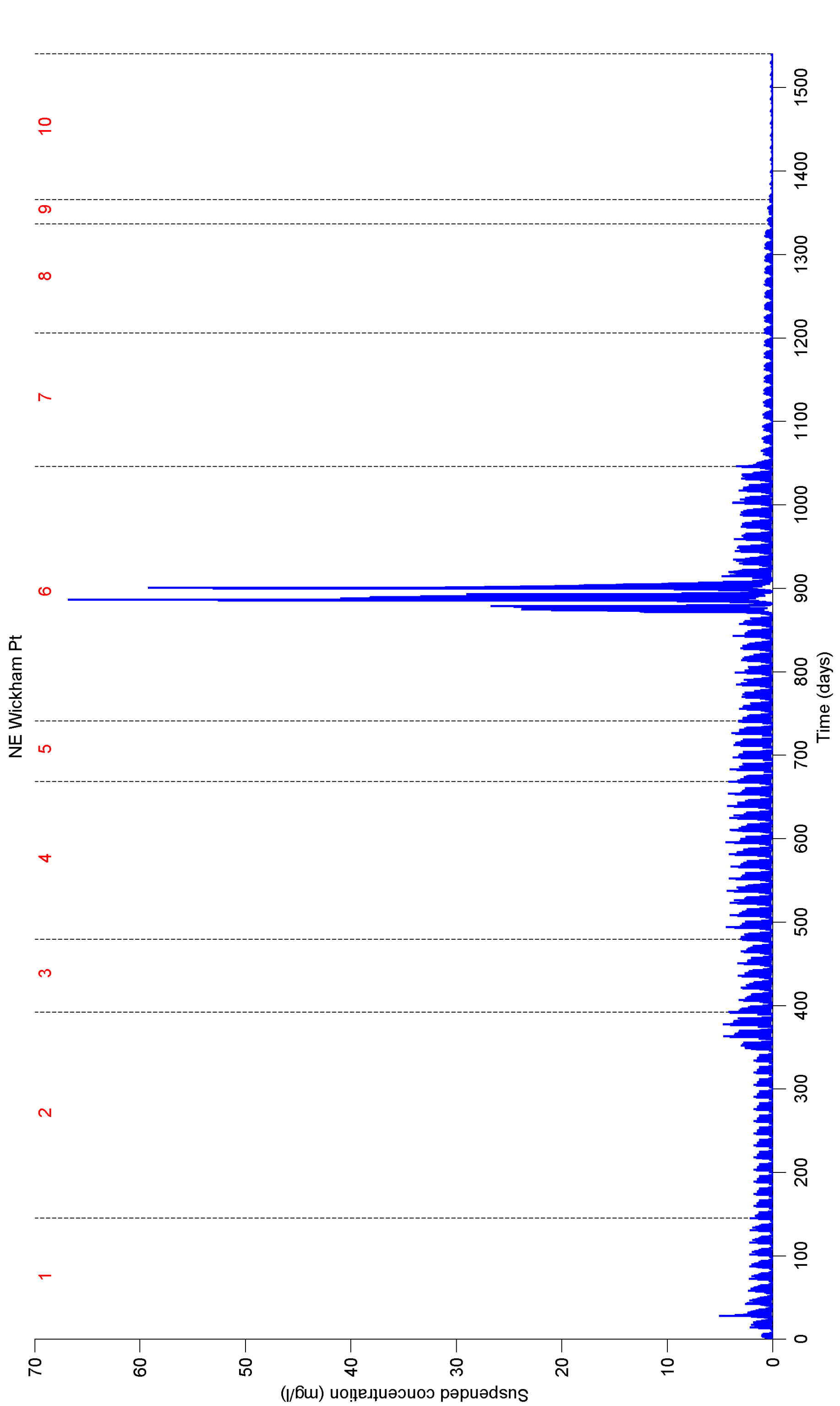


Figure 10 Time-series of suspended sediment concentrations at North East Wickham Point for the whole Dredging Case Study

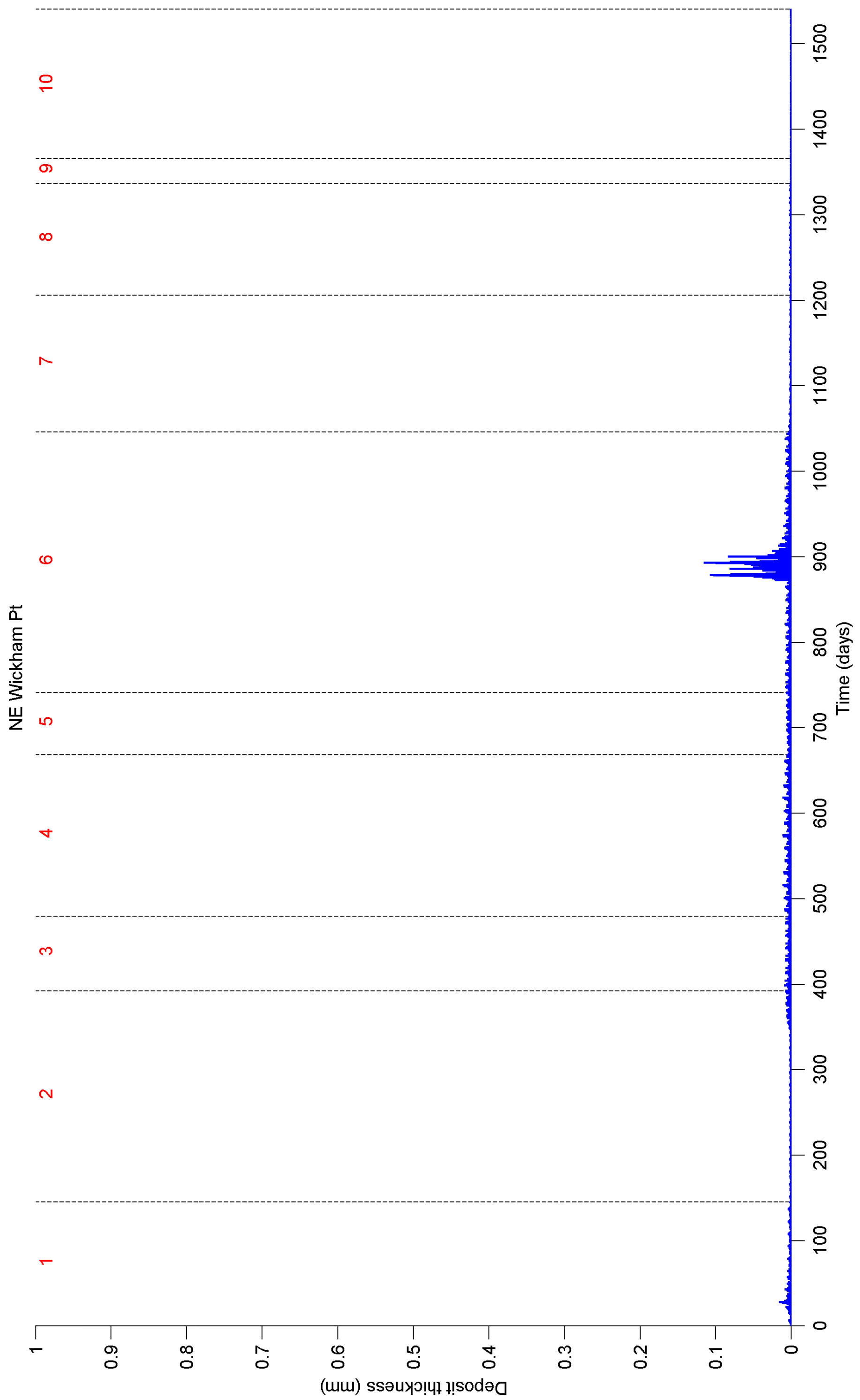


Figure 11 Time-series of deposition at North East Wickham point for the whole Dredging Case Study

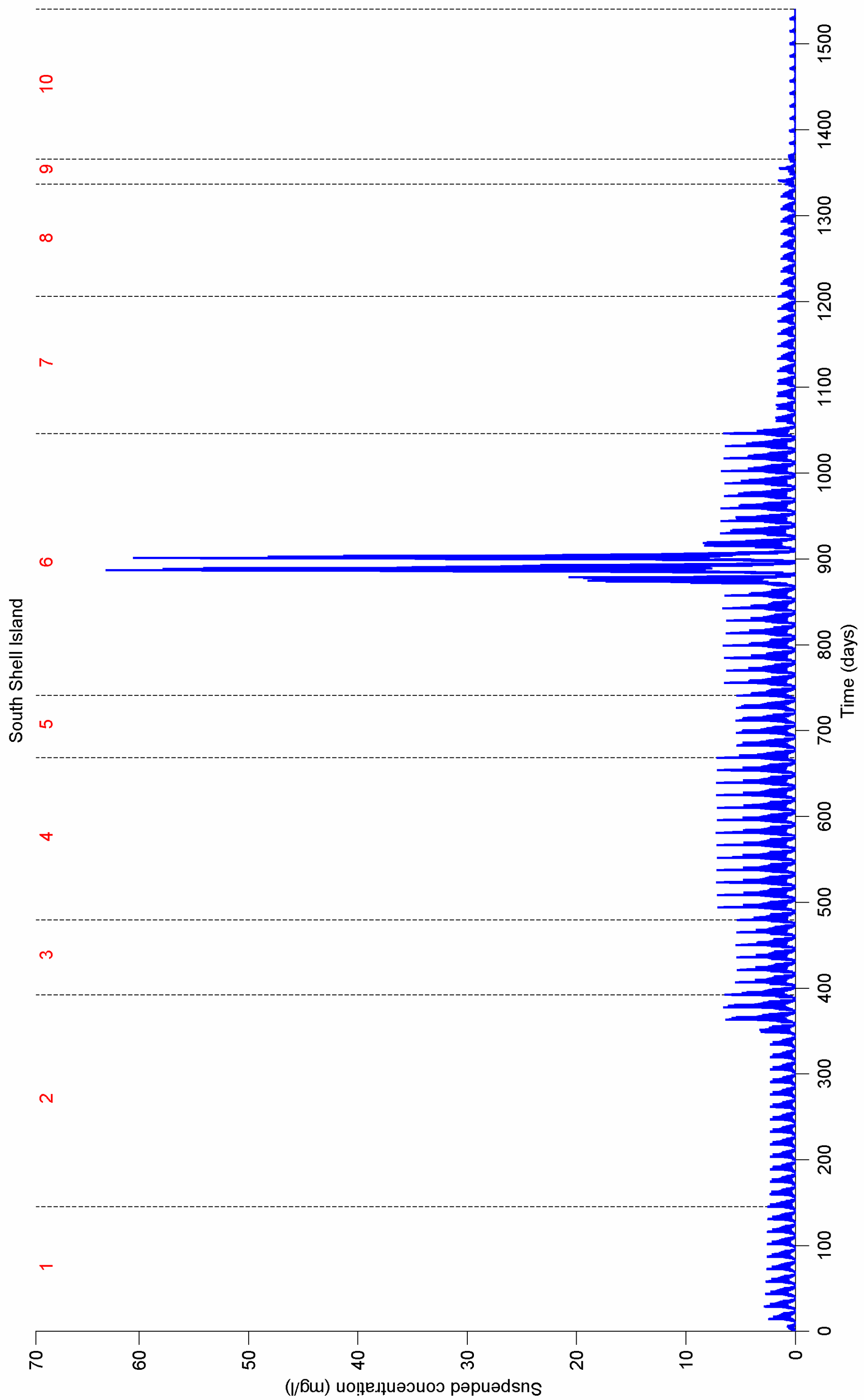


Figure 12 Time-series of suspended sediment concentrations at South Shell Island for the whole Dredging Case Study

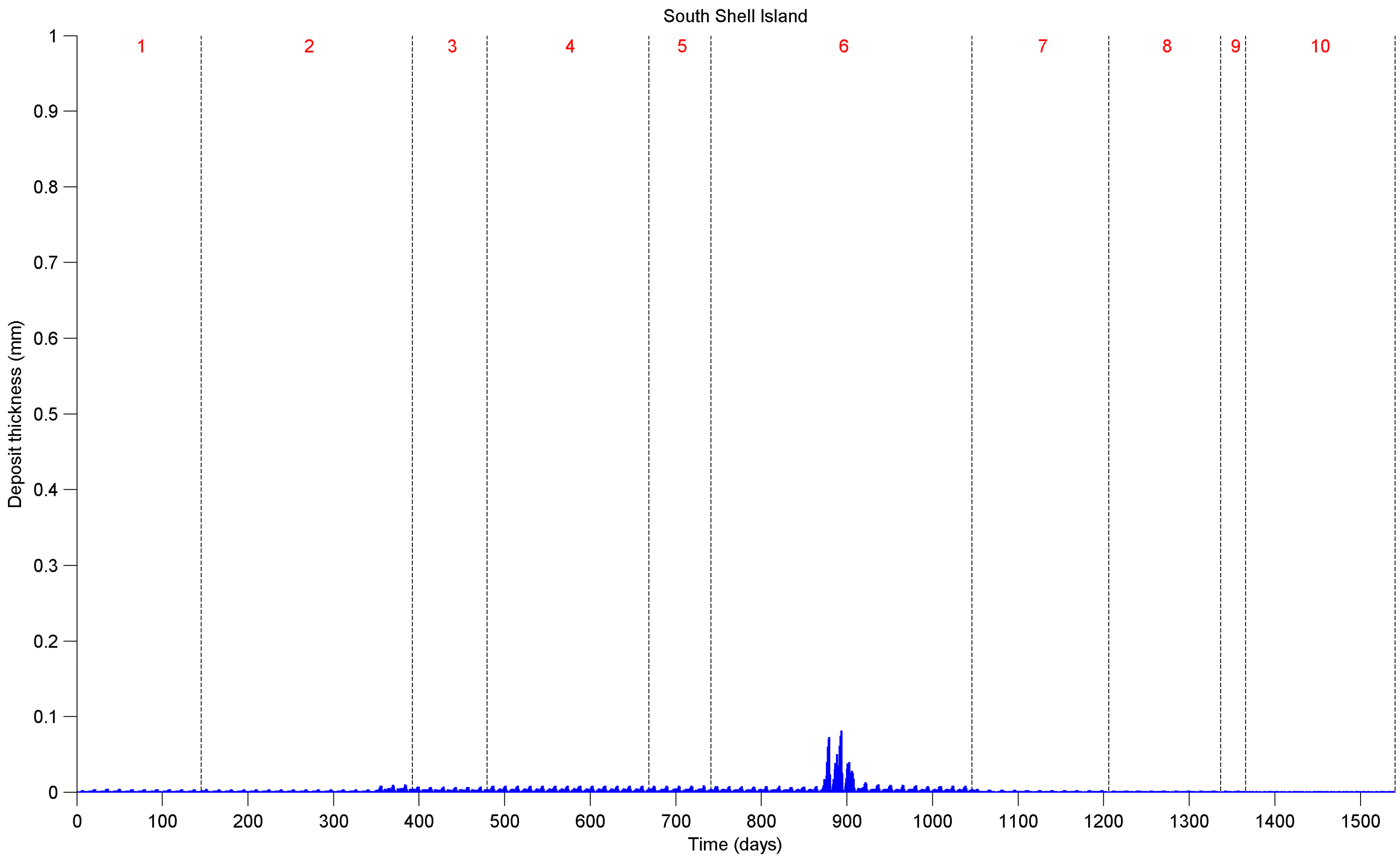


Figure 13 Time-series of deposition at South Shell Island for the whole Dredging Case Study

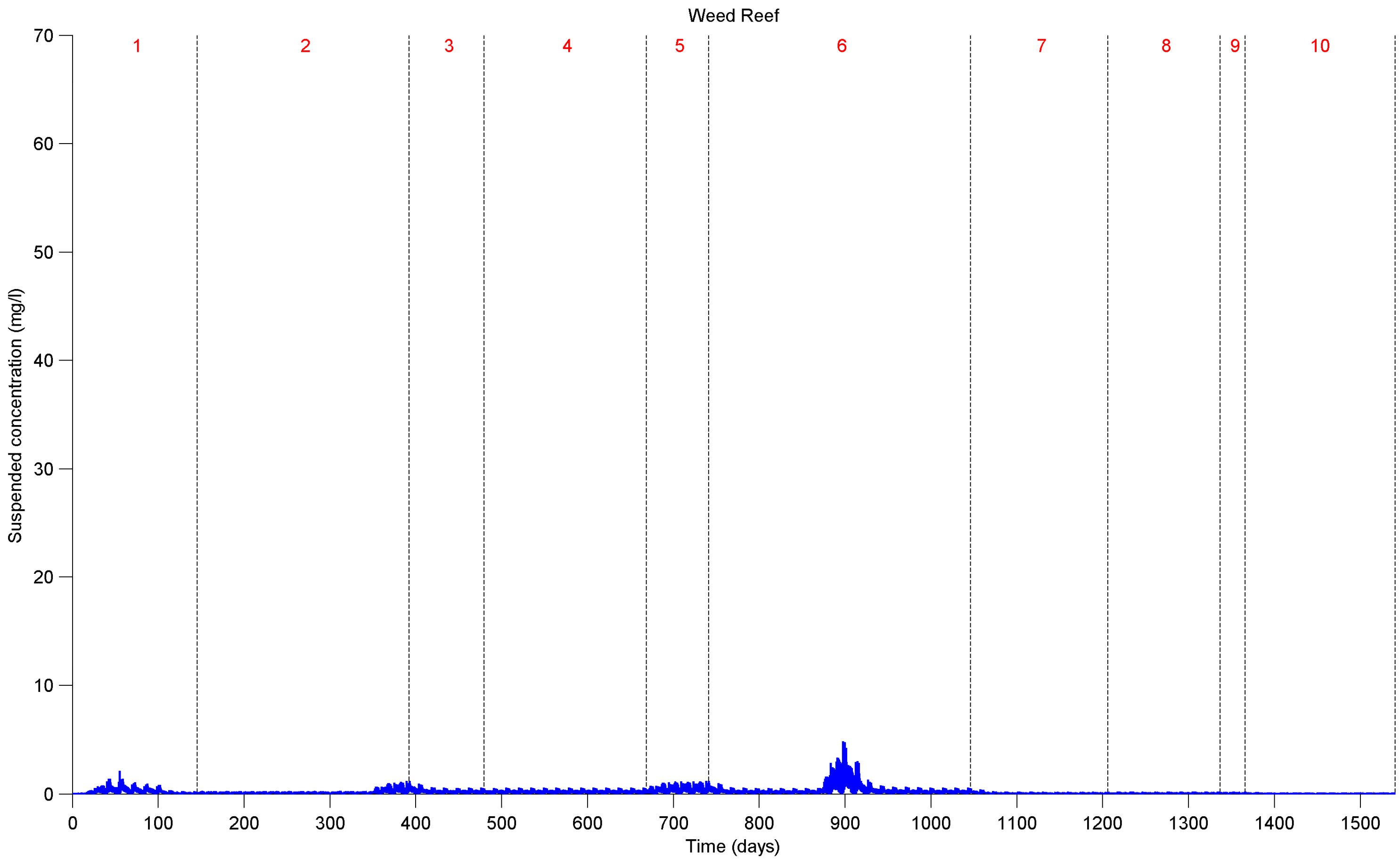


Figure 14 Time-series of suspended sediment concentrations at Weed Reef for the whole Dredging Case Study

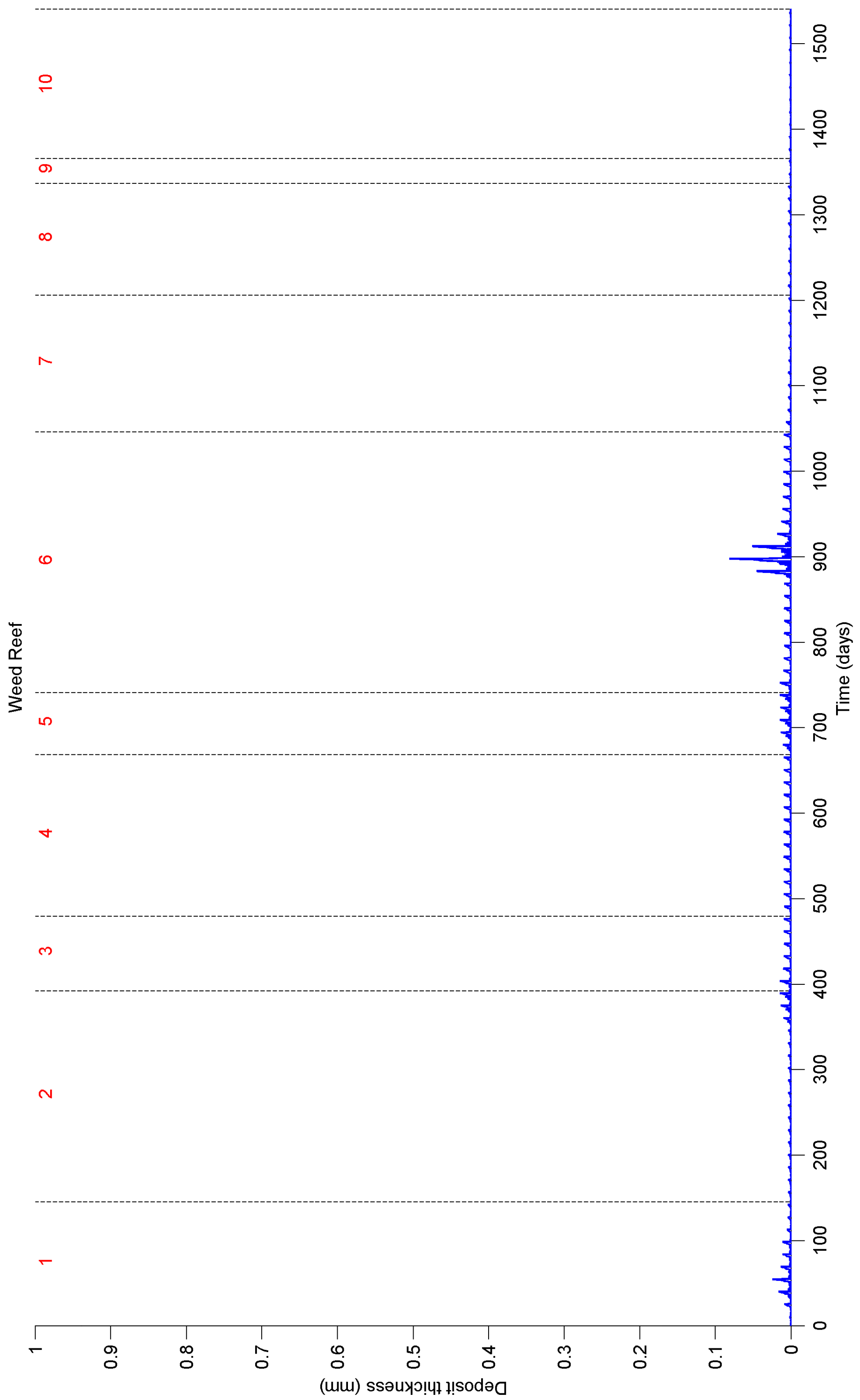


Figure 15 Time-series of deposition at Weed Reef for the whole Dredging Case Study

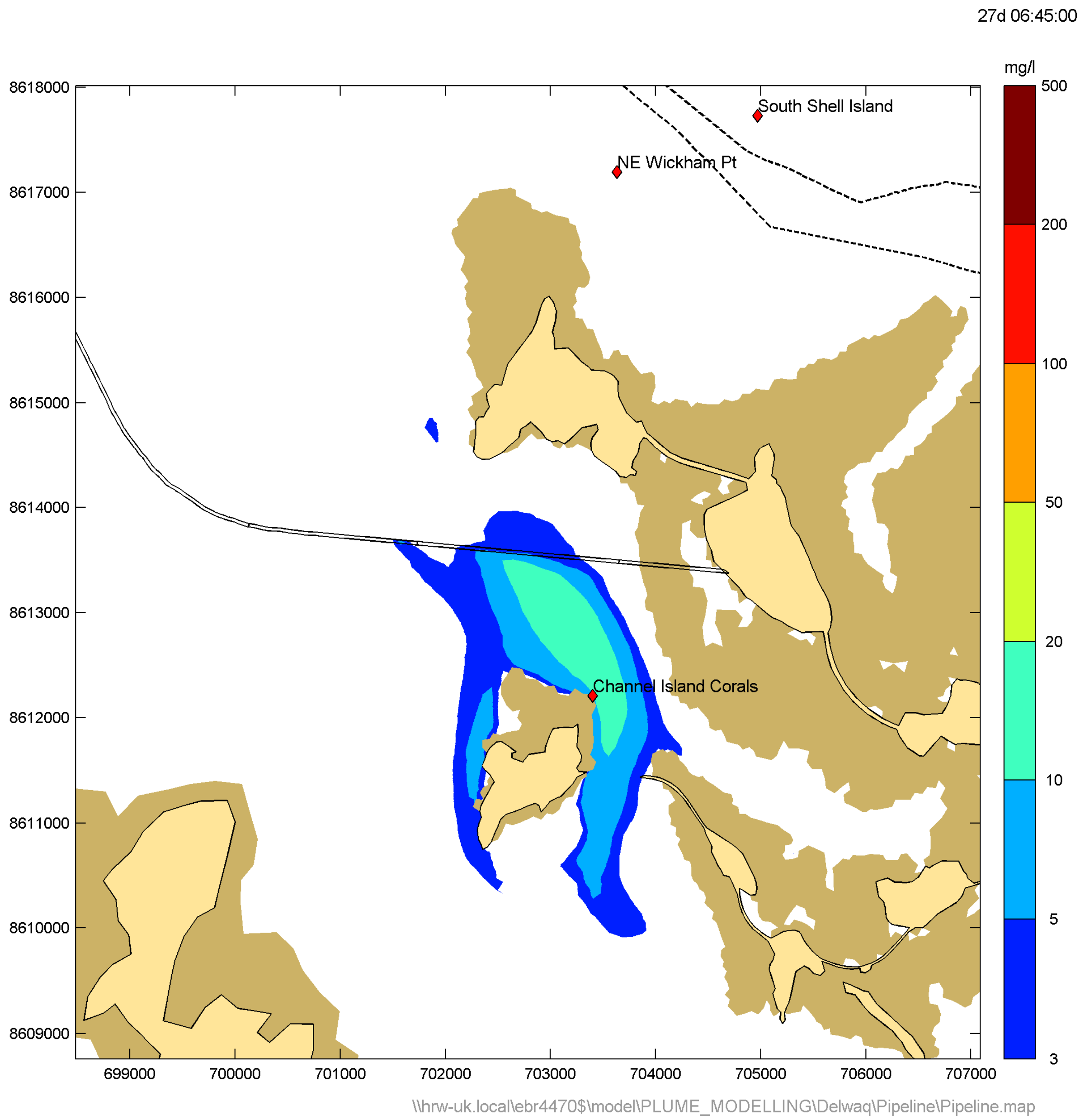


Figure 16 Colour surface plot of peak concentration at Channel Island during the proposed pipeline trench dredge activity

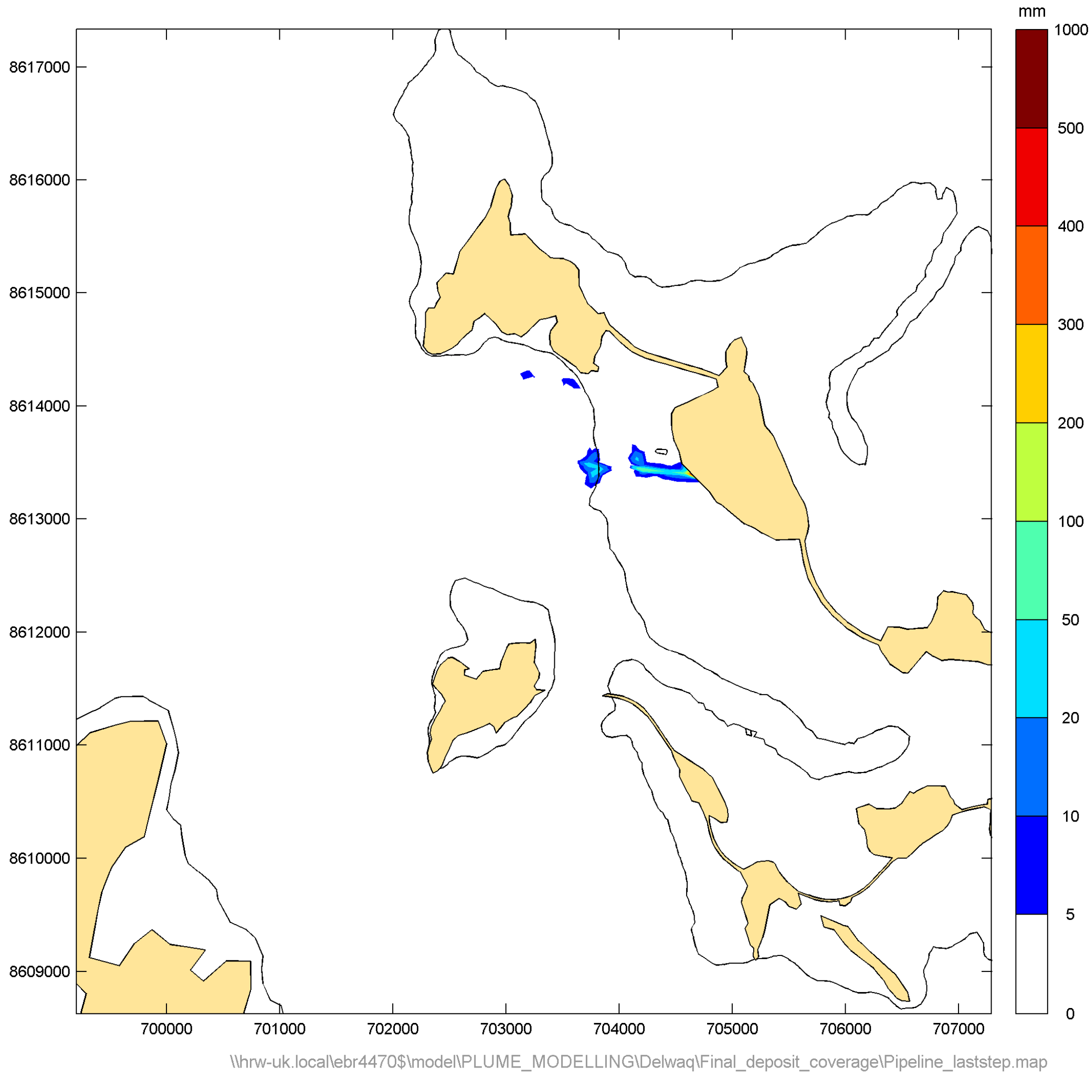


Figure 17 Simulated depth of accumulation after the completion of the pipeline trench dredge

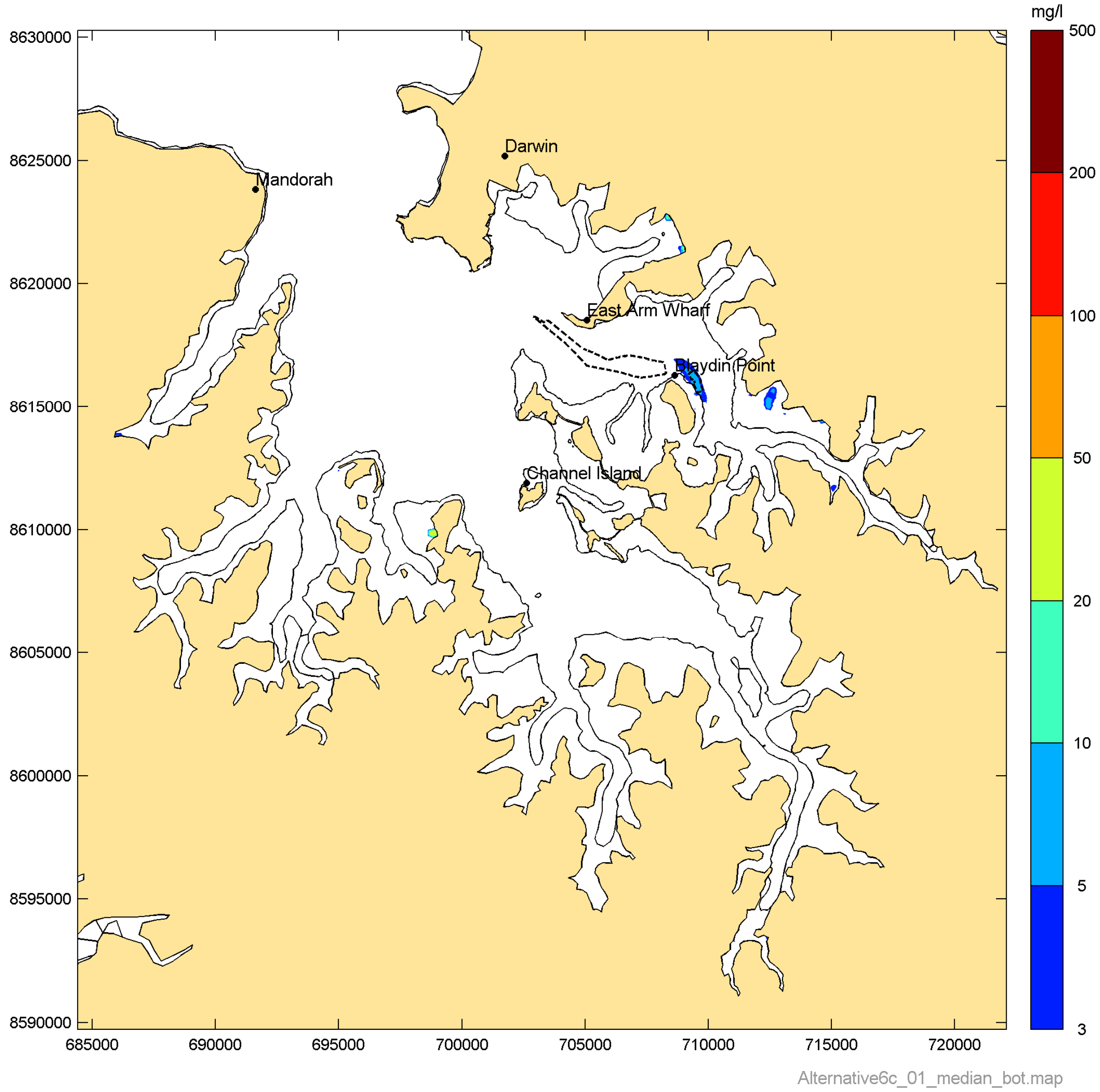


Figure 18 Simulated median suspended sediment concentration in the East Arm for Phase 1

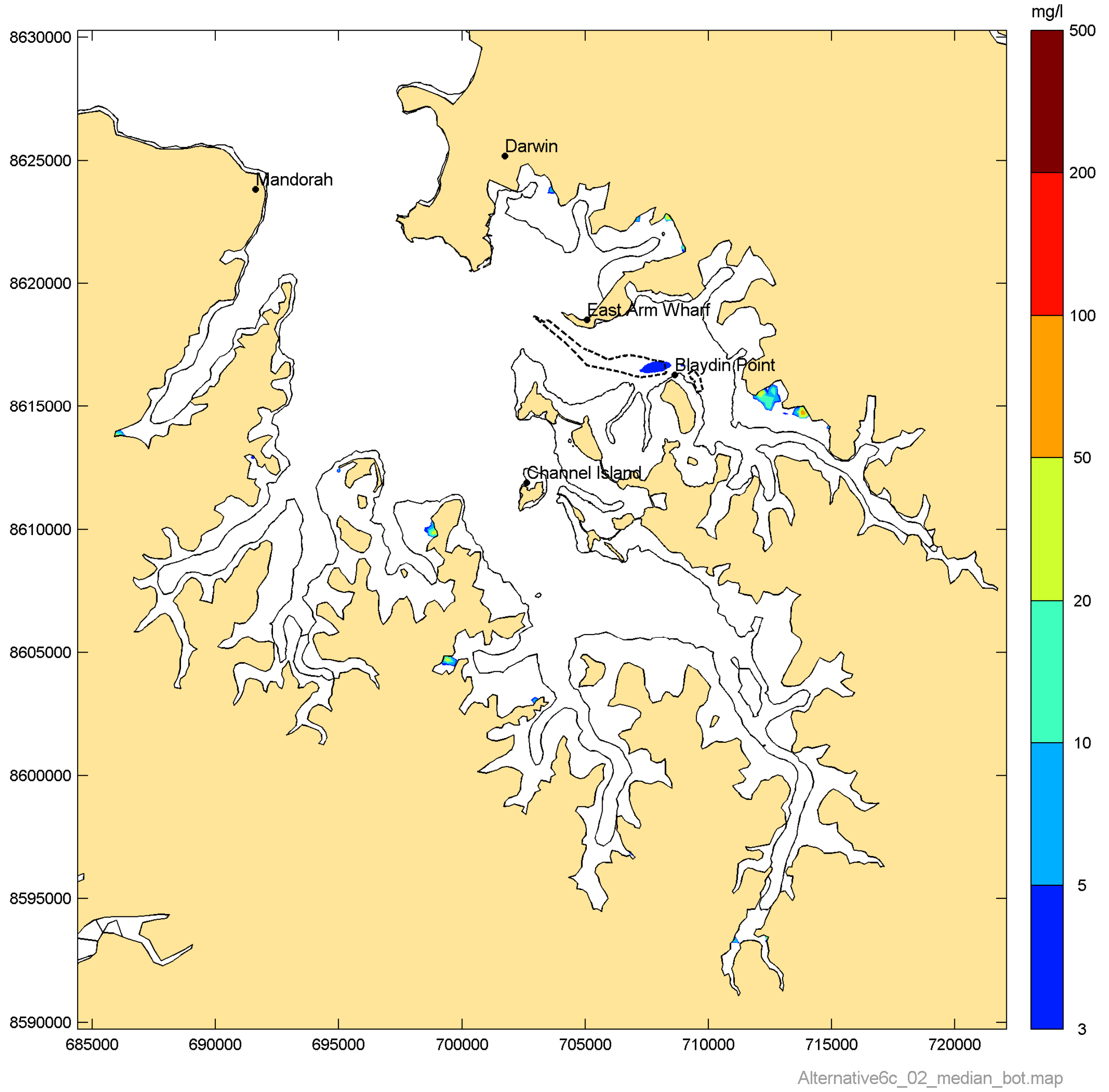


Figure 19 Simulated median suspended sediment concentration in the East Arm for Phase 2

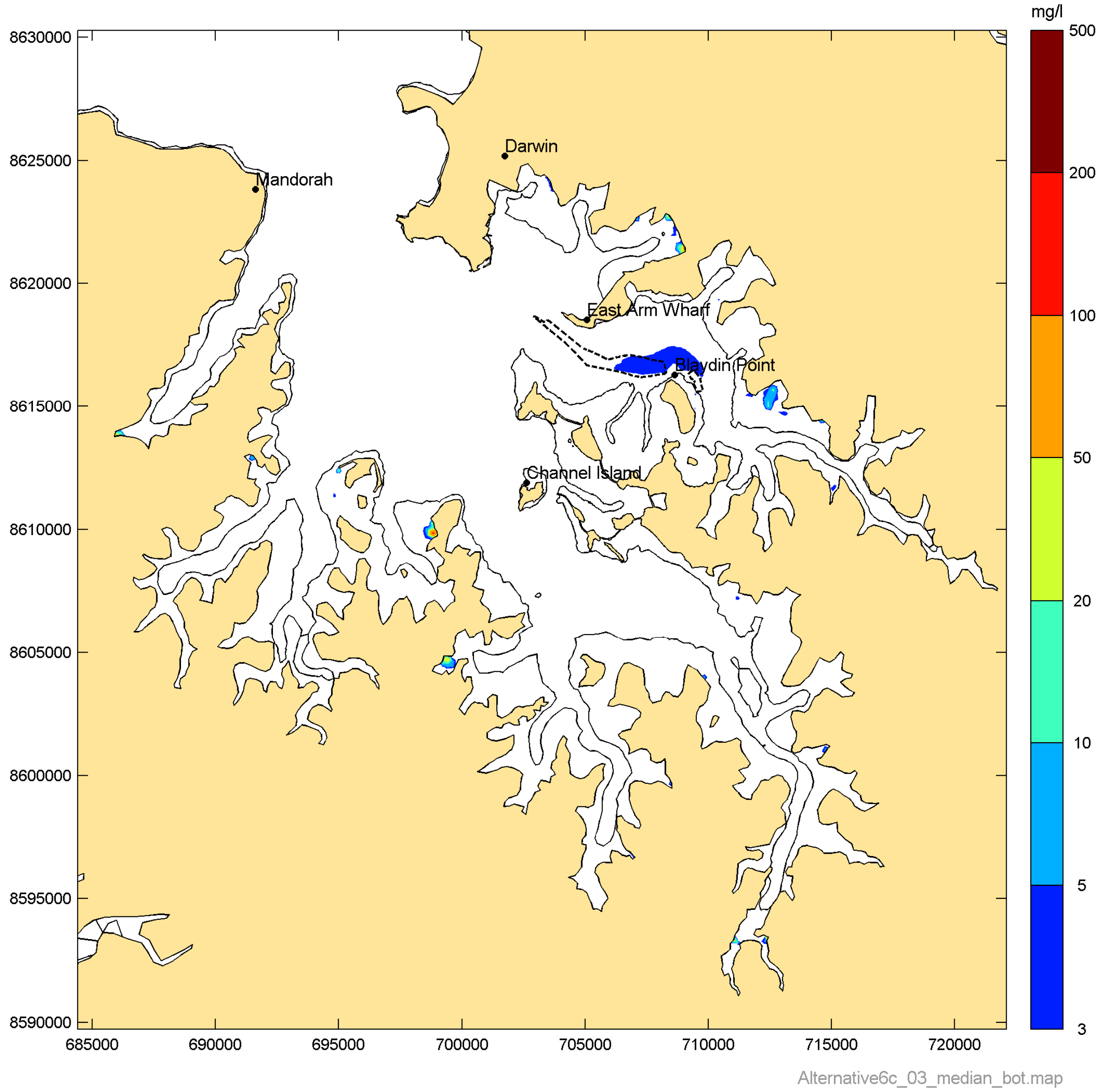


Figure 20 Simulated median suspended sediment concentration in the East Arm for Phase 3

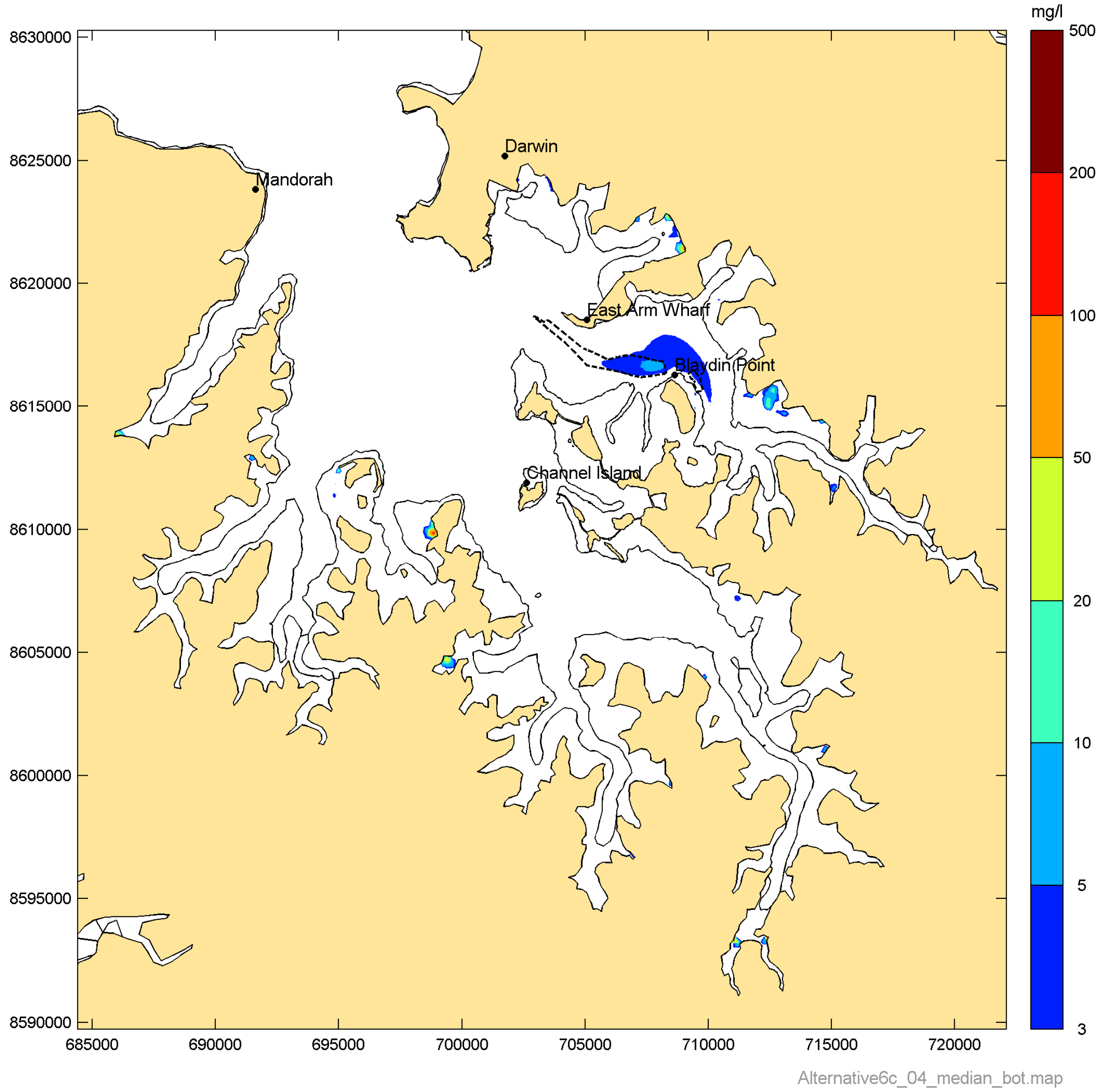


Figure 21 Simulated median suspended sediment concentration in the East Arm for Phase 4

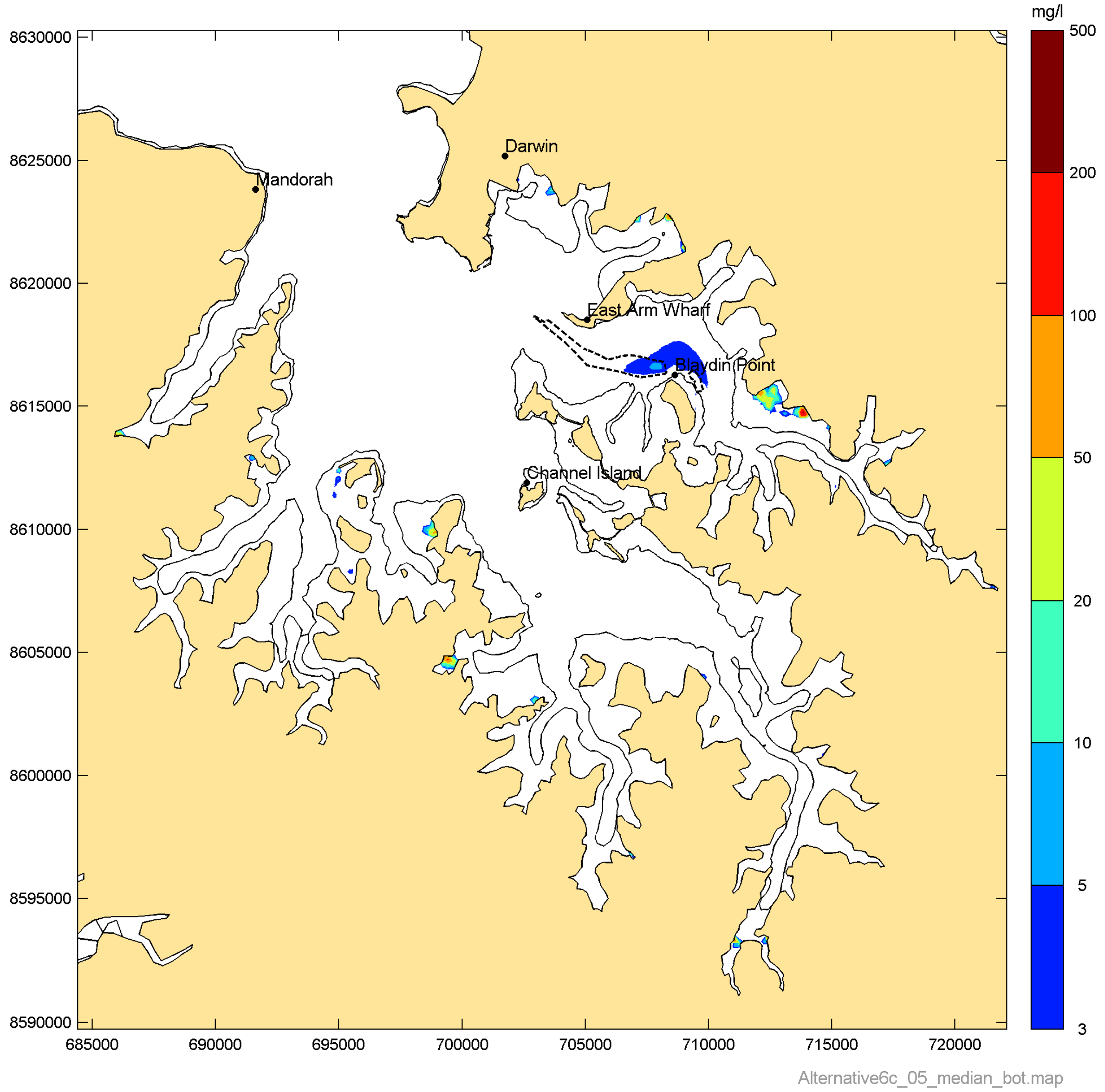


Figure 22 Simulated median suspended sediment concentration in the East Arm for Phase 5

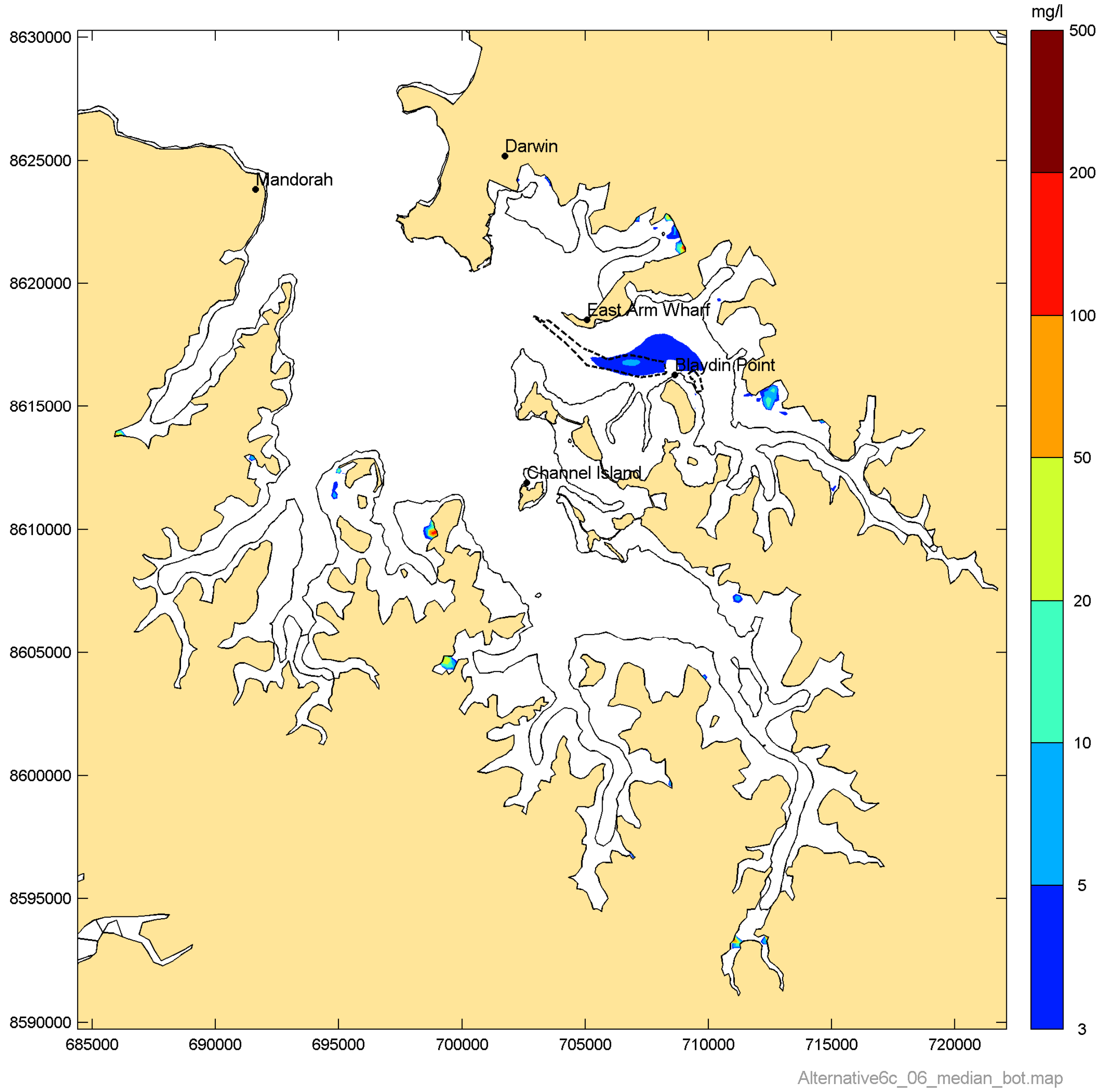


Figure 23 Simulated median suspended sediment concentration in the East Arm for Phase 6

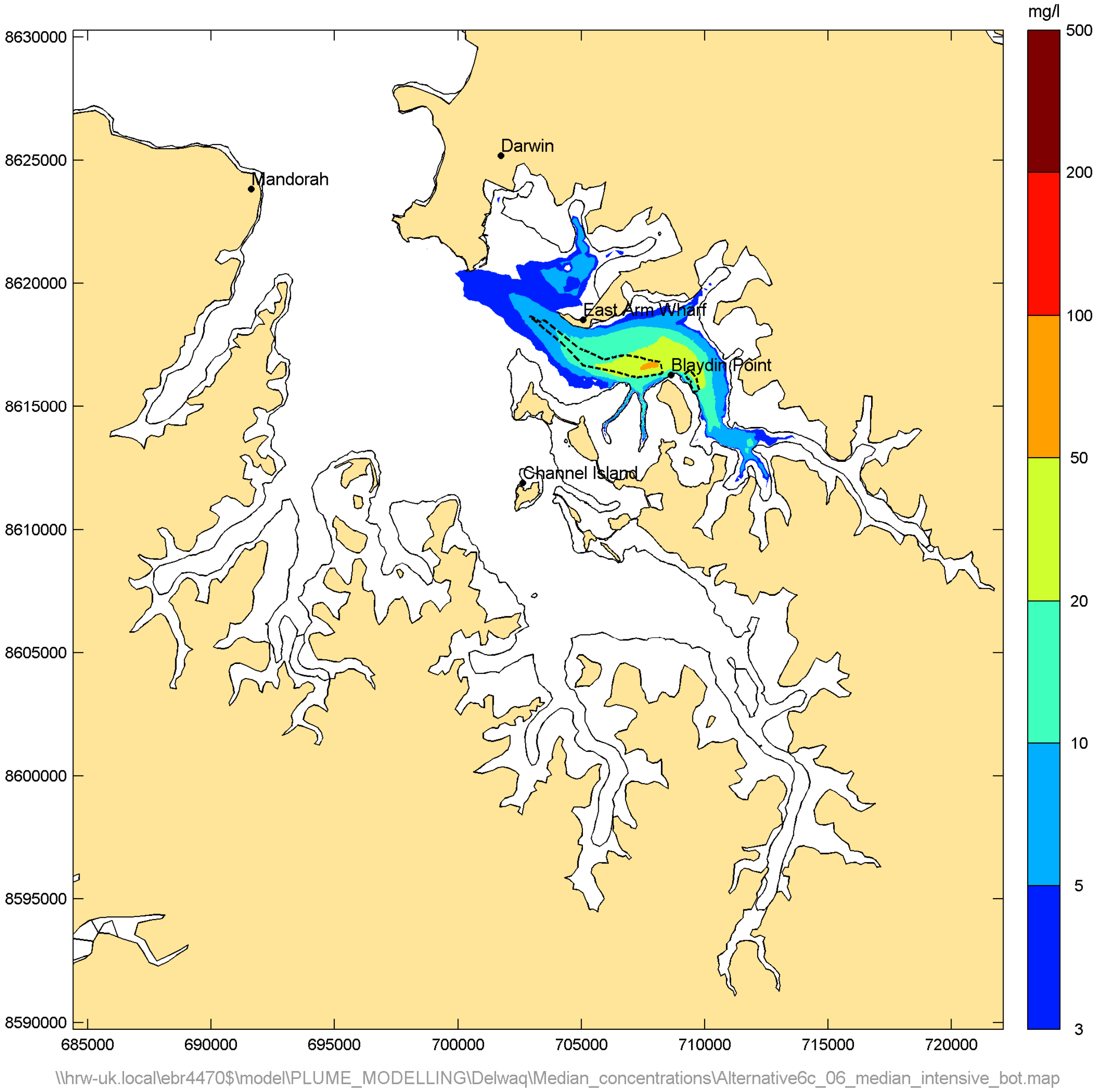


Figure 24 Simulated median suspended sediment concentration in the East Arm for Phase 6 – cutter-suction dredger activity

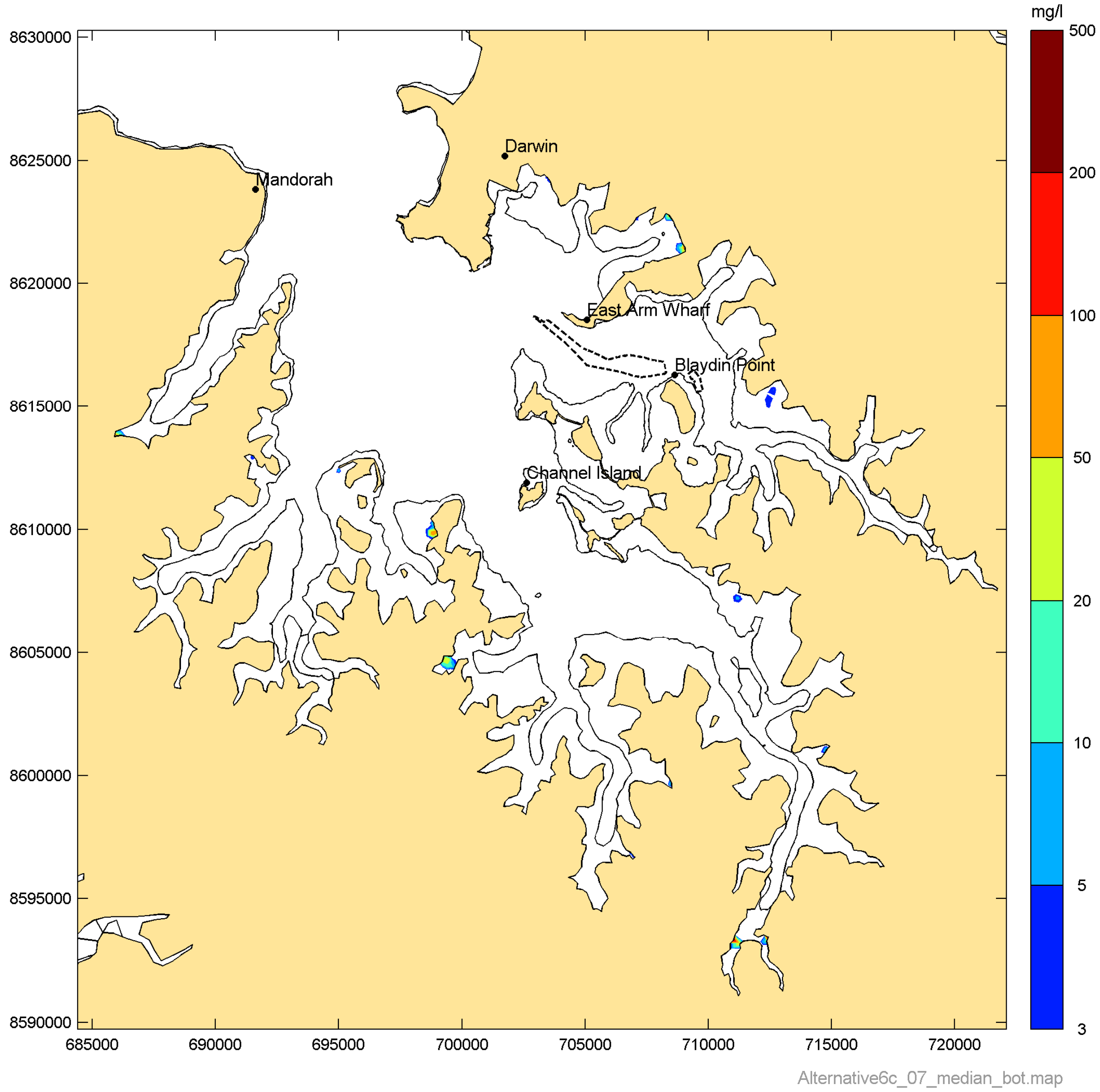


Figure 25 Simulated median suspended sediment concentration in the East Arm for Phase 7

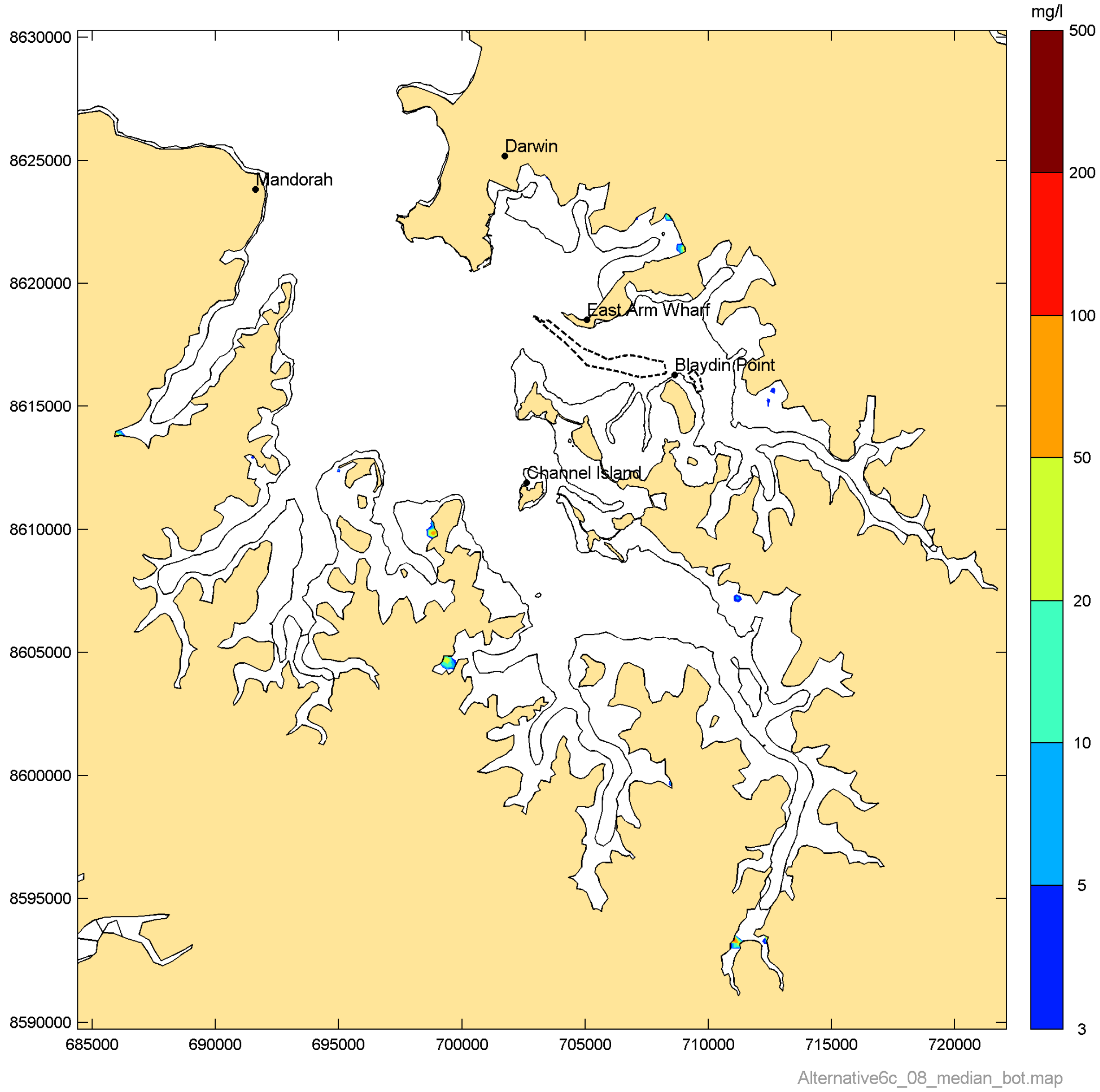


Figure 26 Simulated median suspended sediment concentration in the East Arm for Phase 8

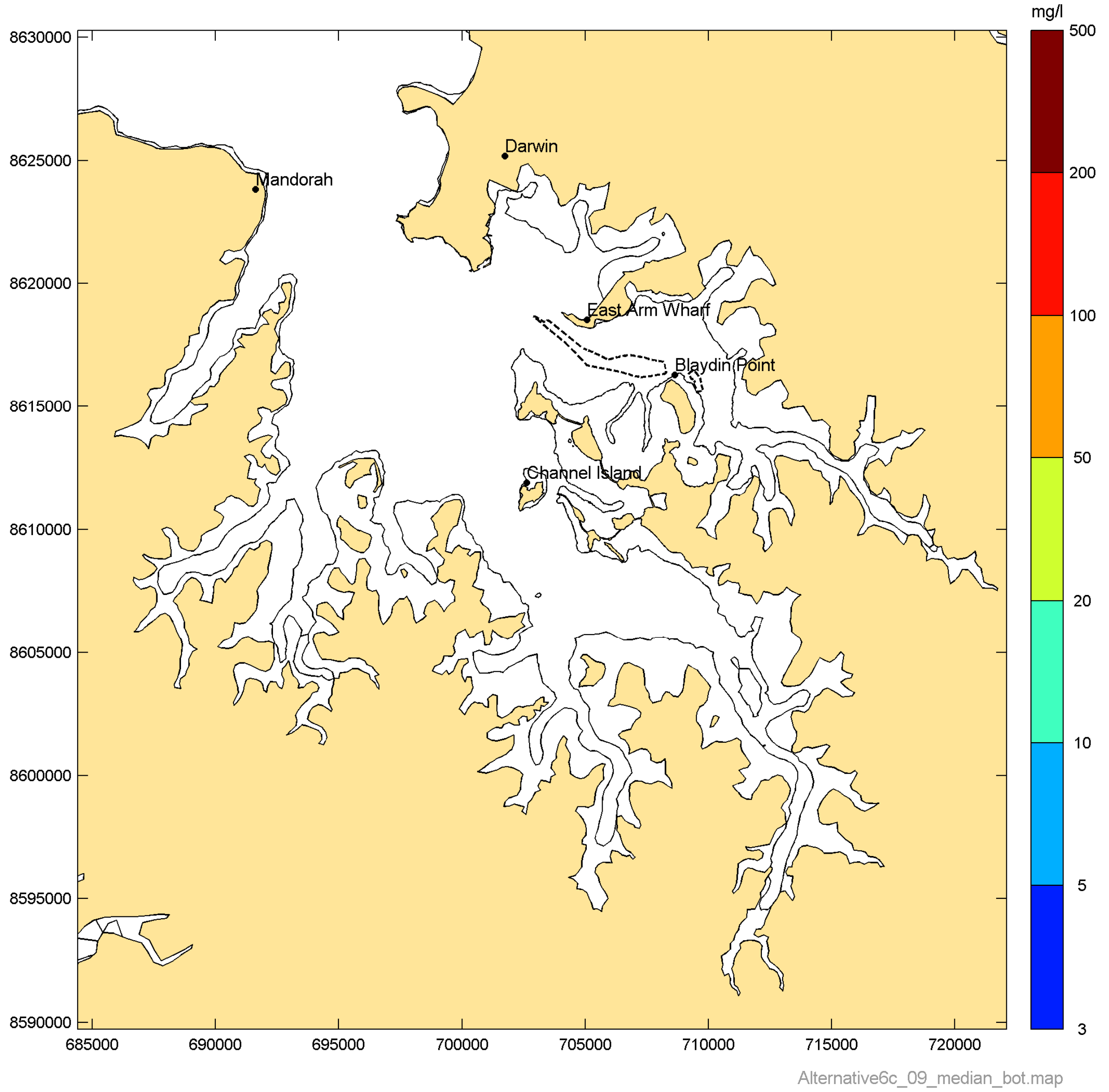


Figure 27 Simulated median suspended sediment concentration in the East Arm for Phase 9

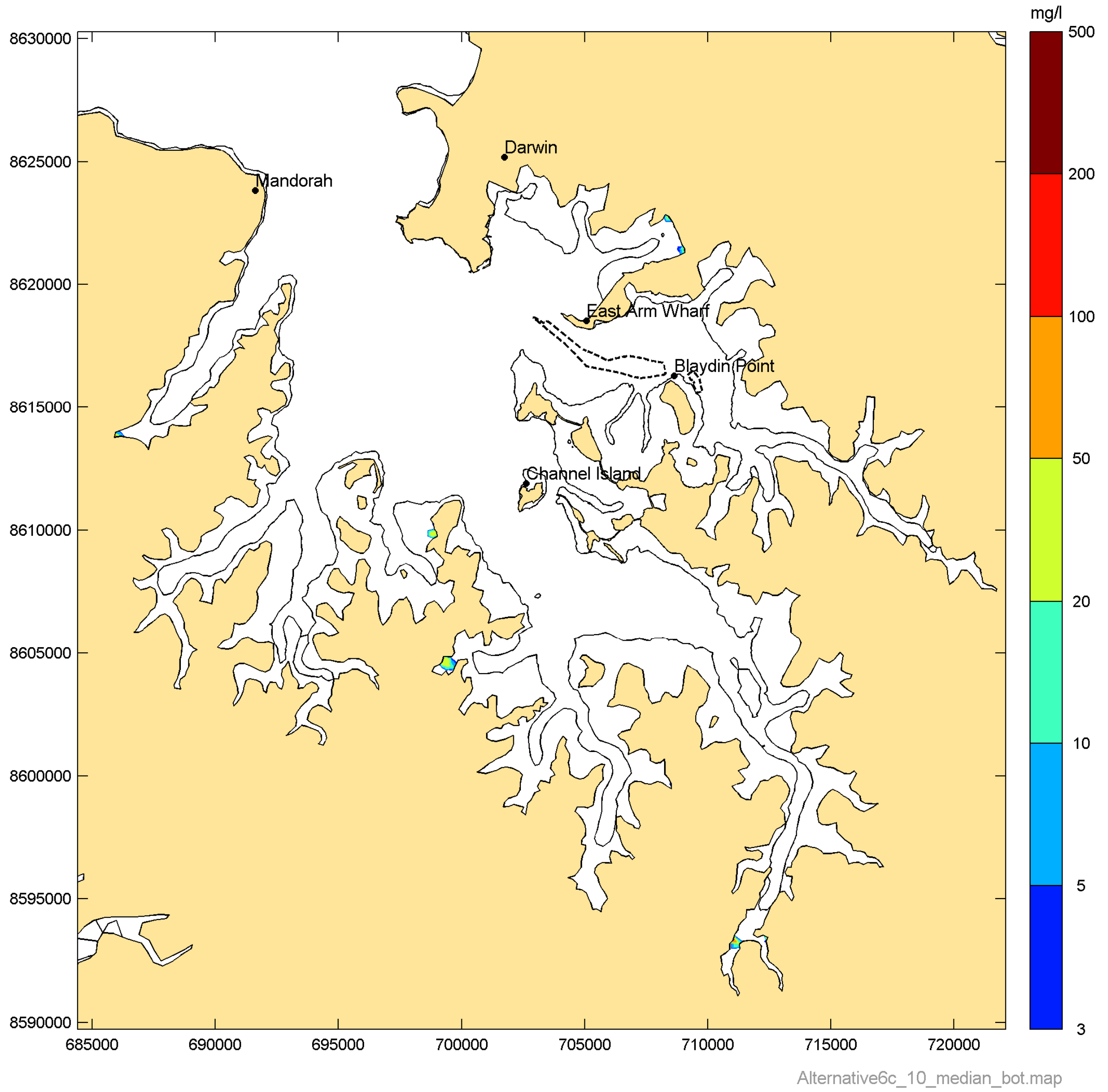


Figure 28 Simulated median suspended sediment concentration in the East Arm for Phase 10

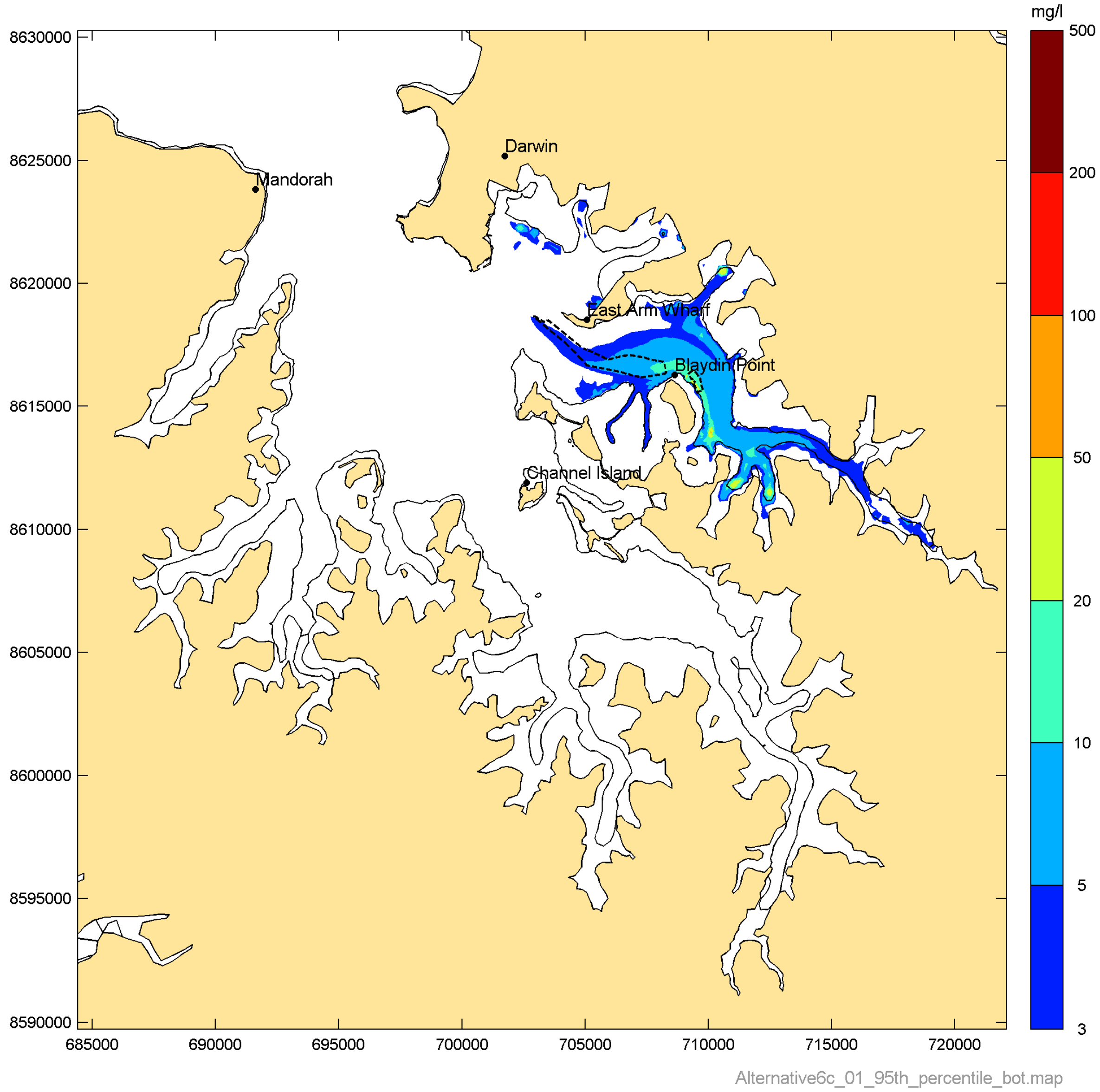


Figure 29 **Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 1**

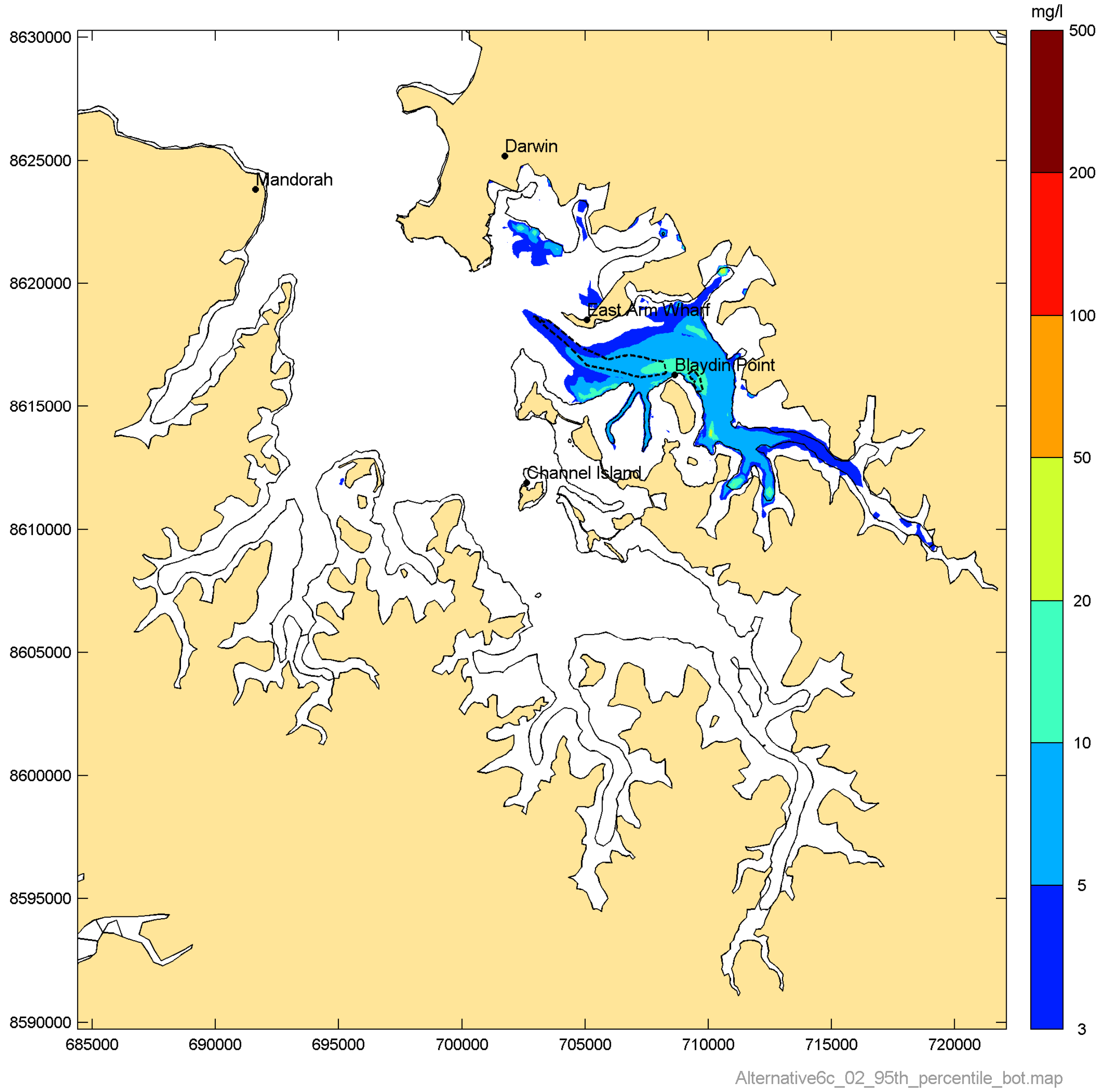


Figure 30 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 2

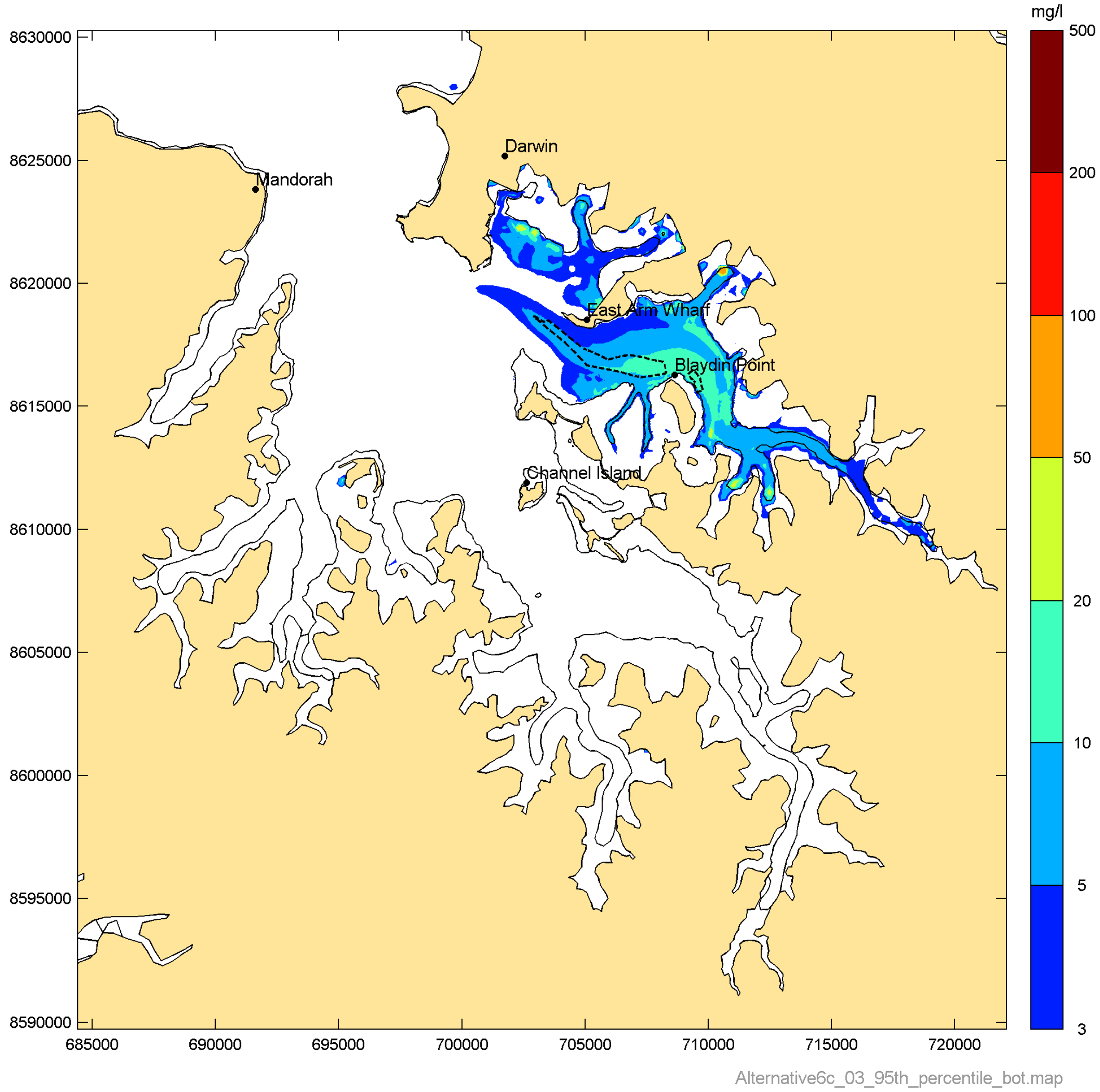


Figure 31 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 3

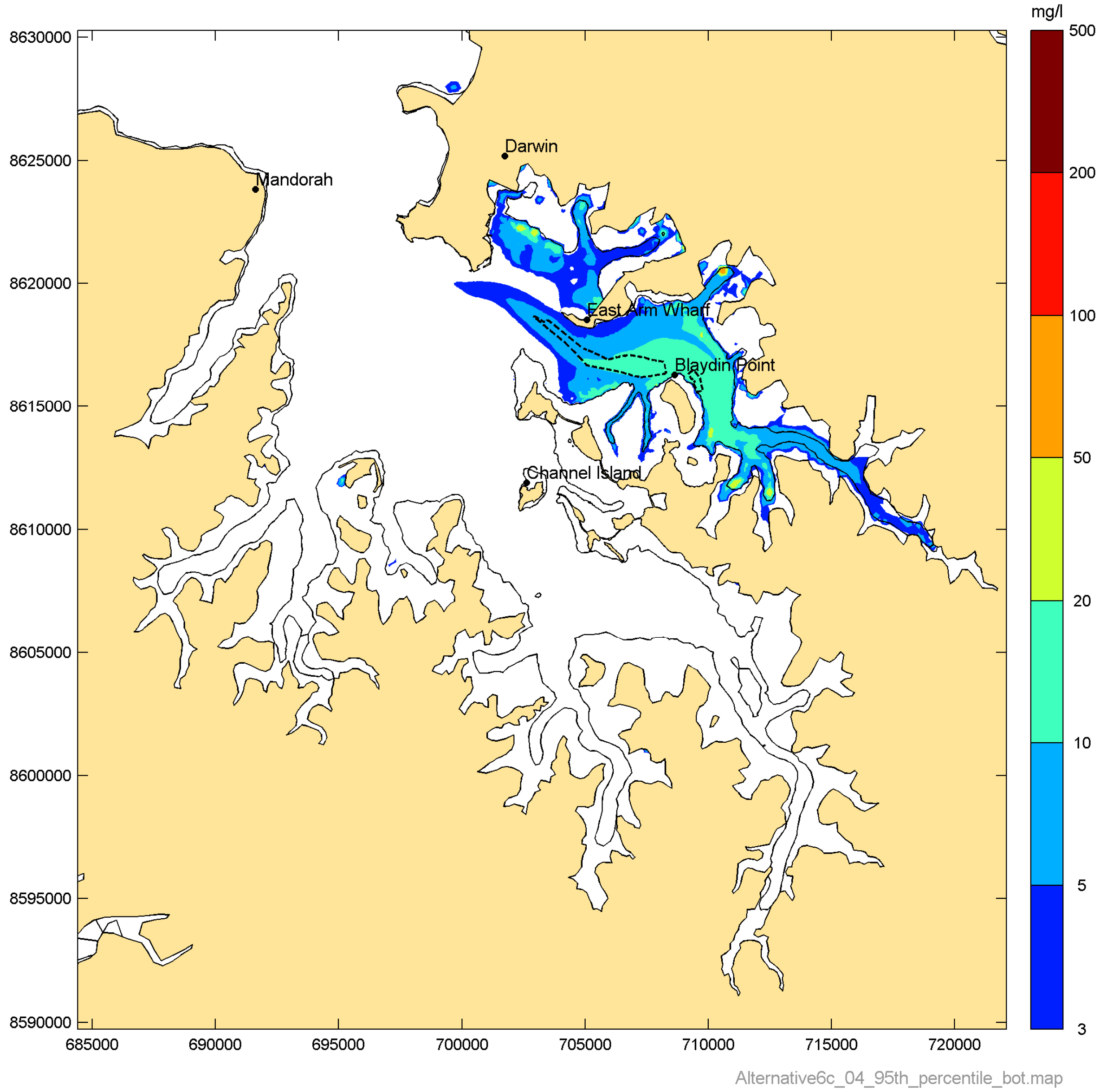


Figure 32 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 4

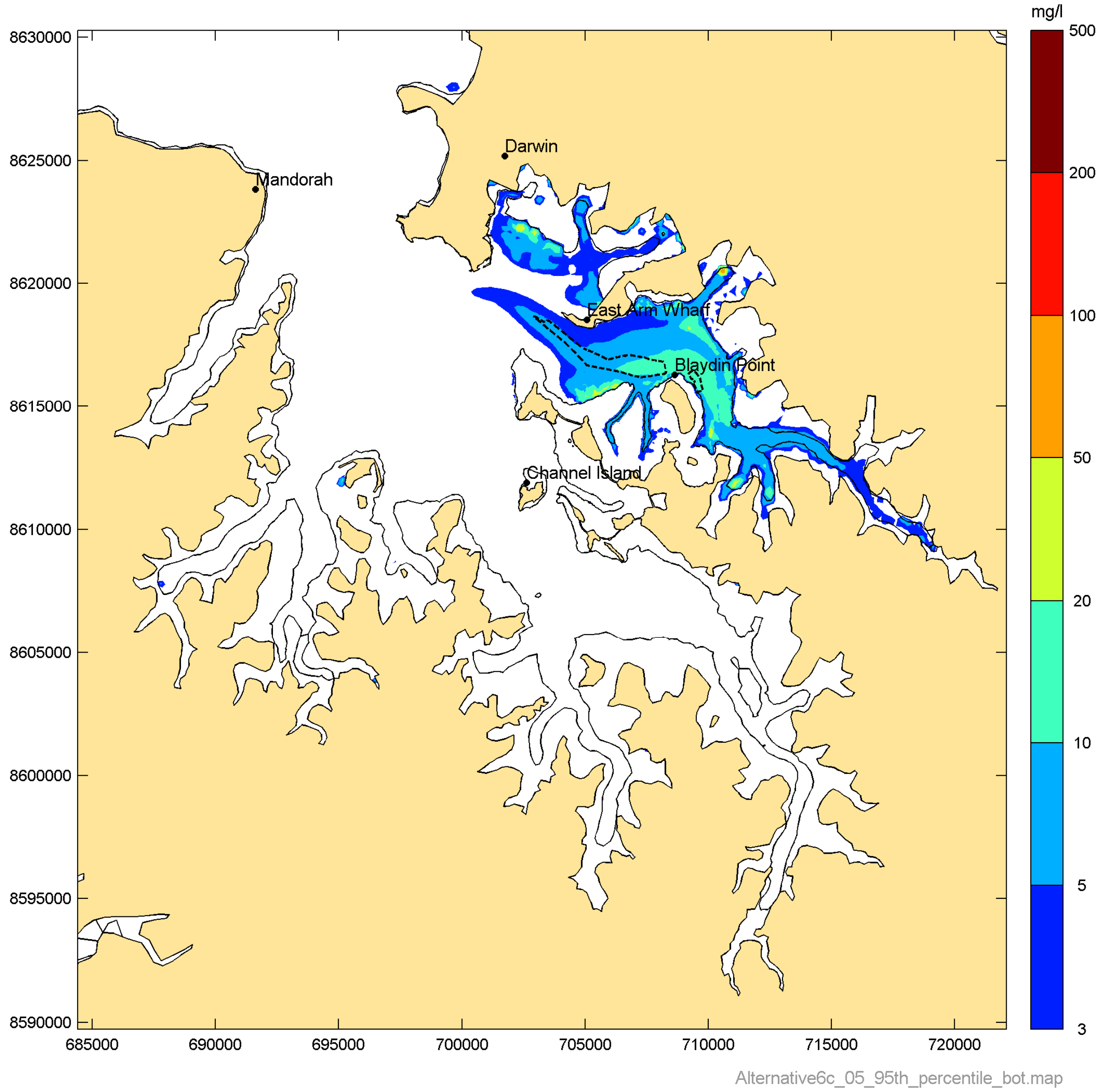


Figure 33 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 5

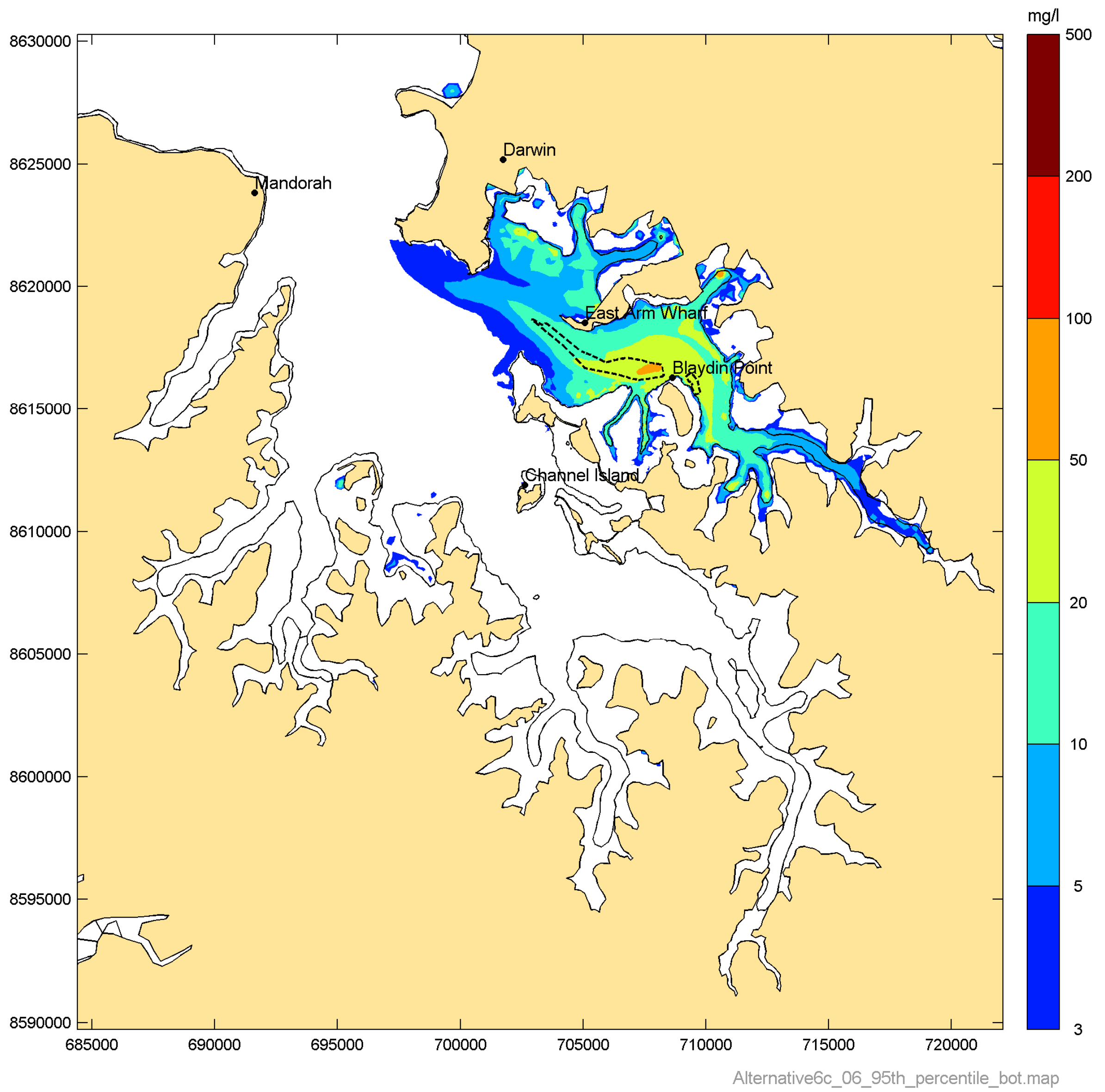


Figure 34 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 6

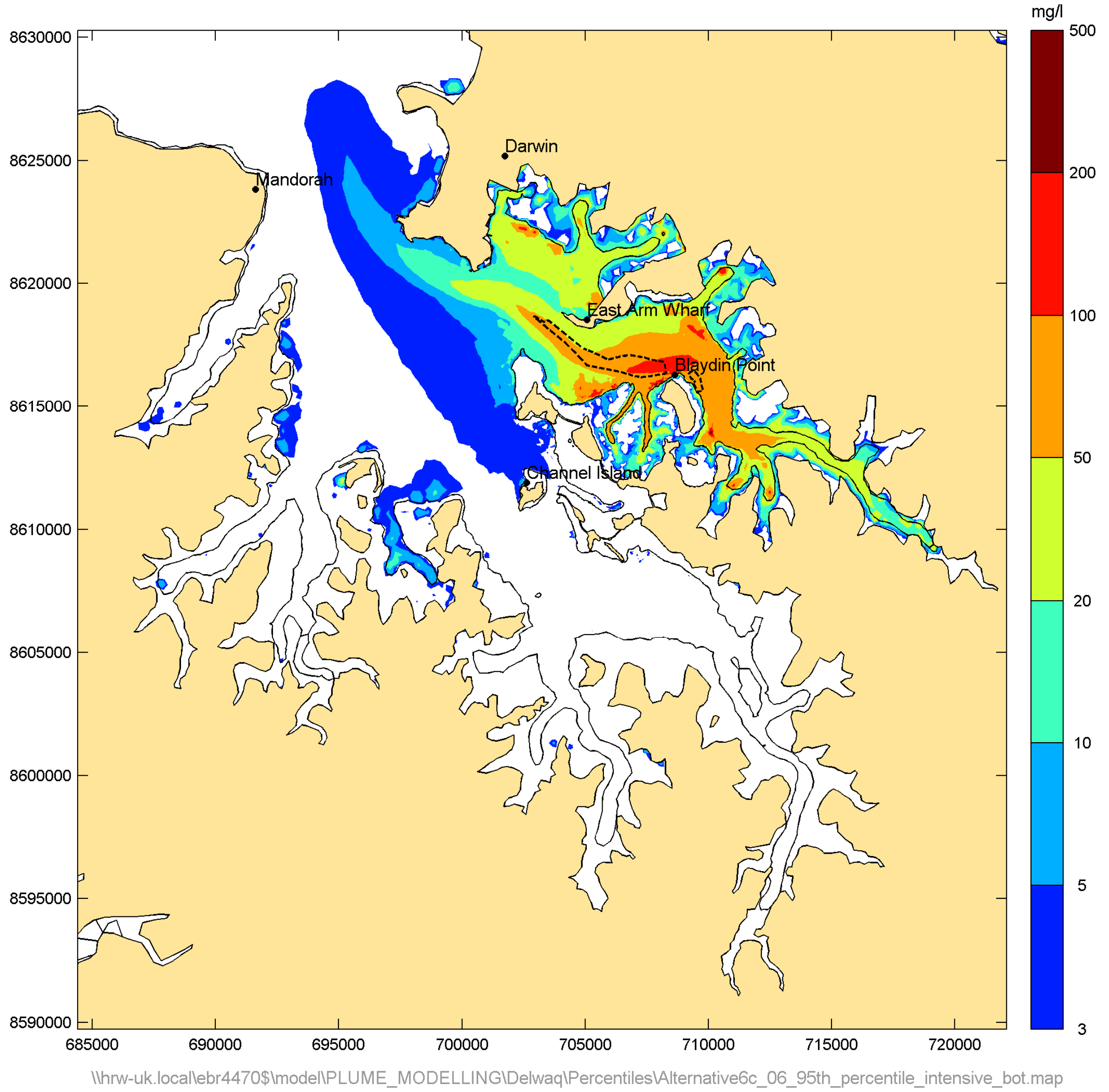


Figure 35 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 6 – cutter-suction dredger activity

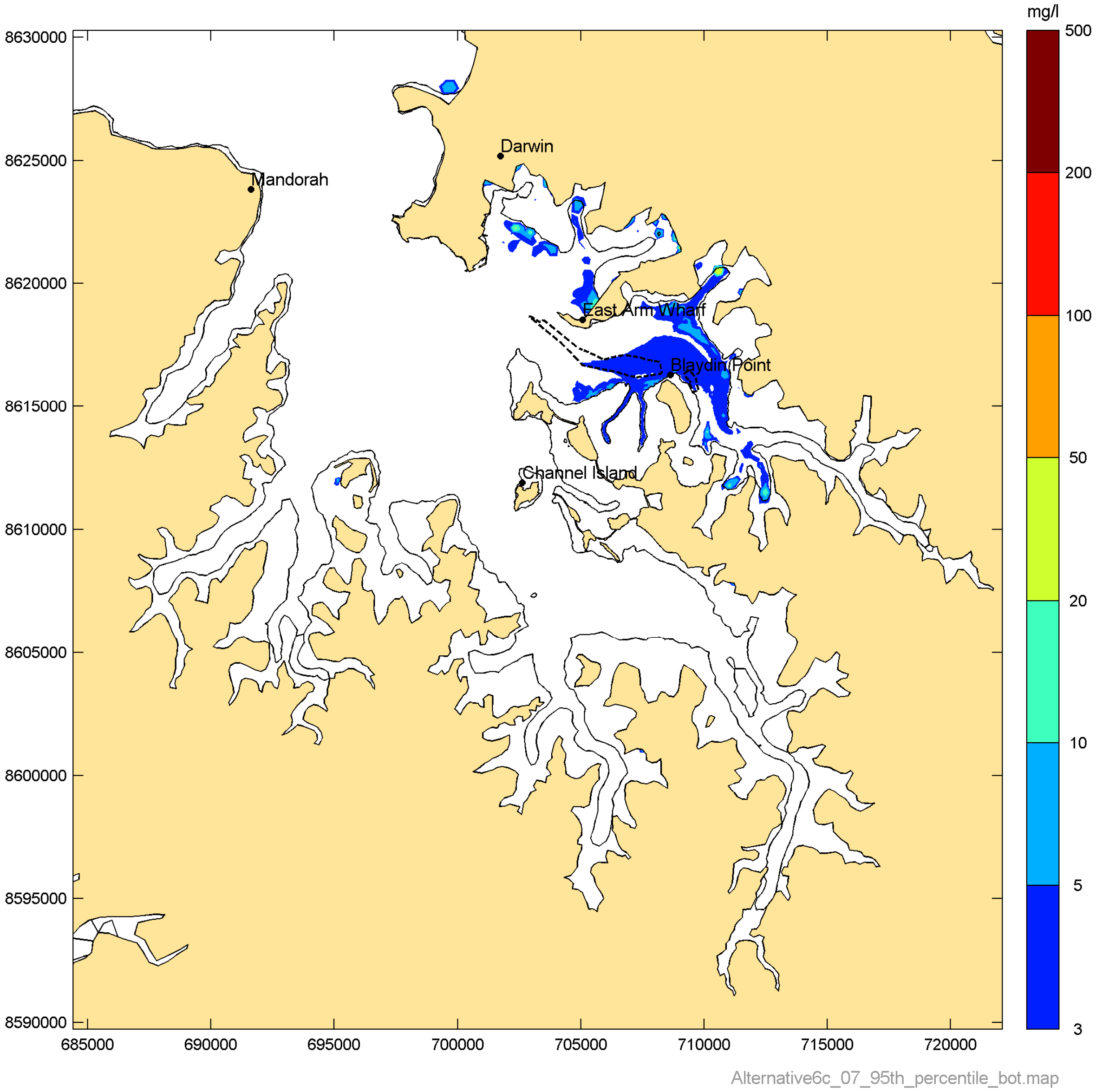


Figure 36 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 7

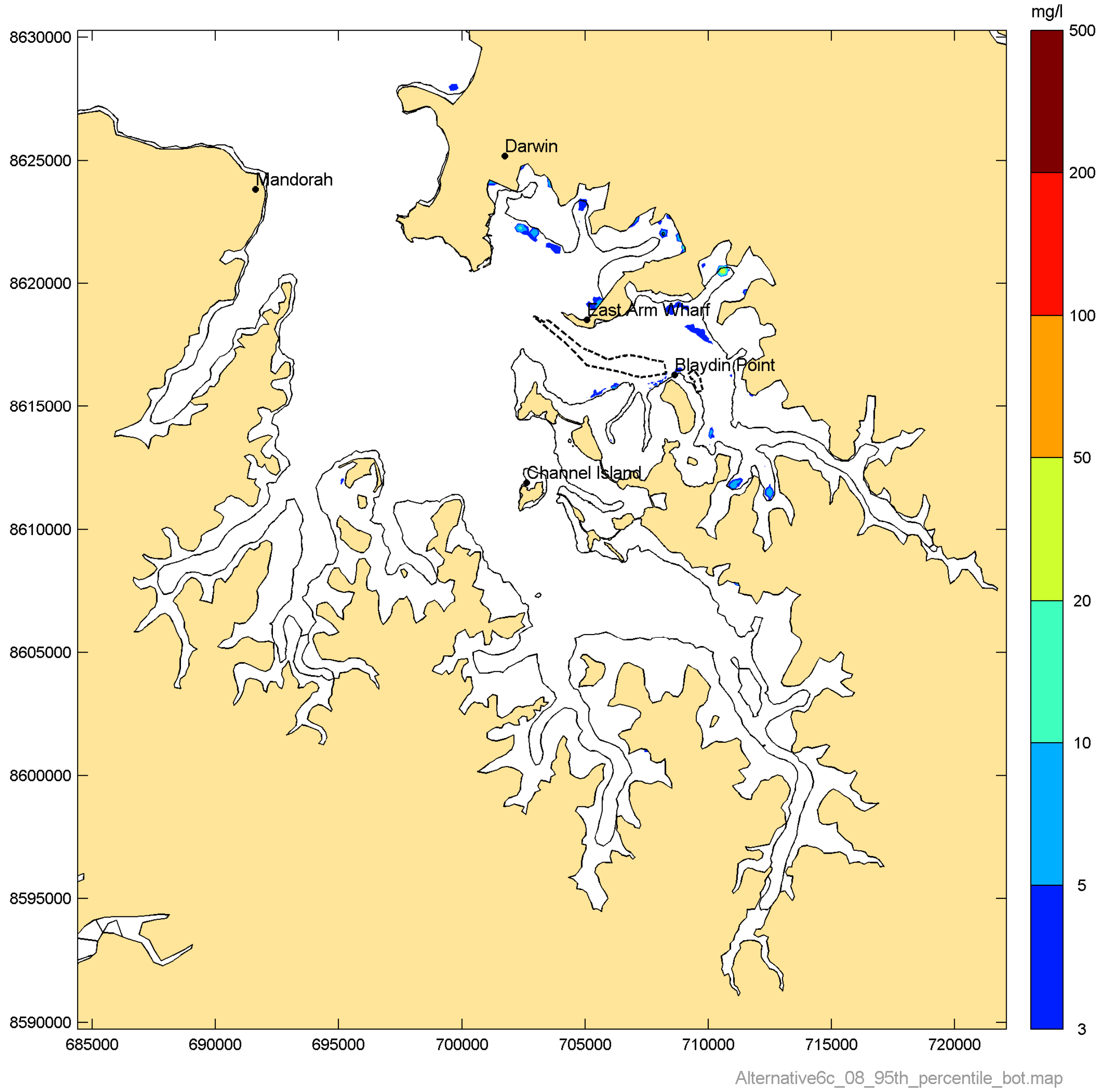


Figure 37 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 8

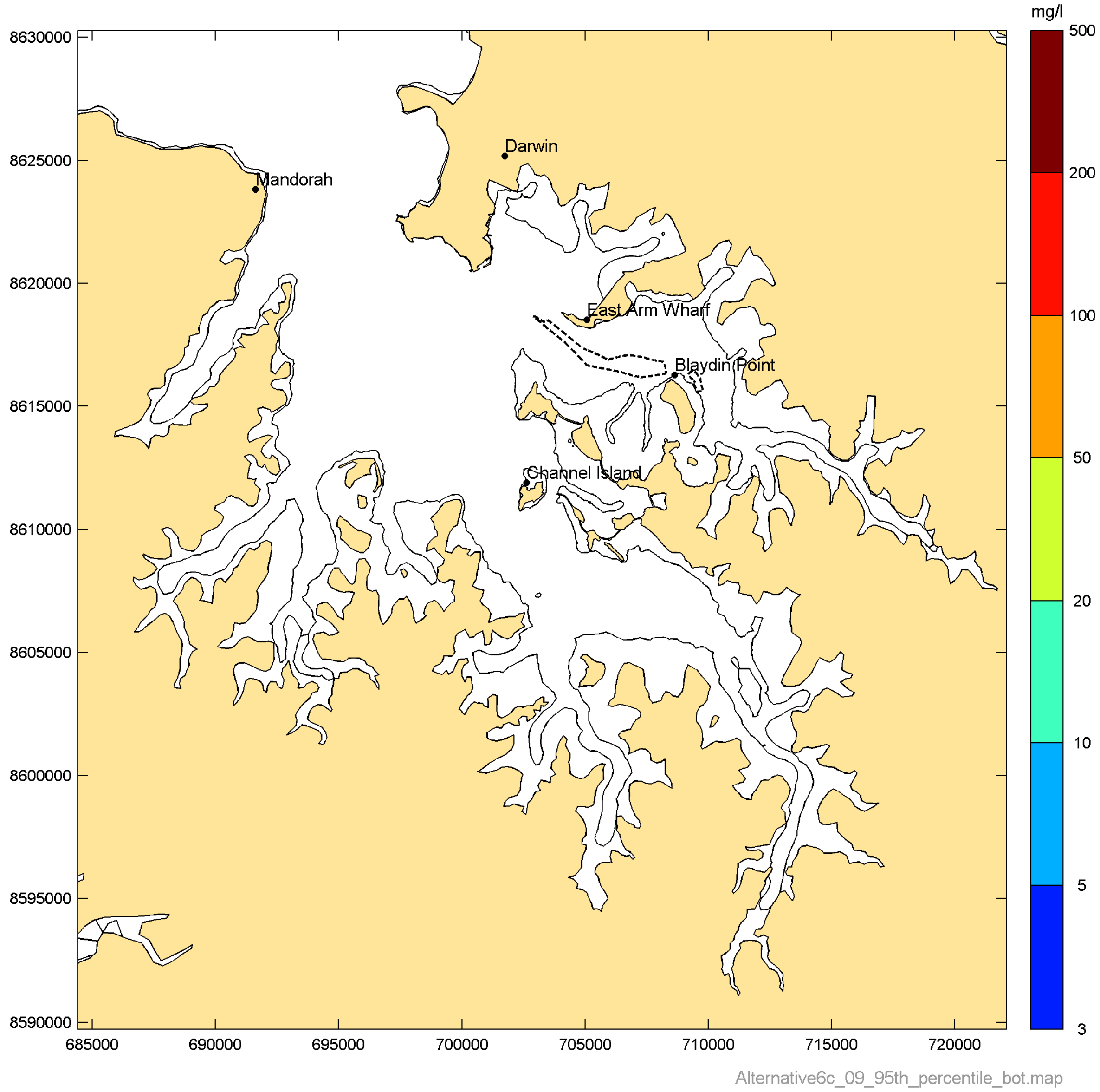


Figure 38 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 9

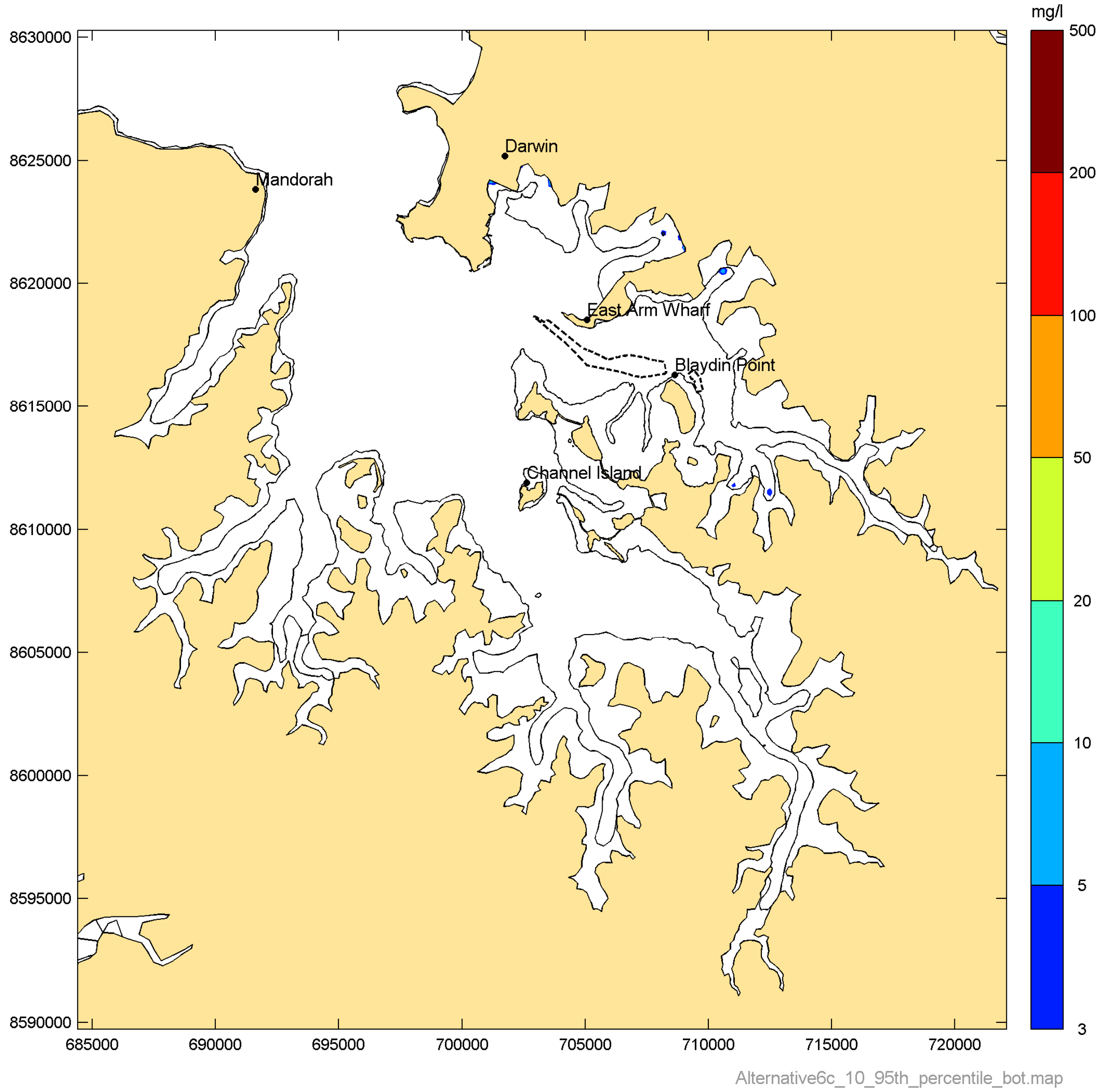


Figure 39 Simulated 95th percentile suspended sediment concentration in the East Arm for Phase 10

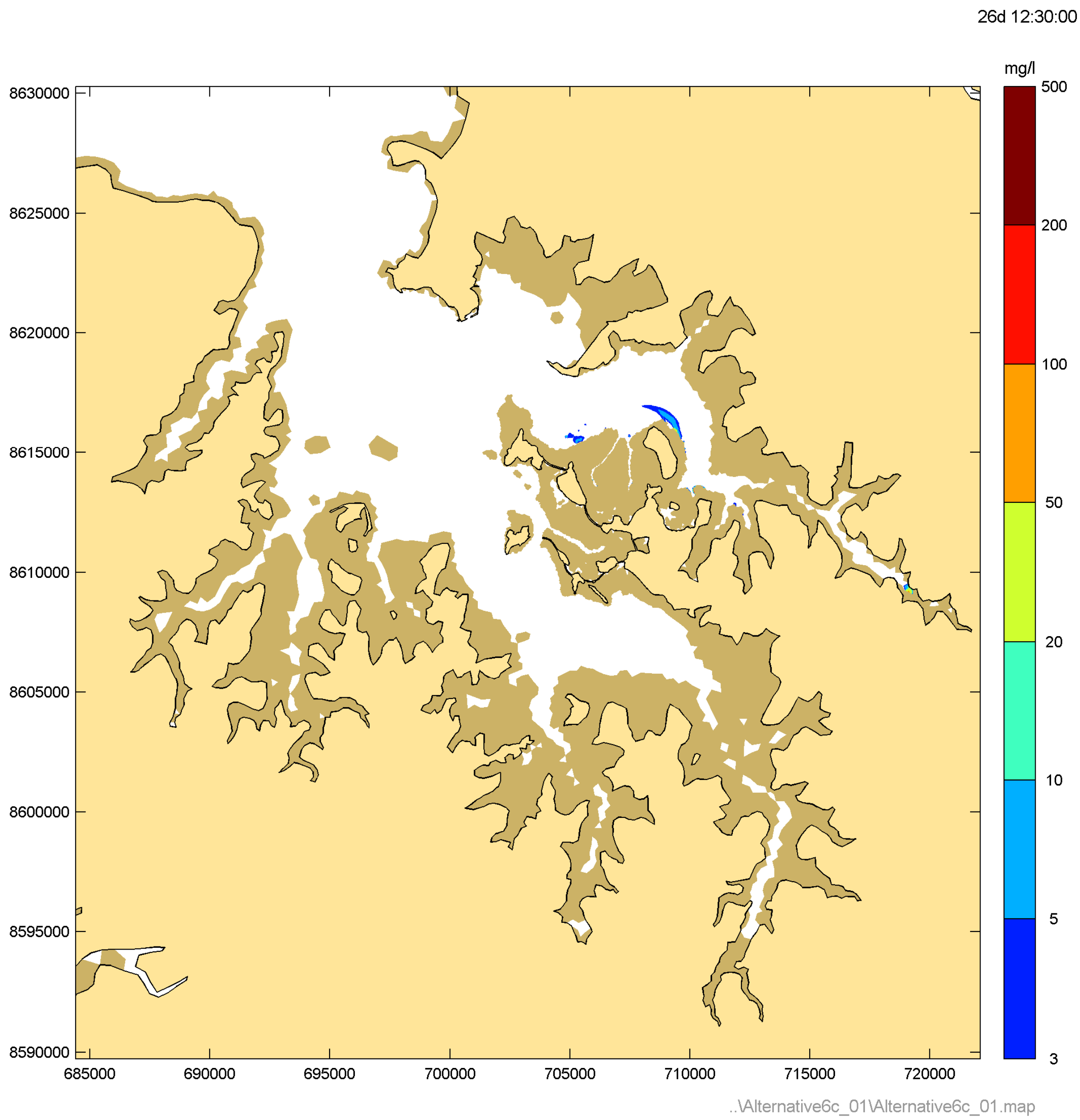


Figure 40 Instantaneous suspended sediment concentrations during Phase 1 peak ebb – Neap tide

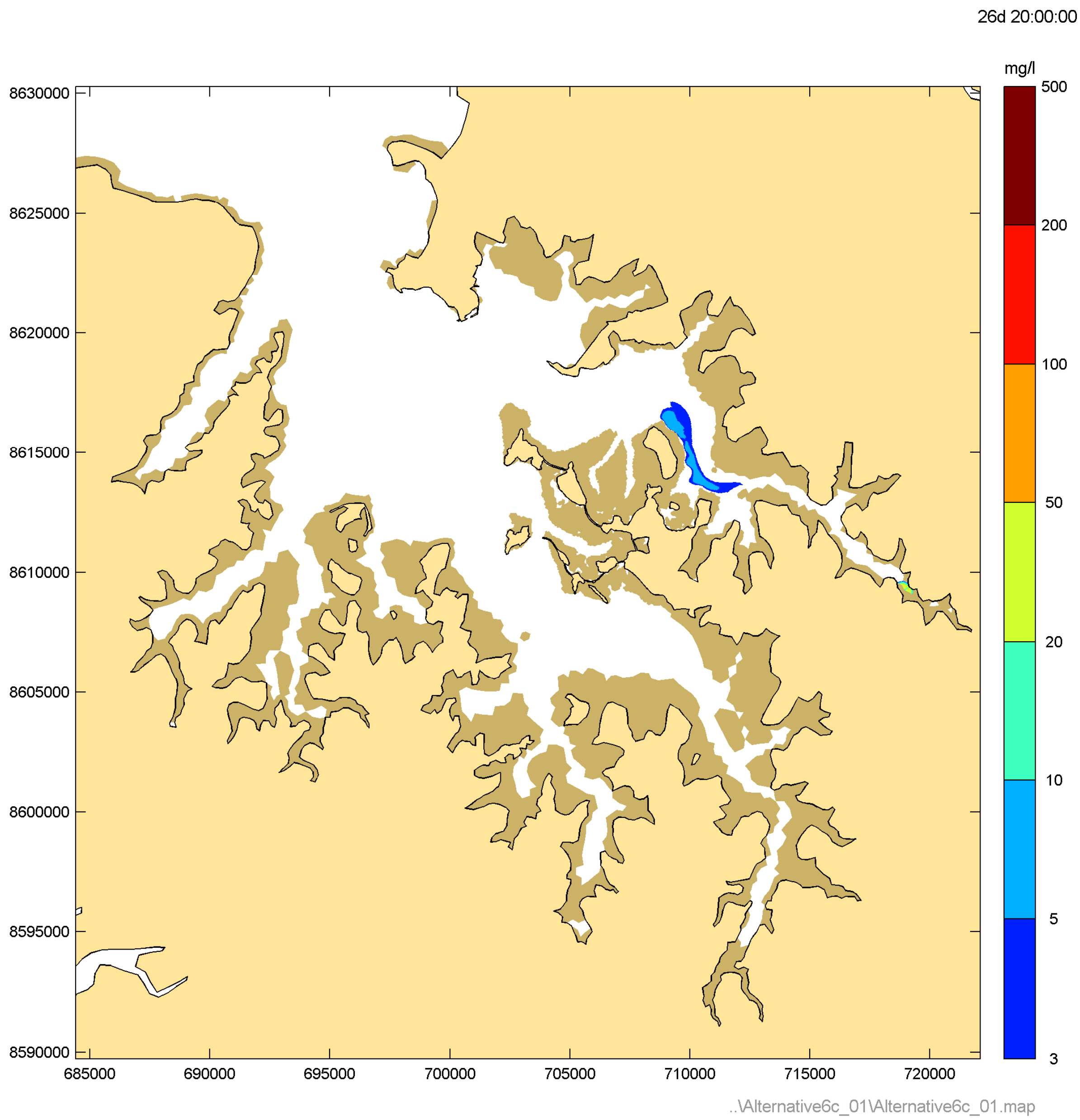


Figure 41 Instantaneous suspended sediment concentrations during Phase 1 peak flood – Neap tide

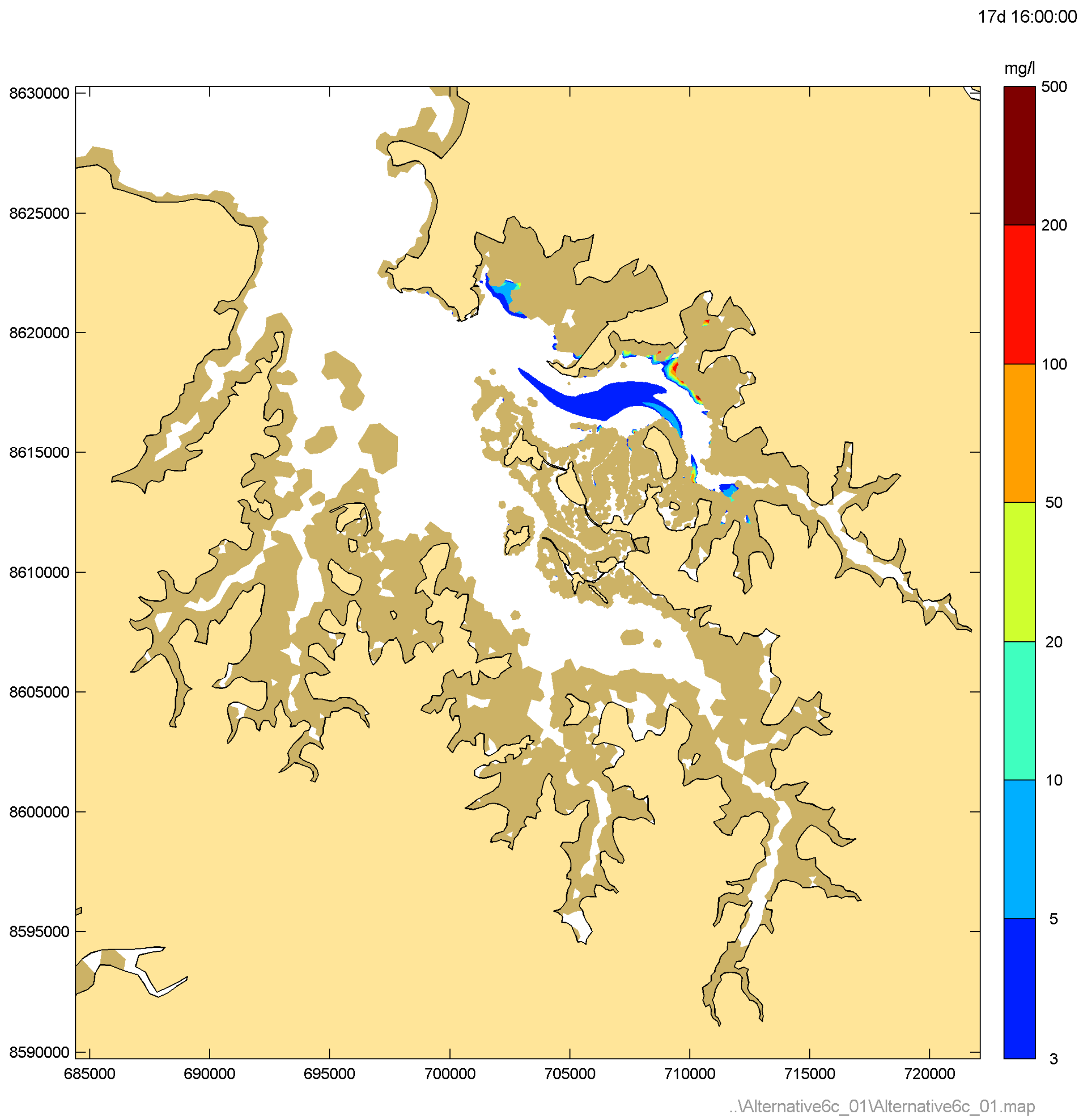


Figure 42 Instantaneous suspended sediment concentrations during Phase 1 peak ebb – spring tide

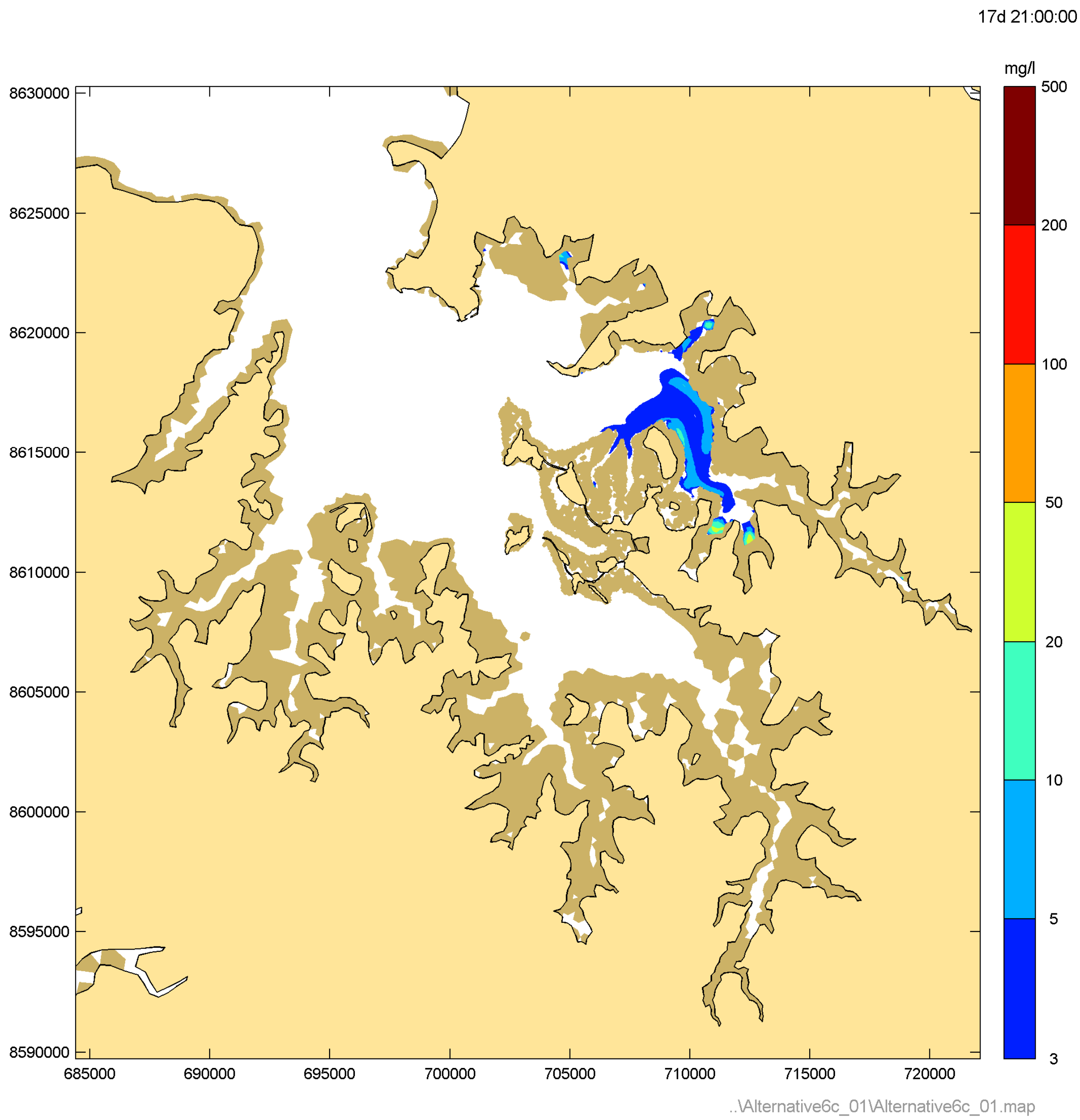


Figure 43 Instantaneous suspended sediment concentrations during Phase 1 peak flood – spring tide

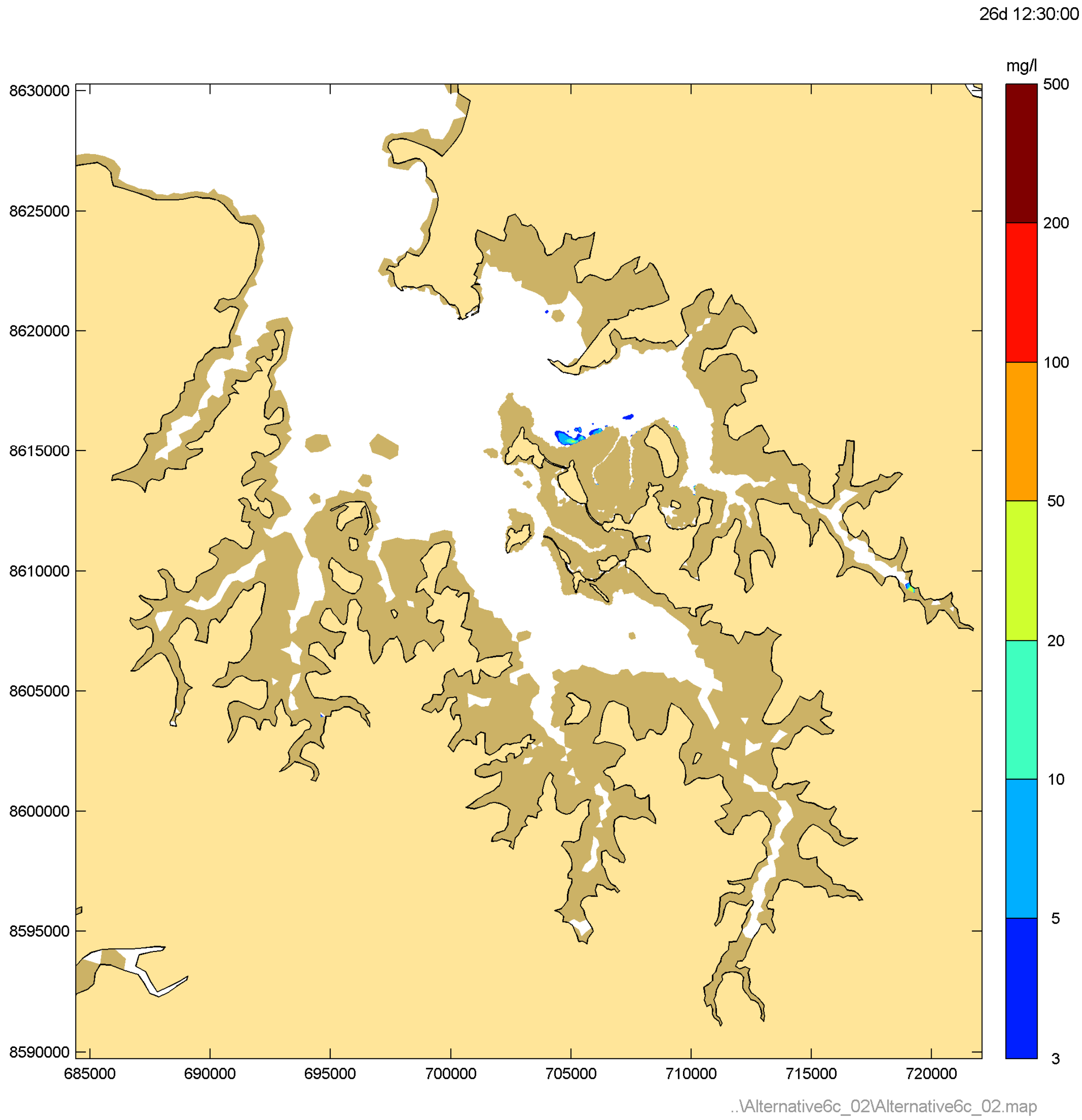


Figure 44 Instantaneous suspended sediment concentrations during Phase 2 peak ebb – Neap tide

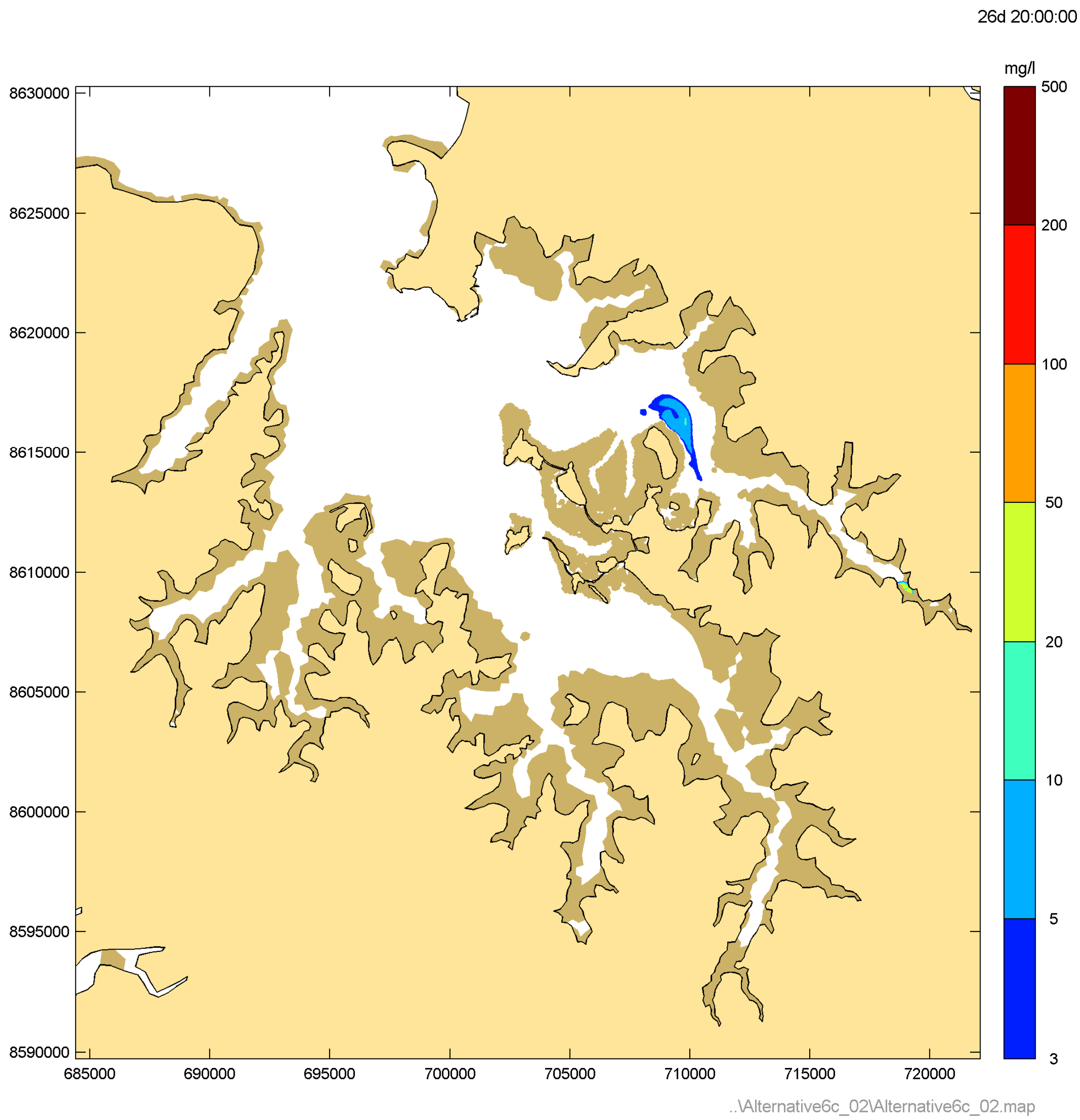


Figure 45 **Instantaneous suspended sediment concentrations during Phase 2 peak flood – Neap tide**

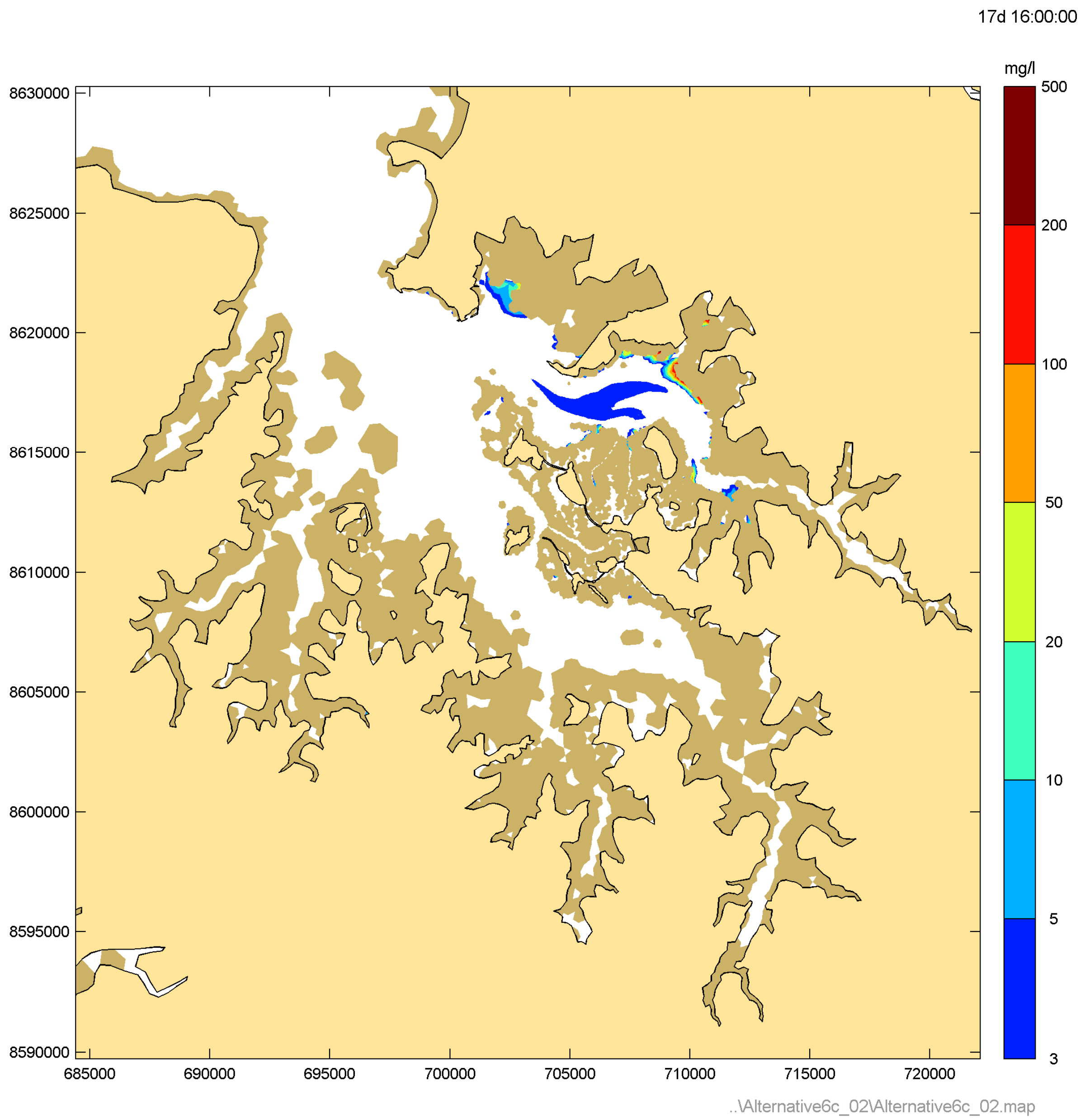


Figure 46 Instantaneous suspended sediment concentrations during Phase 2 peak ebb – spring tide

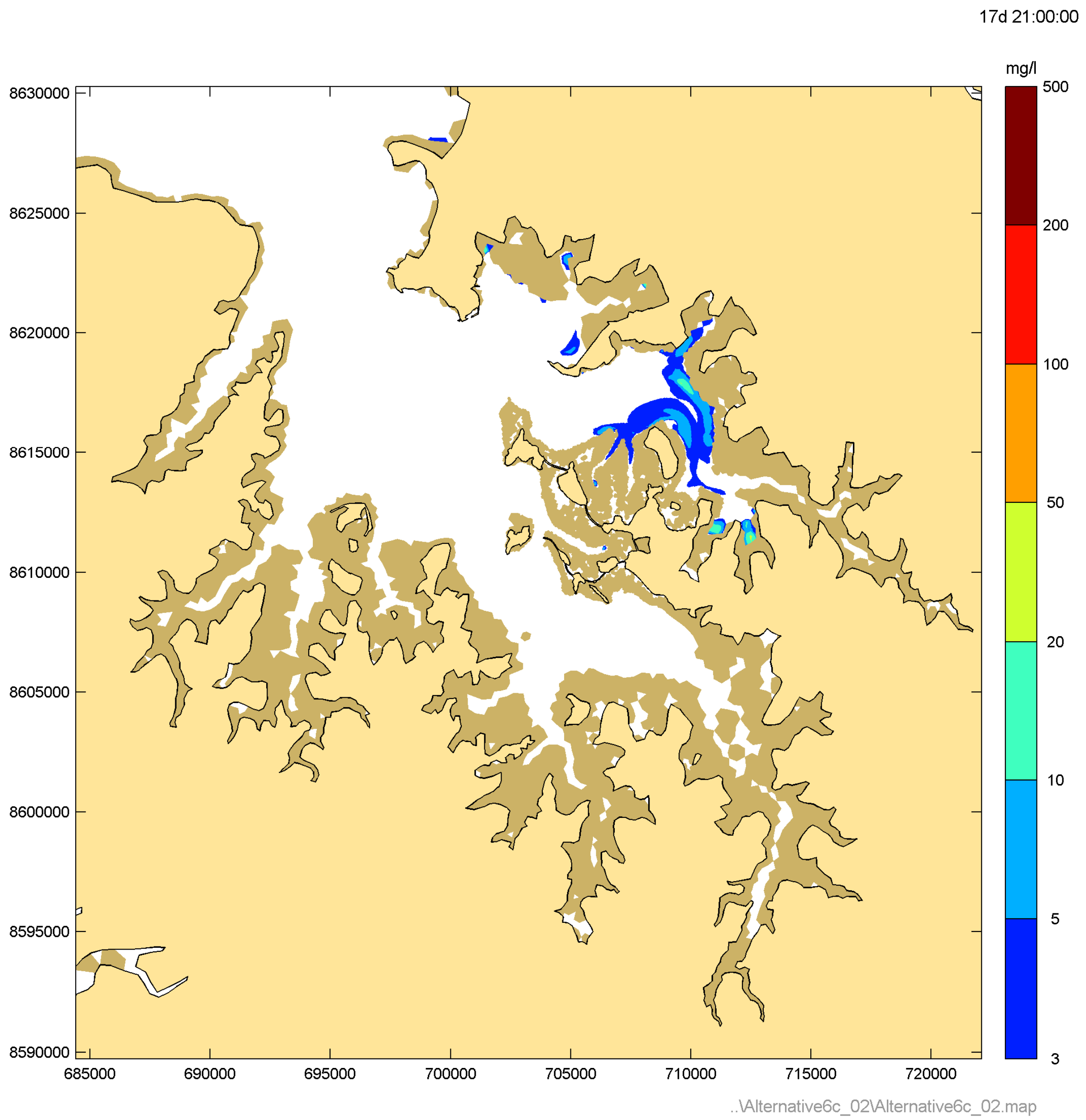


Figure 47 **Instantaneous suspended sediment concentrations during Phase 2 peak flood – spring tide**

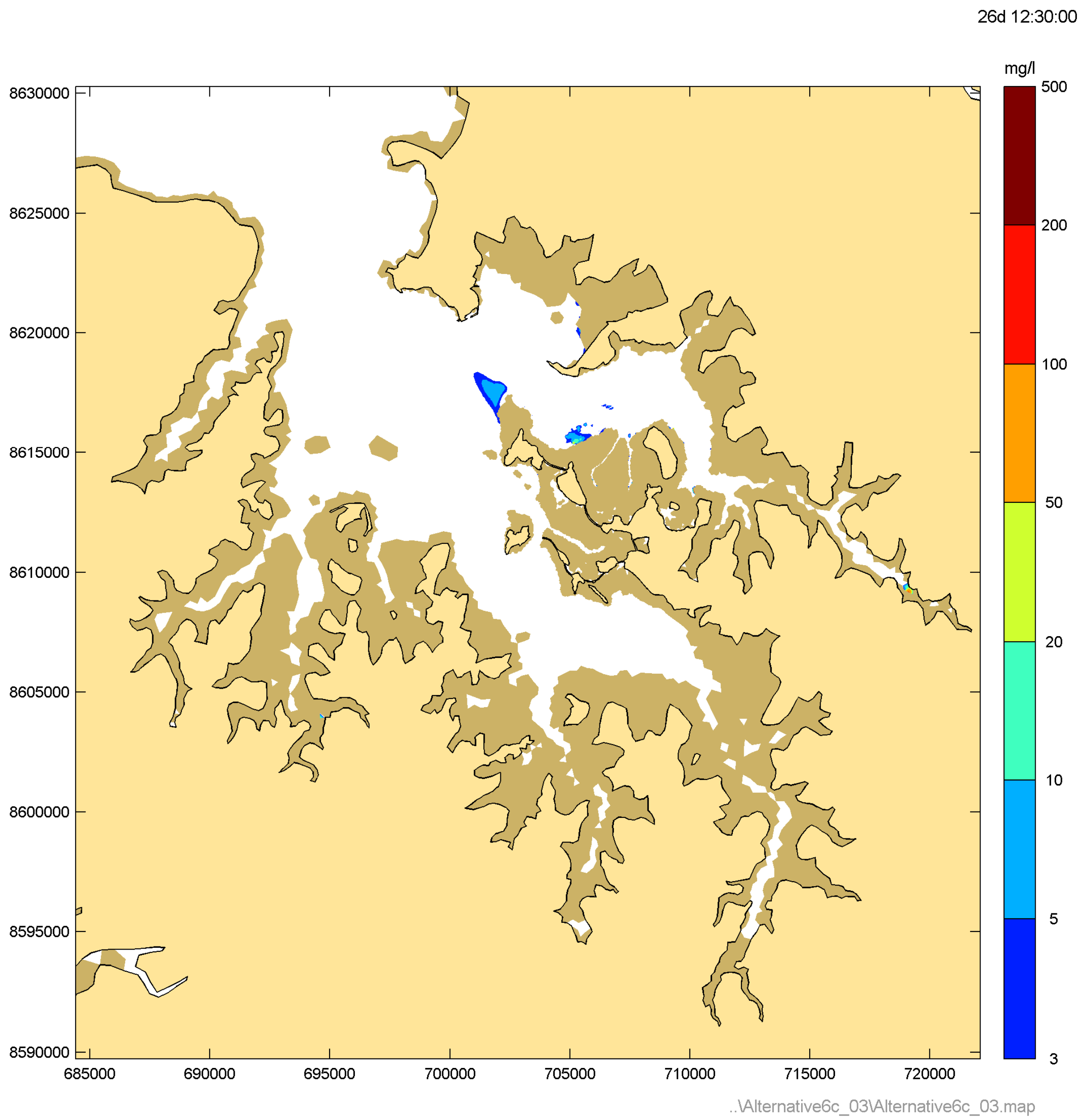


Figure 48 **Instantaneous suspended sediment concentrations during Phase 3 peak ebb – Neap tide**

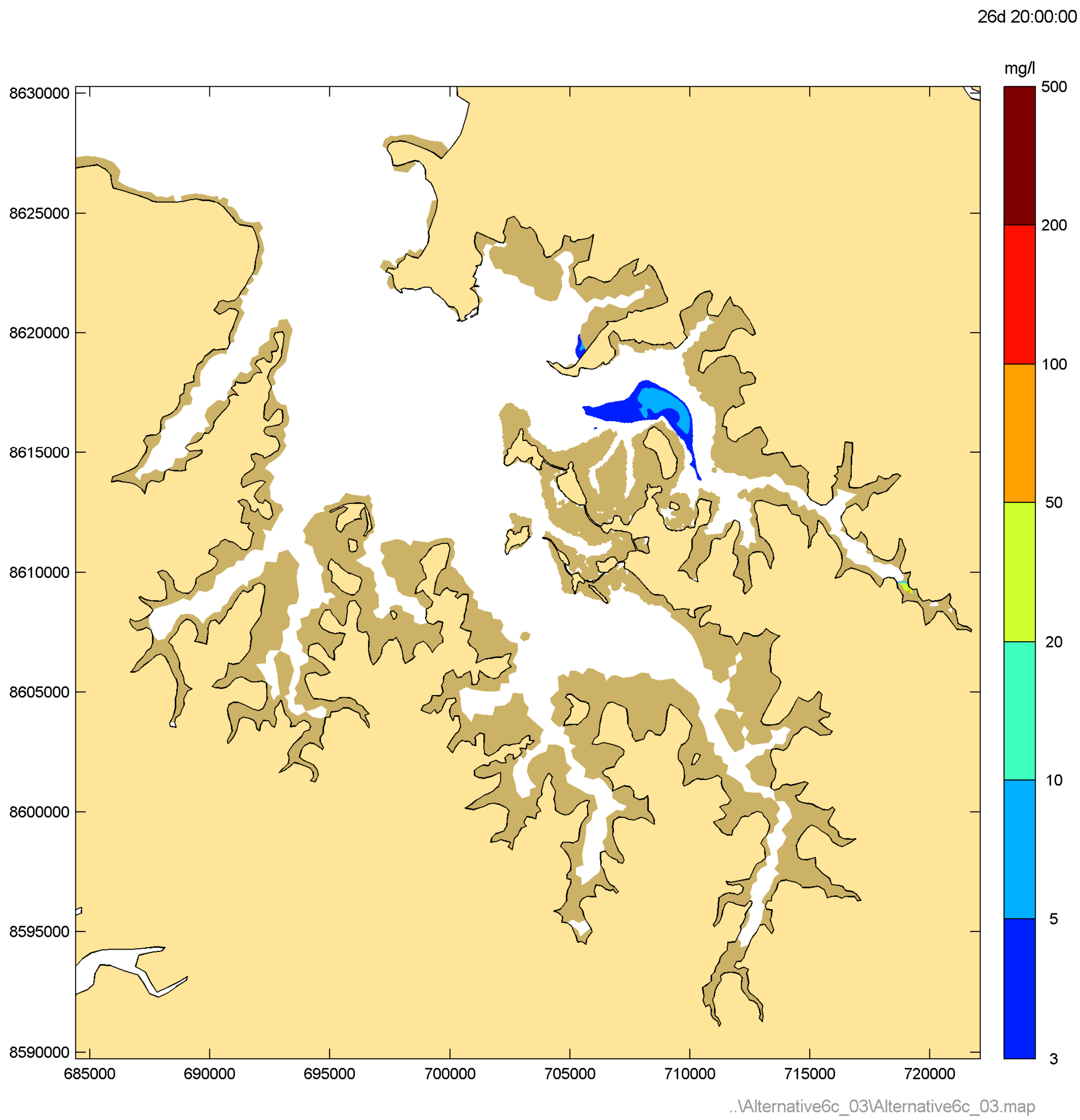


Figure 49 Instantaneous suspended sediment concentrations during Phase 3 peak flood – Neap tide

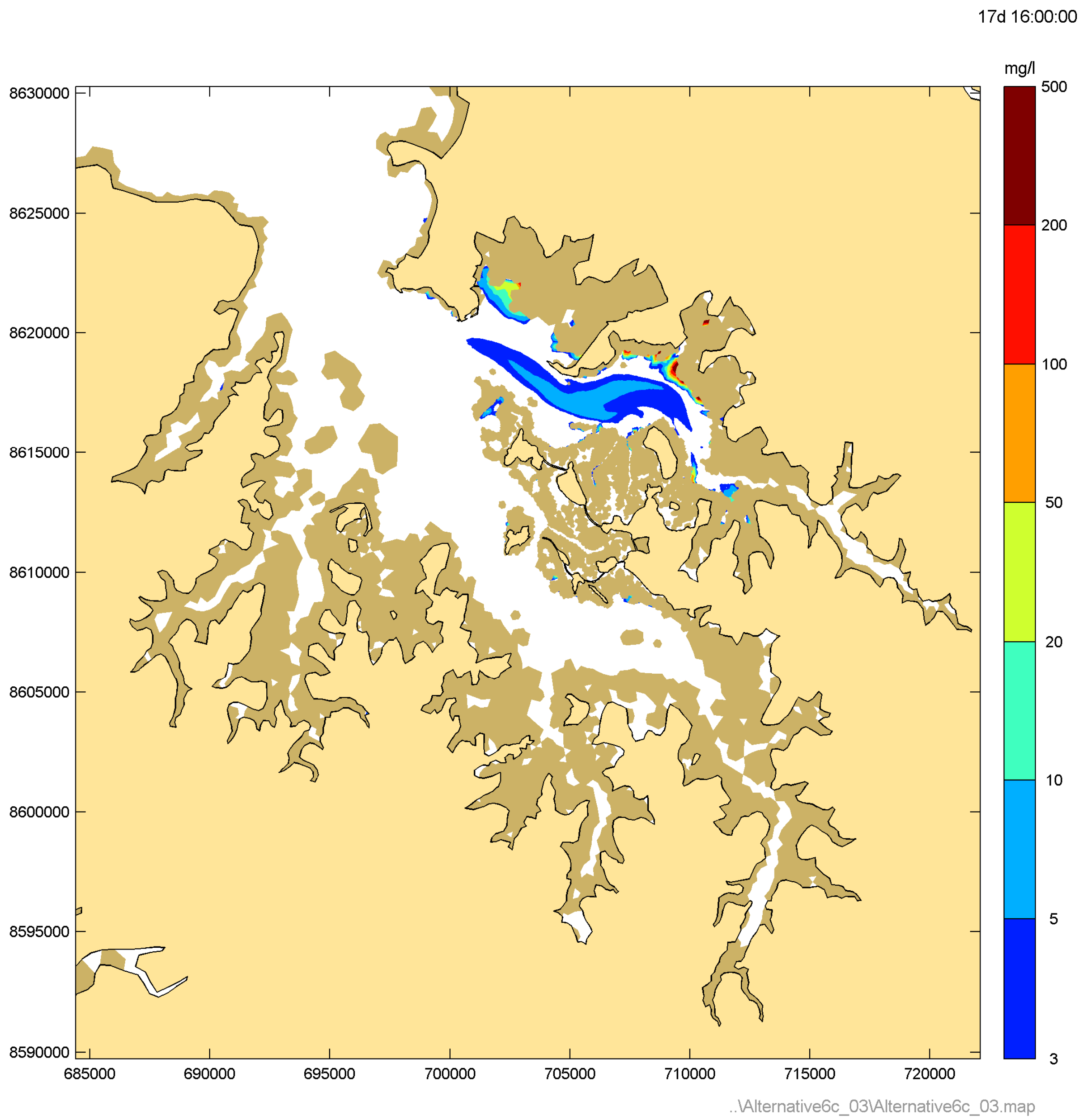


Figure 50 Instantaneous suspended sediment concentrations during Phase 3 peak ebb – spring tide

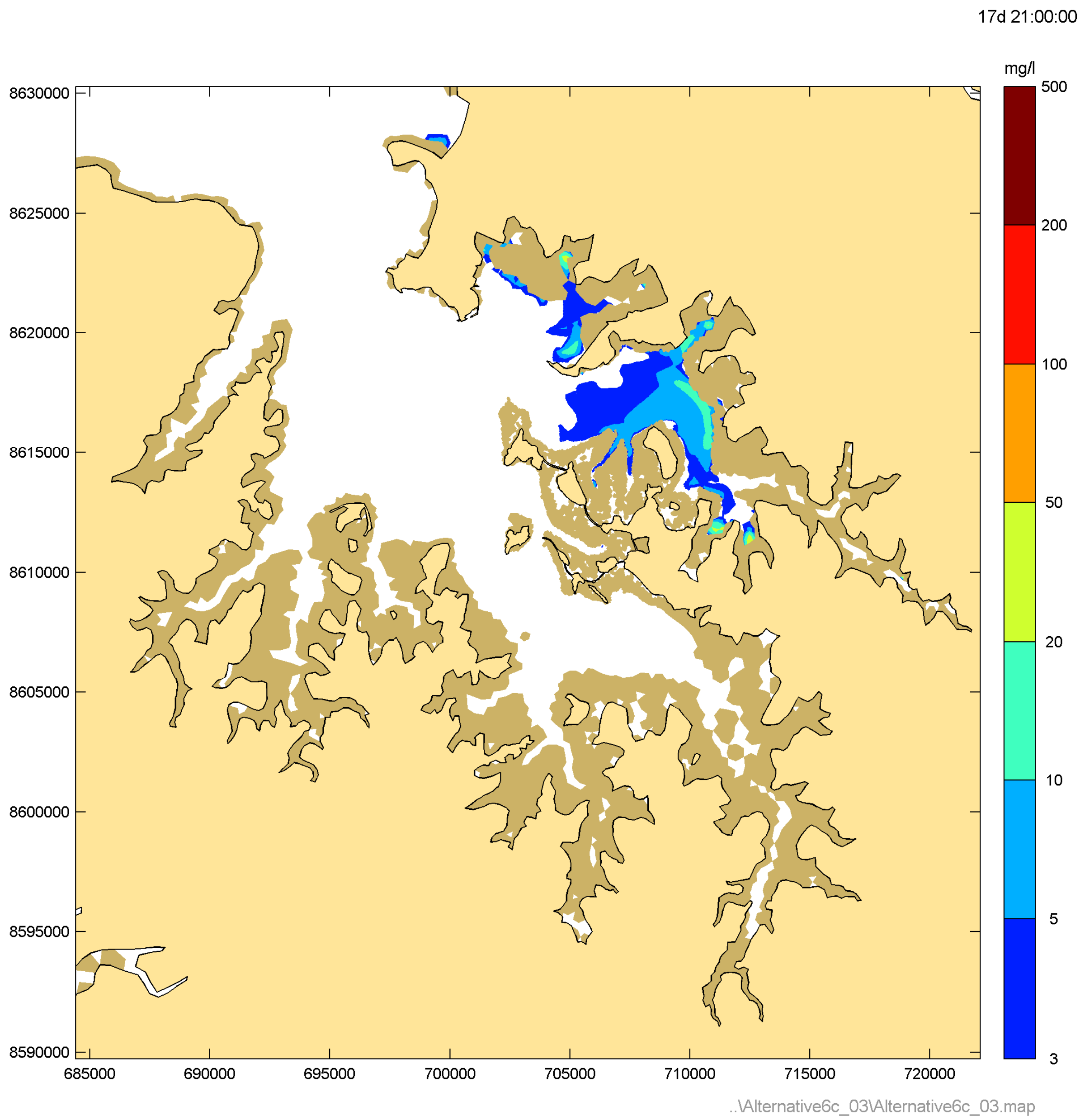


Figure 51 Instantaneous suspended sediment concentrations during Phase 3 peak flood – spring tide

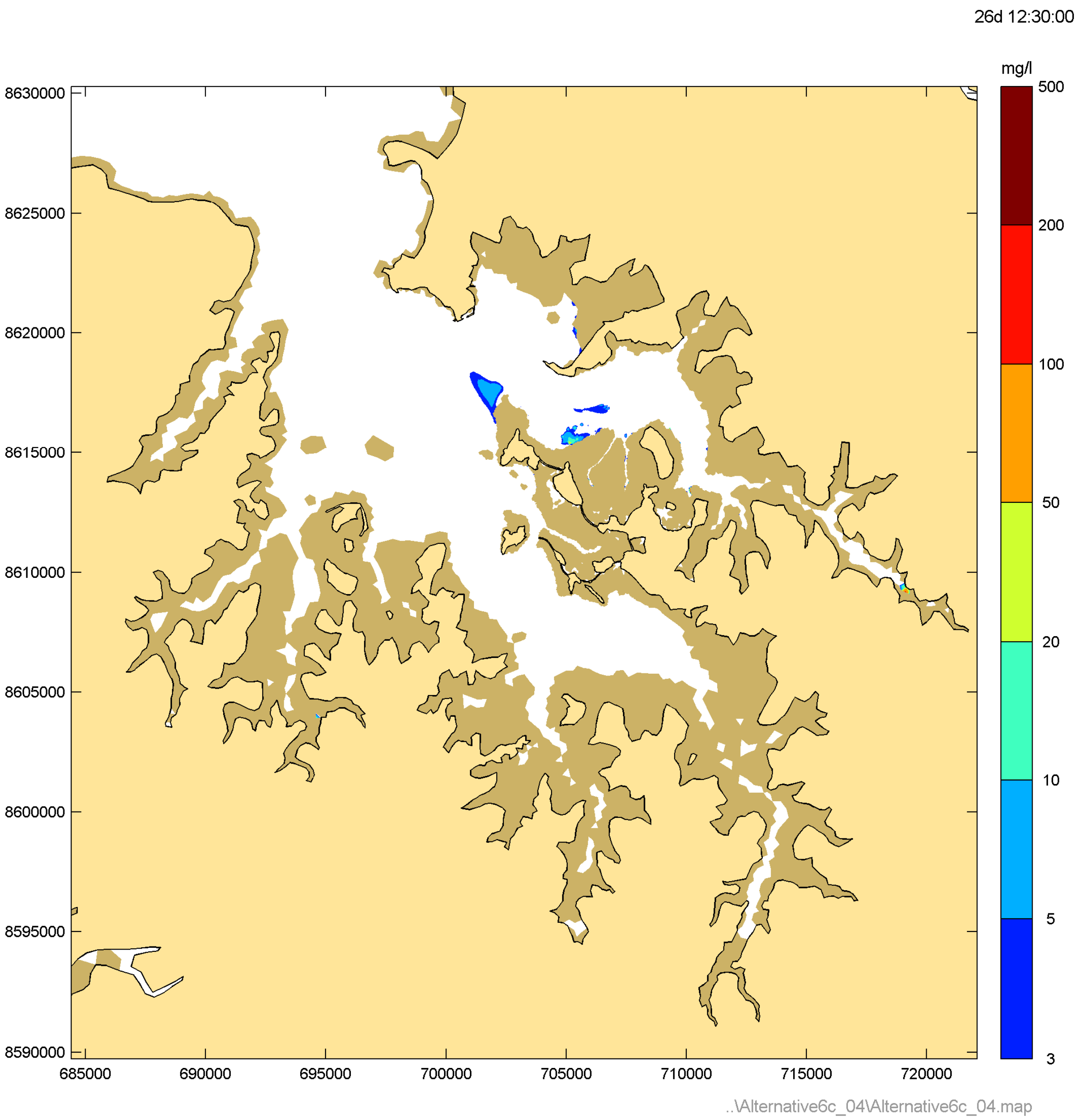


Figure 52 **Instantaneous suspended sediment concentrations during Phase 4 peak ebb – Neap tide**

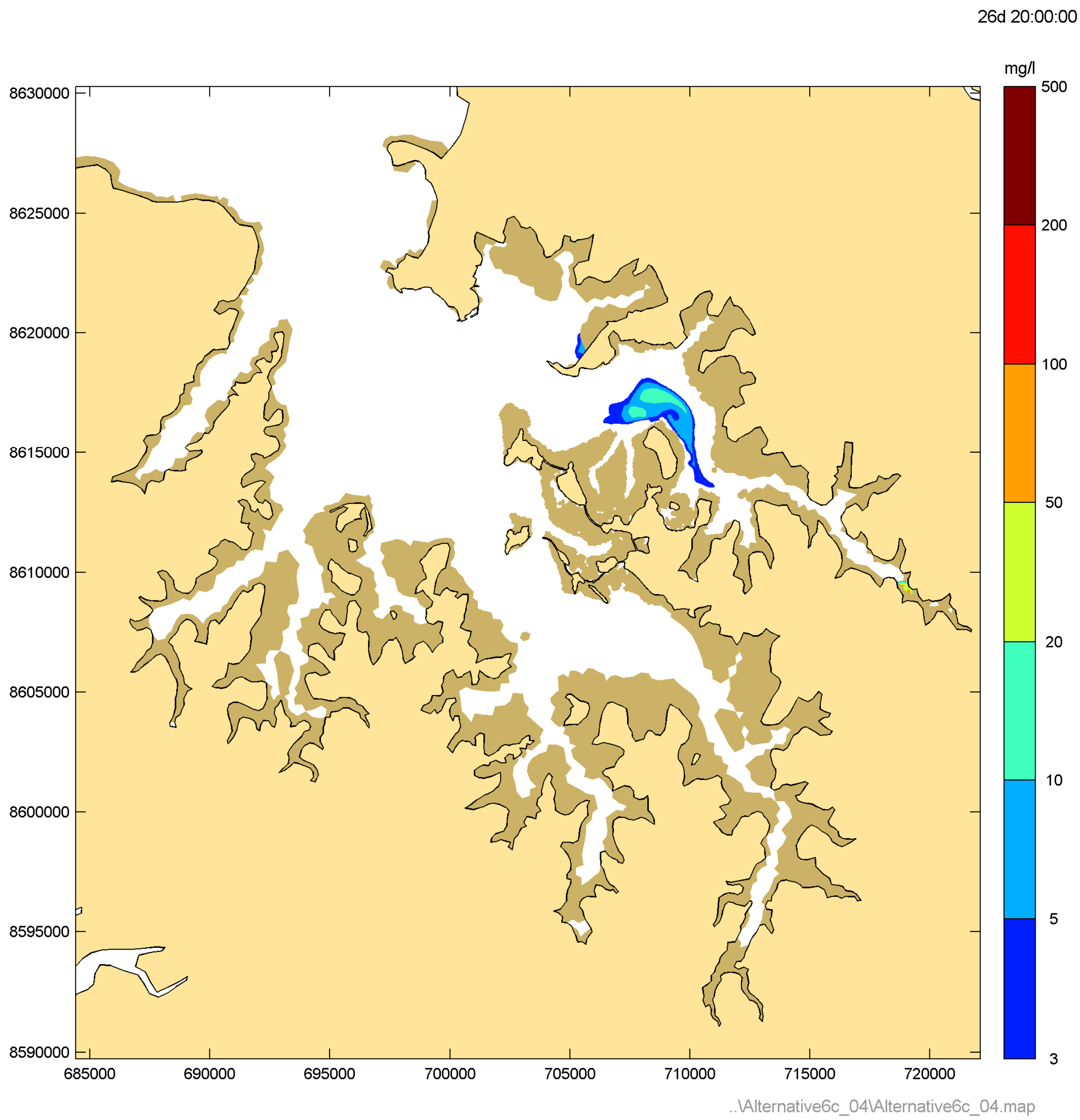


Figure 53 Instantaneous suspended sediment concentrations during Phase 4 peak flood – Neap tide

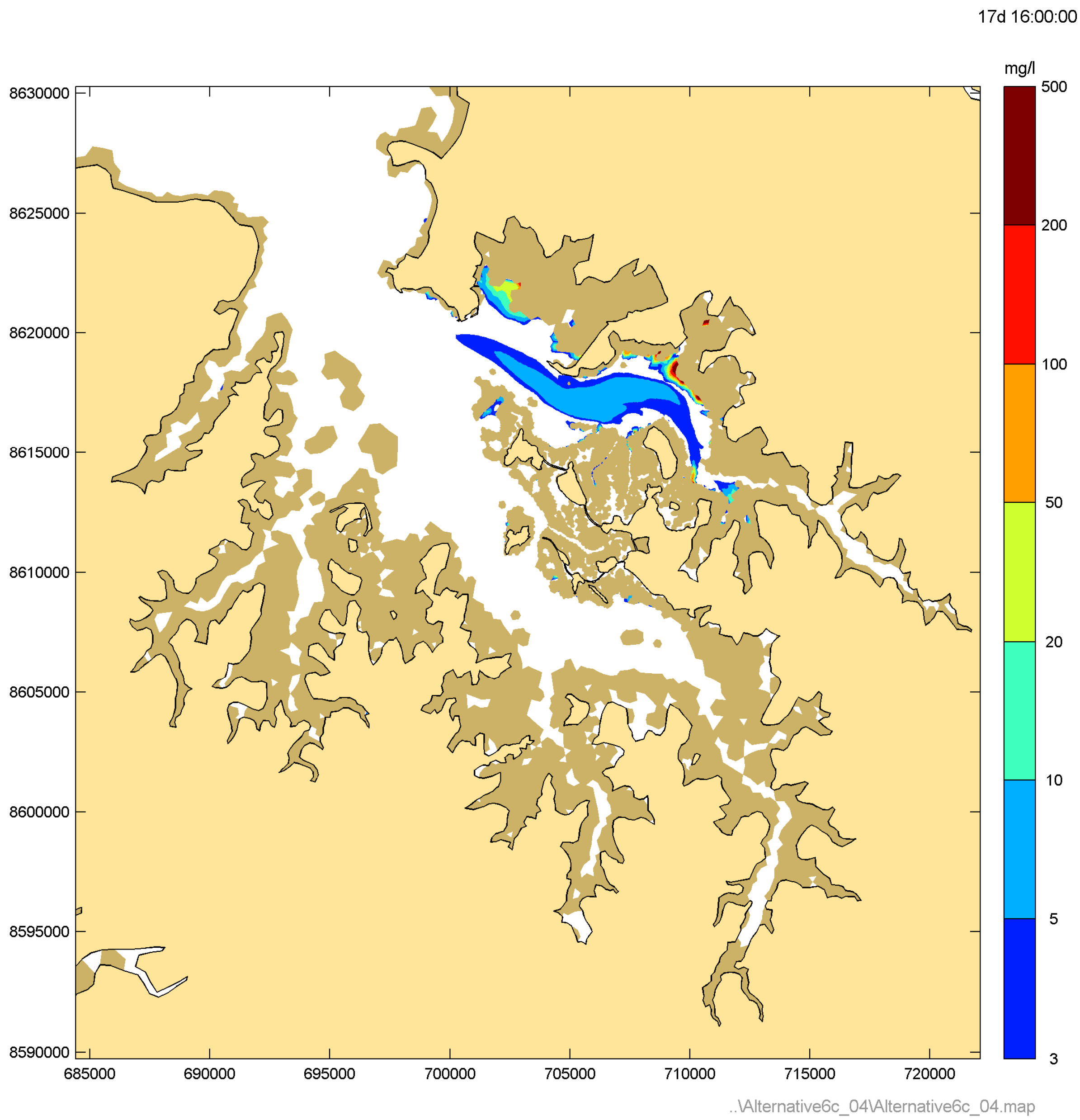


Figure 54 Instantaneous suspended sediment concentrations during Phase 4 peak ebb – Spring tide

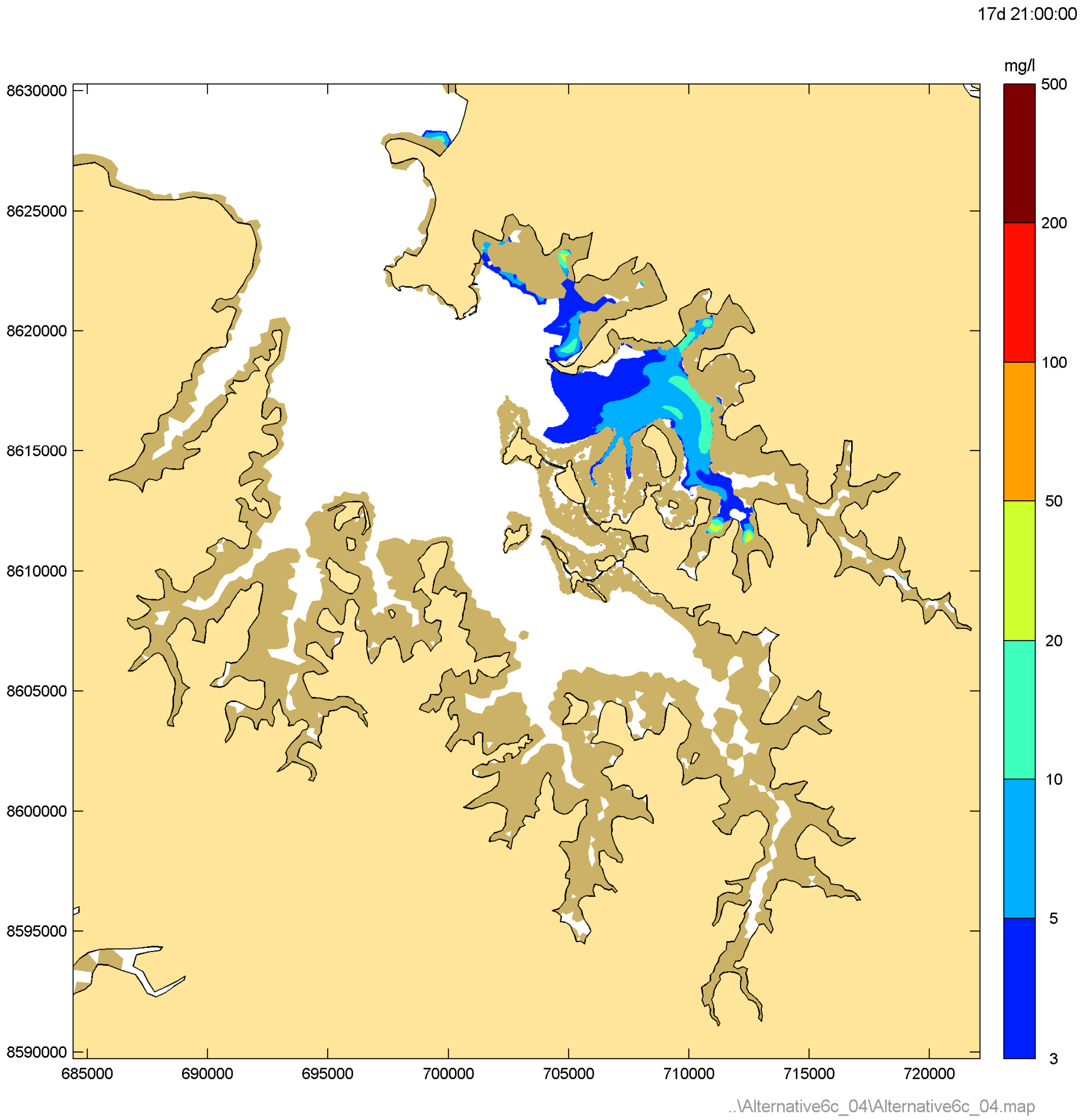


Figure 55 Instantaneous suspended sediment concentrations during Phase 4 peak flood – Spring tide

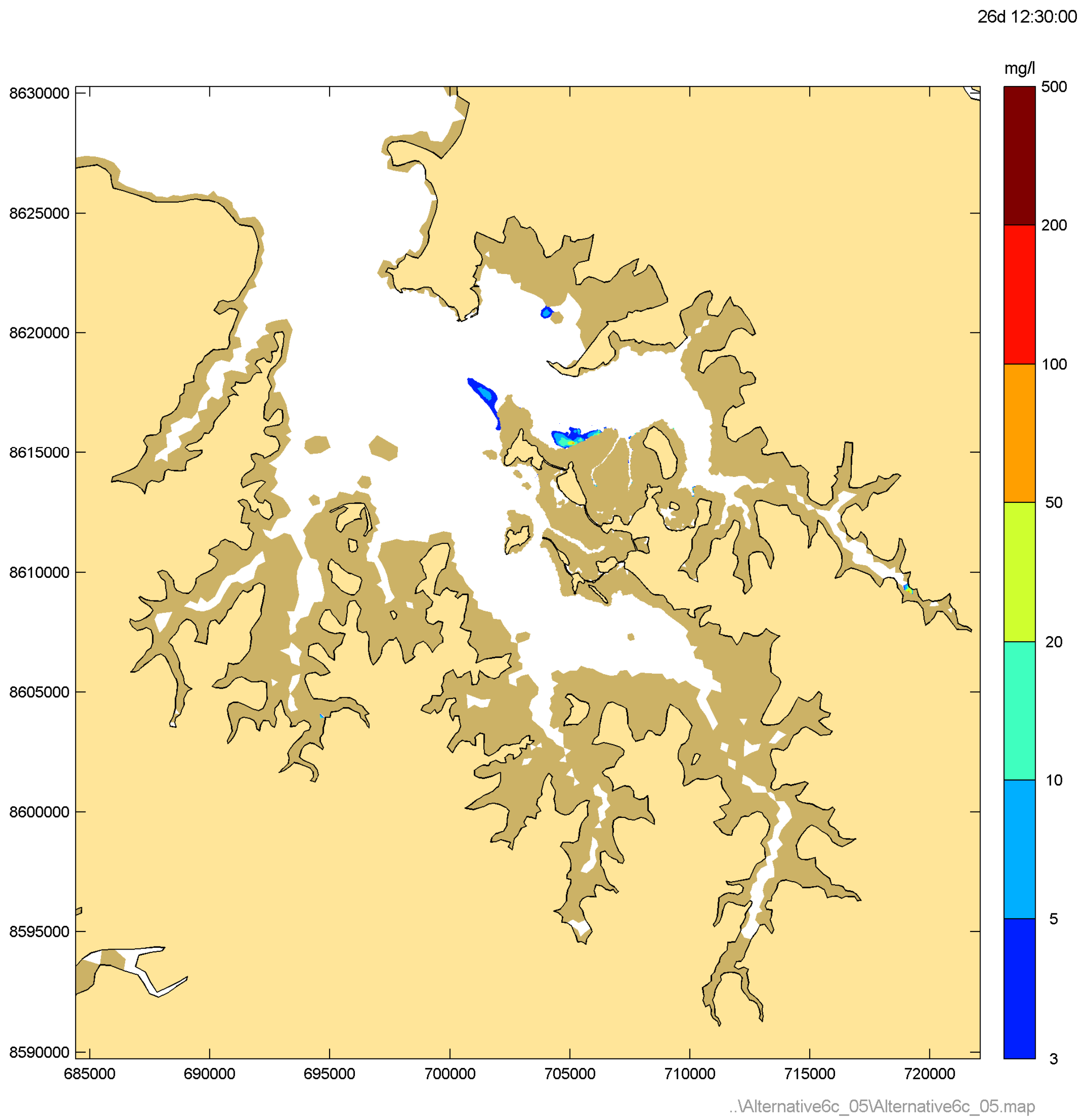


Figure 56 Instantaneous suspended sediment concentrations during Phase 5 peak ebb – Neap tide

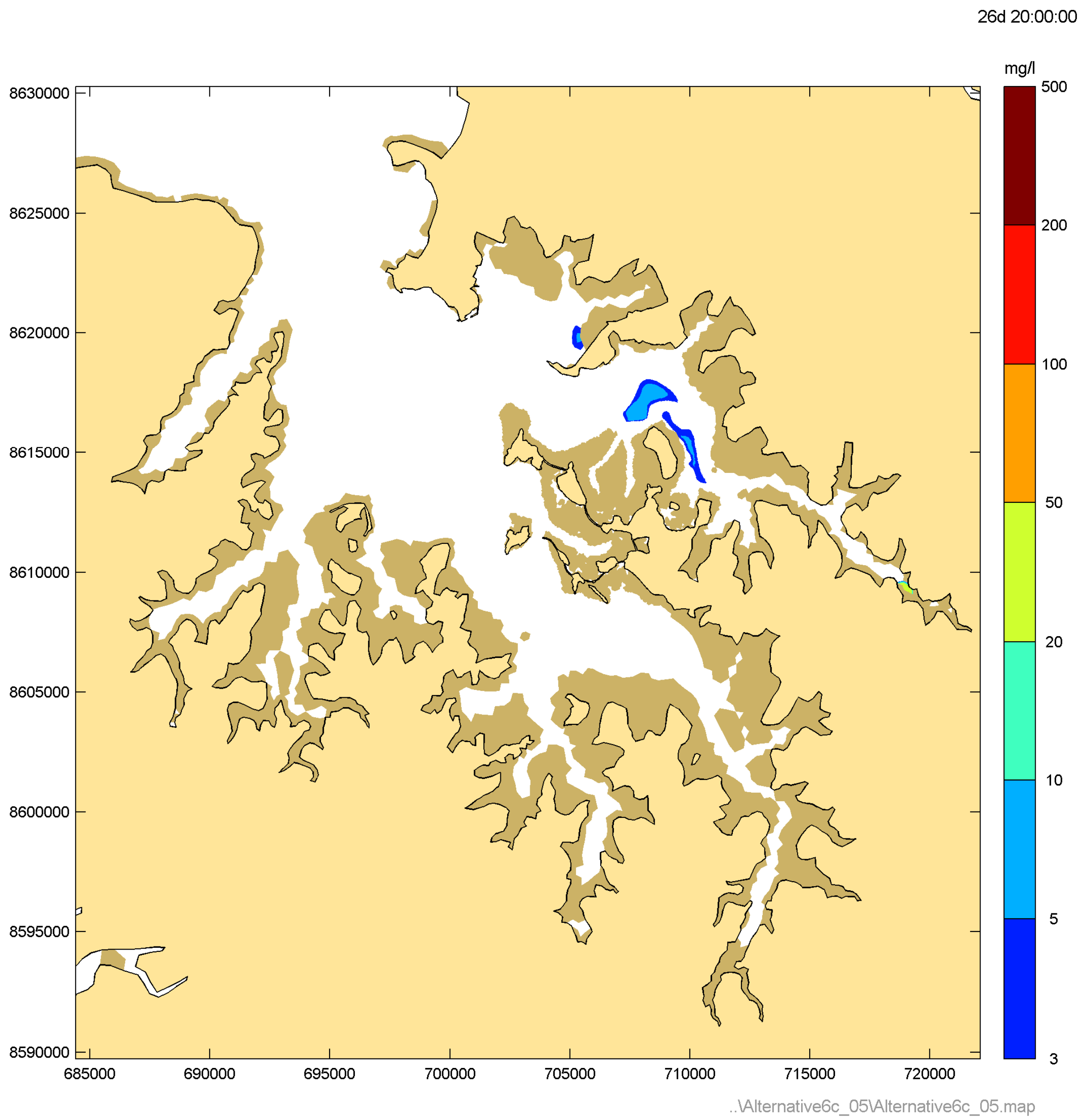


Figure 57 Instantaneous suspended sediment concentrations during Phase 5 peak flood – Neap tide

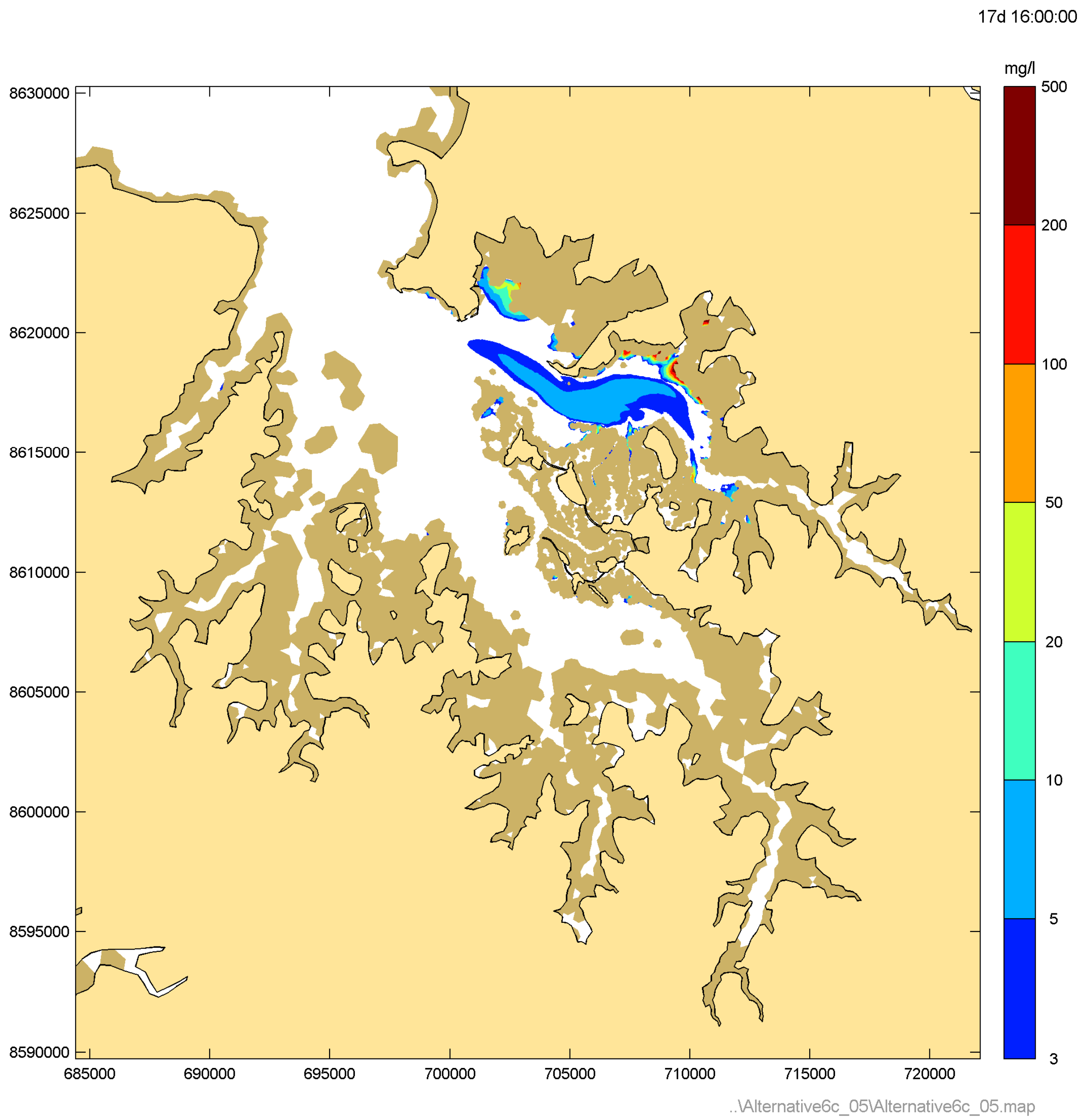


Figure 58 Instantaneous suspended sediment concentrations during Phase 5 peak ebb – Spring tide

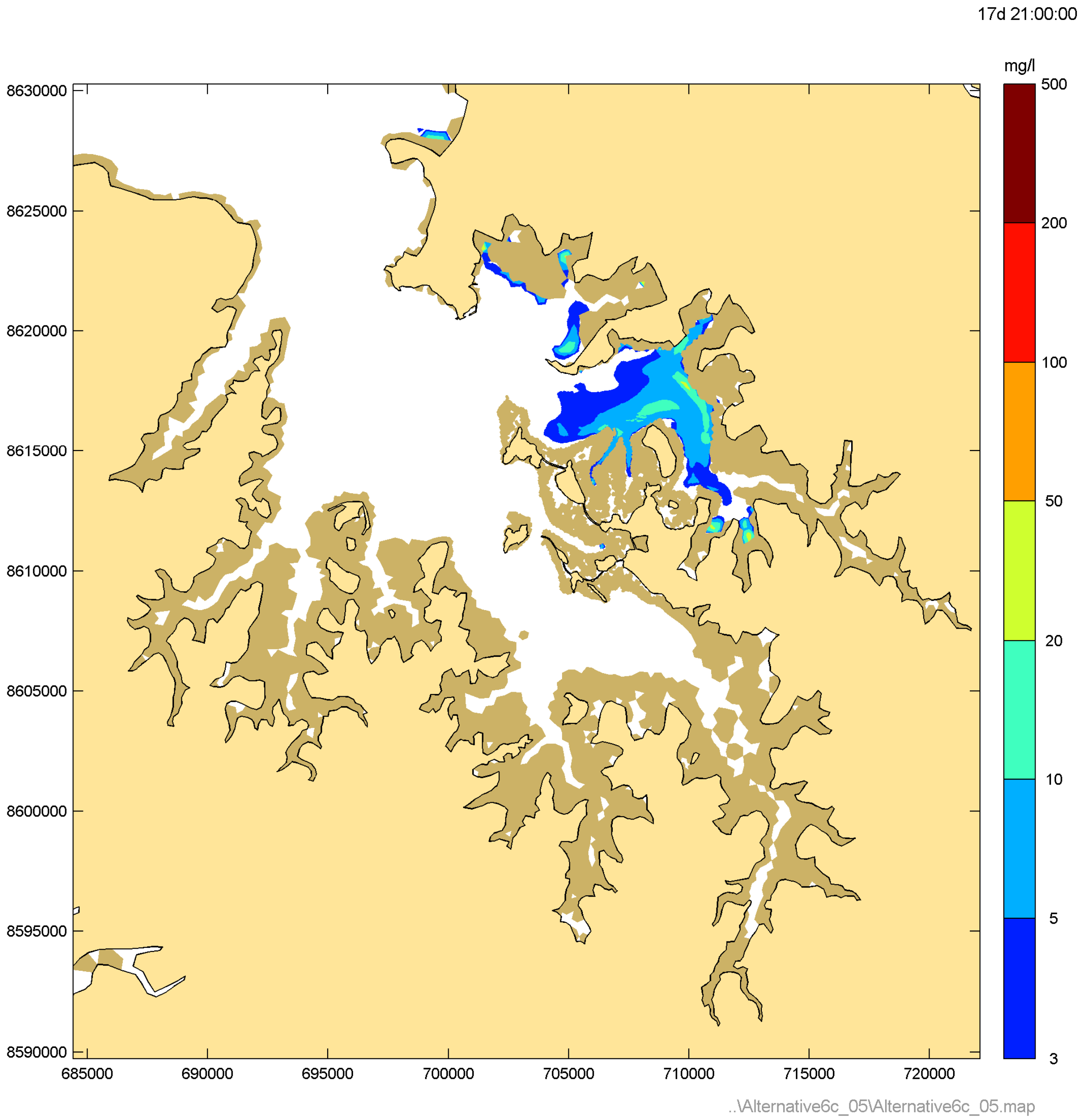


Figure 59 Instantaneous suspended sediment concentrations during Phase 5 peak flood – Spring tide

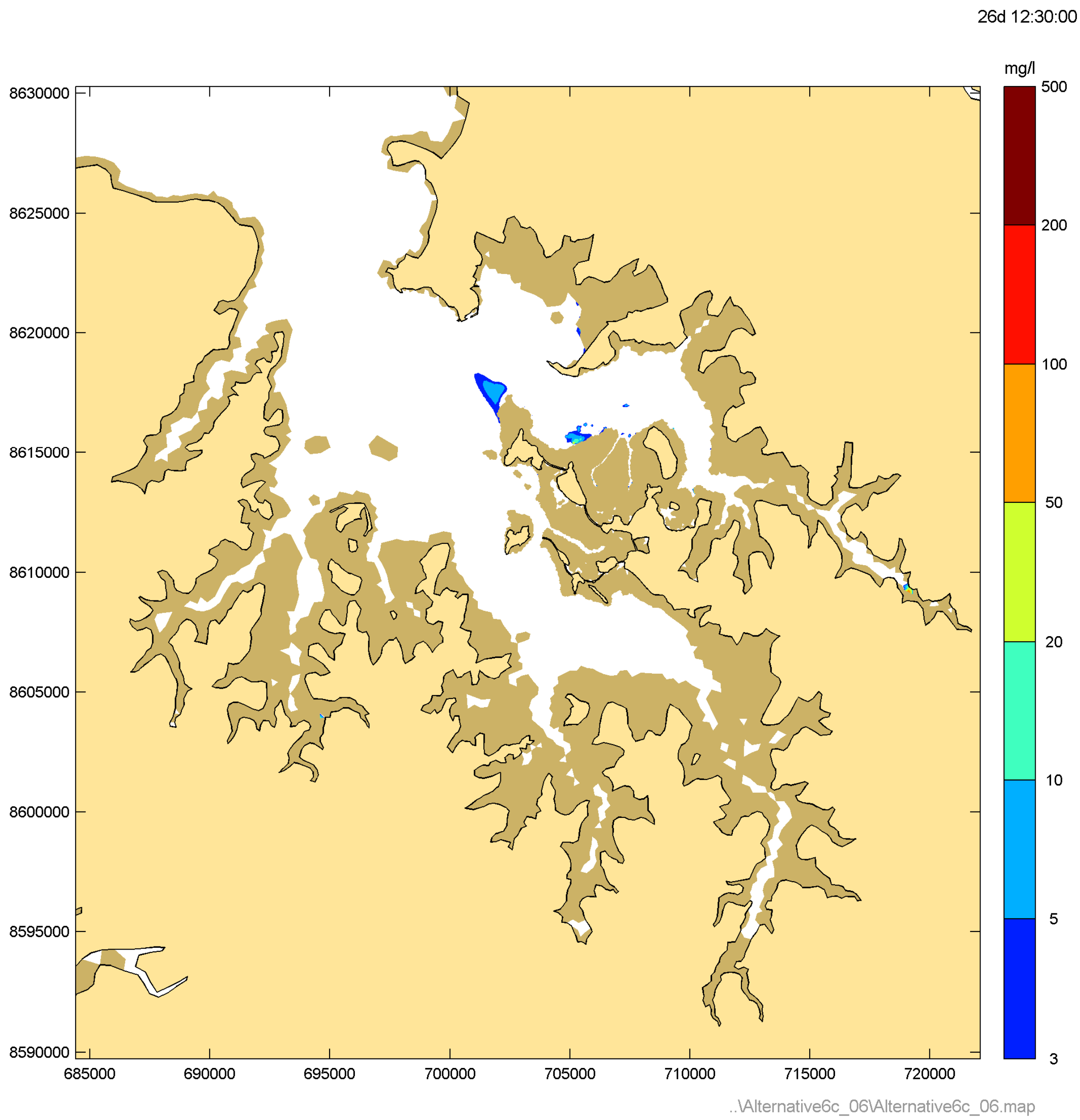


Figure 60 Instantaneous suspended sediment concentrations during Phase 6 peak ebb – Neap tide

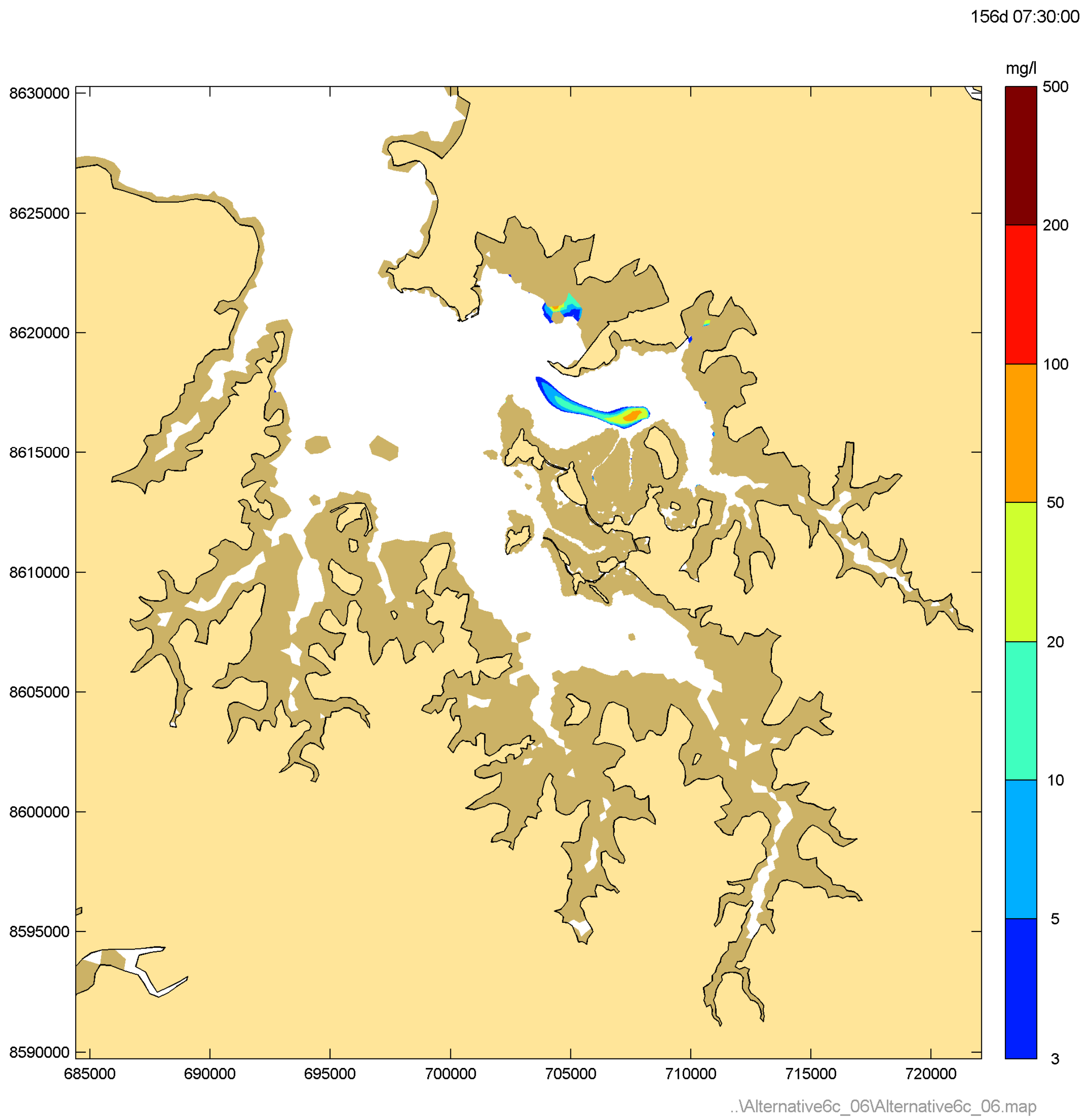


Figure 61 Instantaneous suspended sediment concentrations during Phase 6 peak ebb – Neap tide (cutter-suction dredger activity)

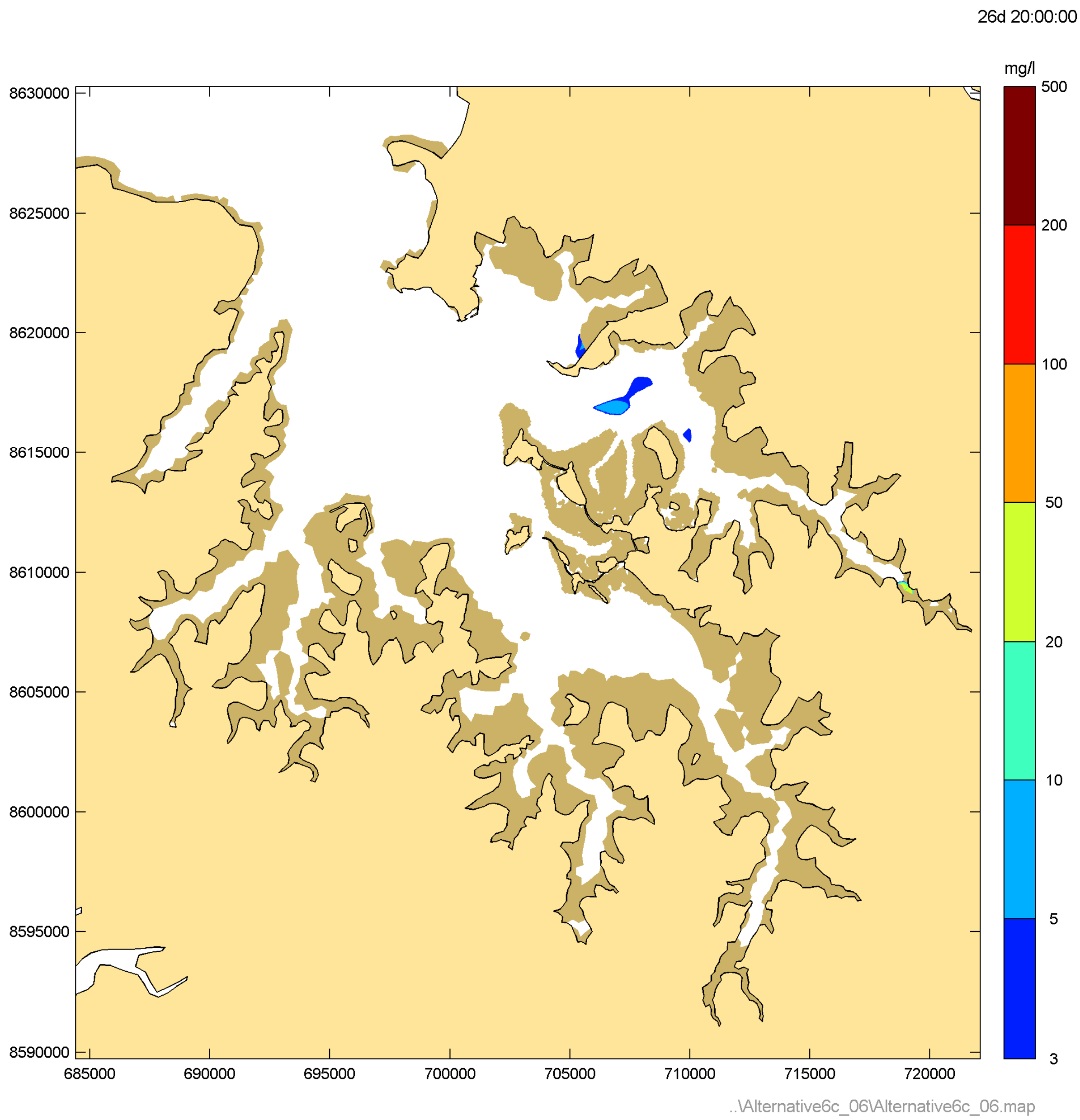


Figure 62 Instantaneous suspended sediment concentrations during Phase 6 peak flood – Neap tide

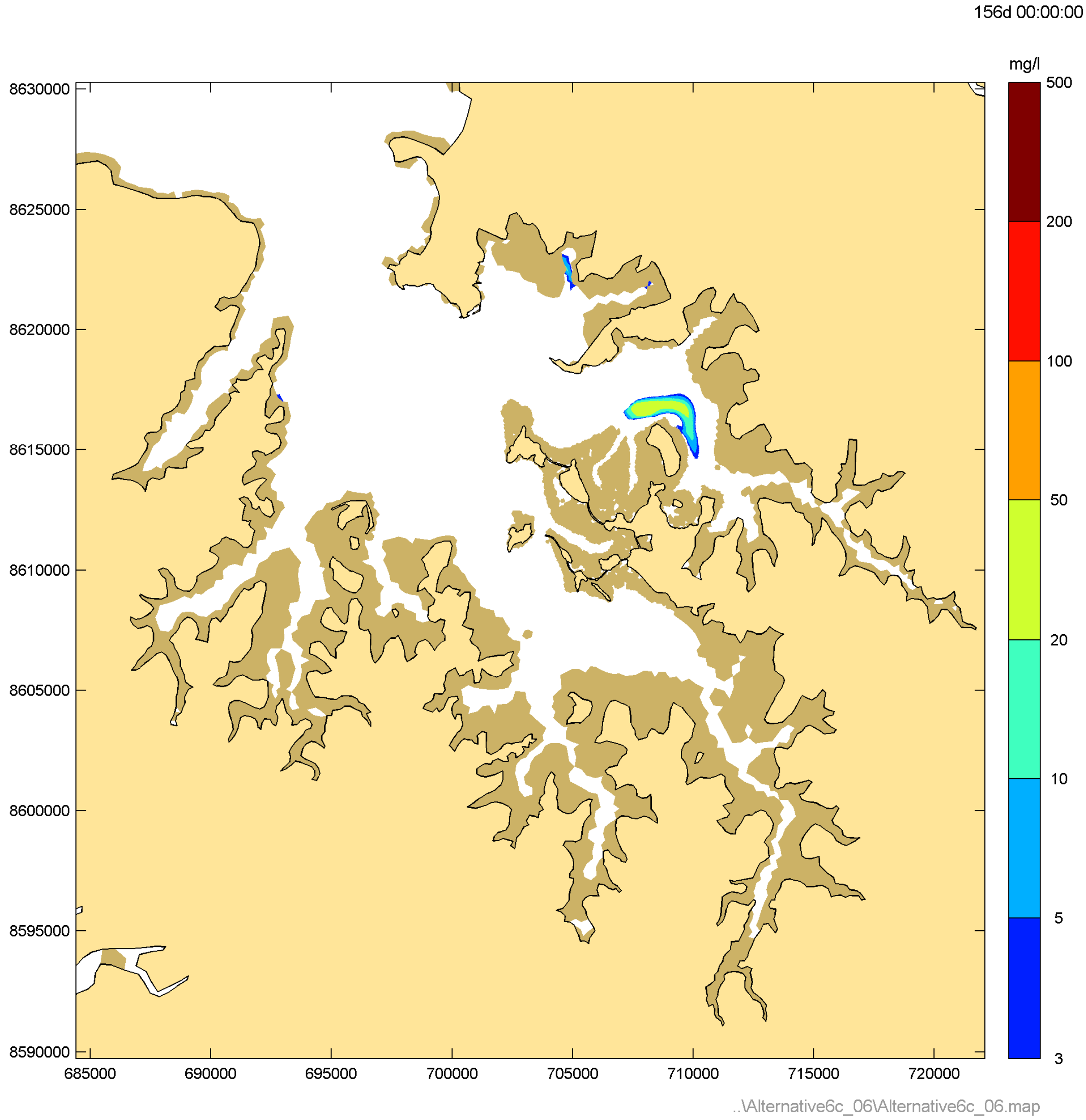


Figure 63 Instantaneous suspended sediment concentrations during Phase 6 peak flood – Neap tide (cutter-suction dredger activity)

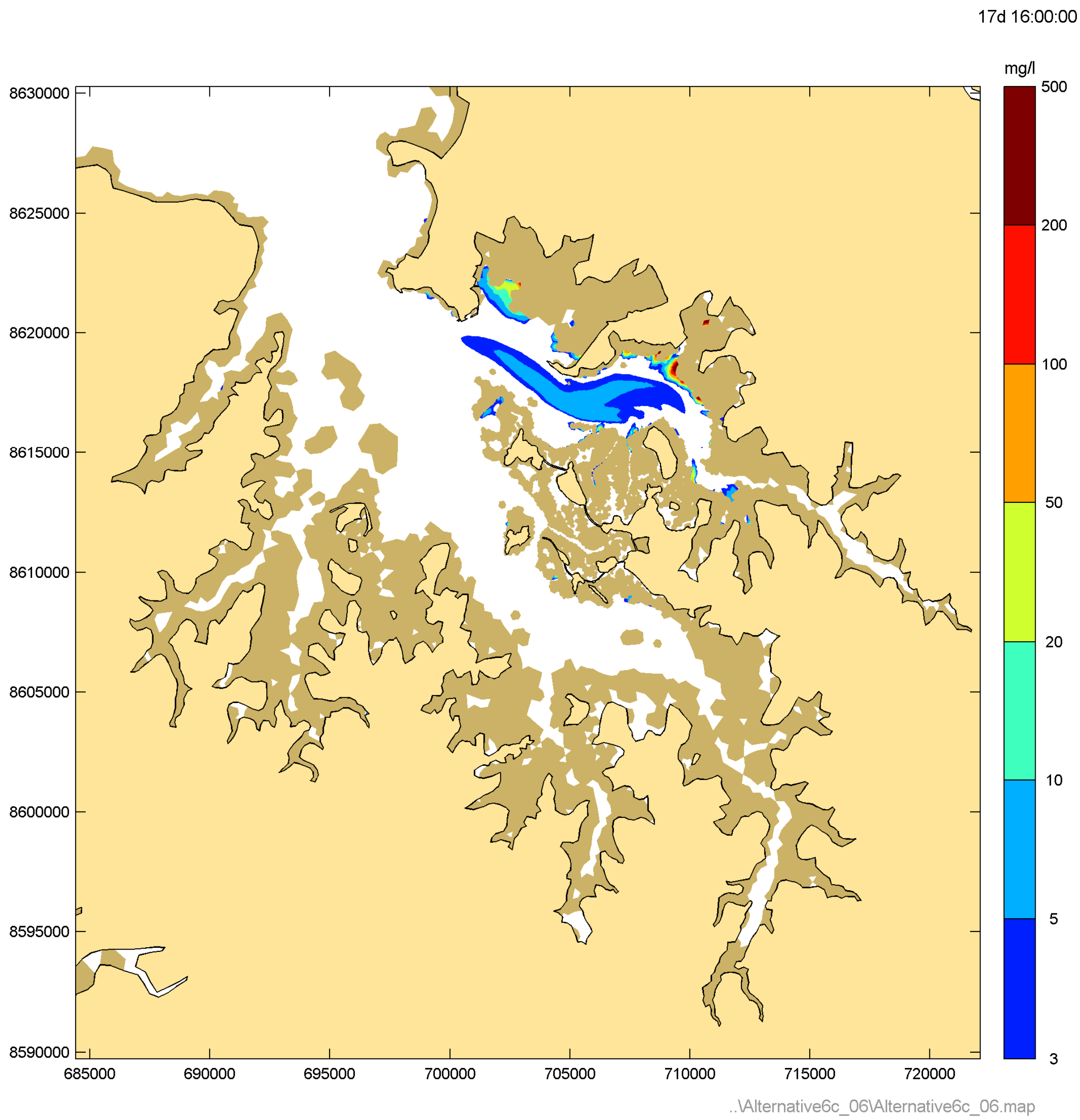


Figure 64 Instantaneous suspended sediment concentrations during Phase 6 peak ebb – Spring tide

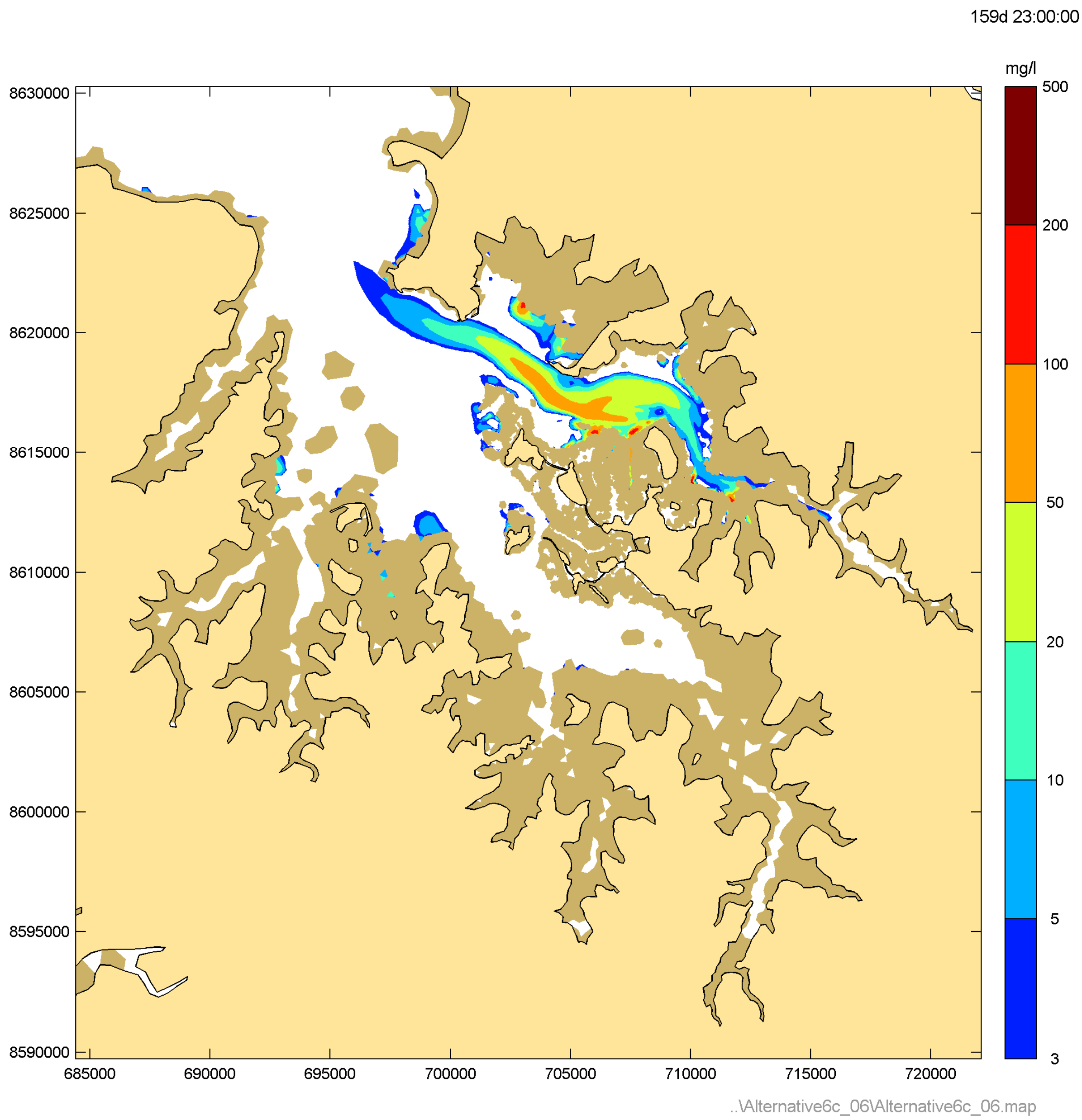


Figure 65 **Instantaneous suspended sediment concentrations during Phase 6 peak ebb – Spring tide (cutter-suction dredger activity)**

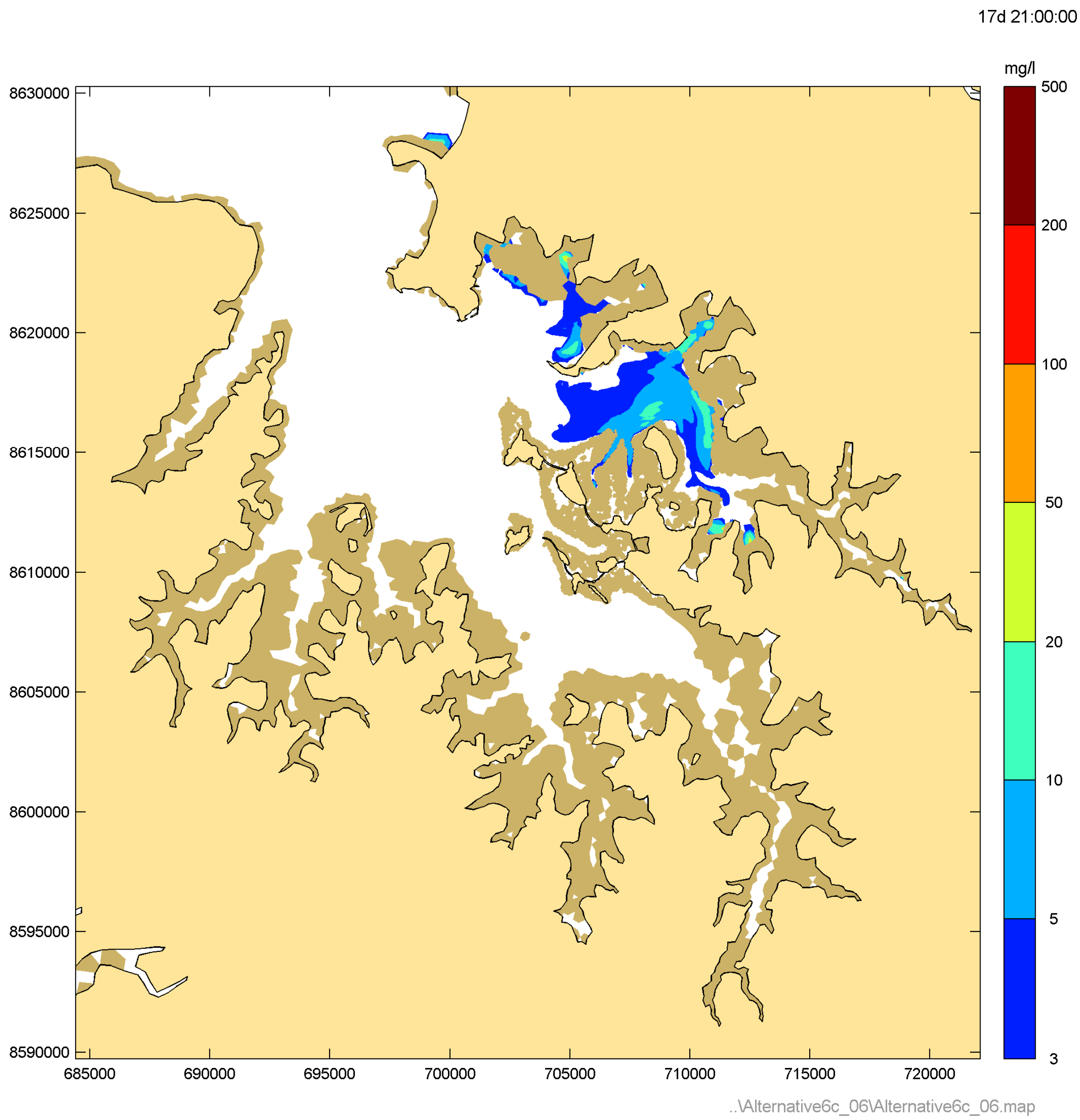


Figure 66 Instantaneous suspended sediment concentrations during Phase 6 peak flood – Spring tide

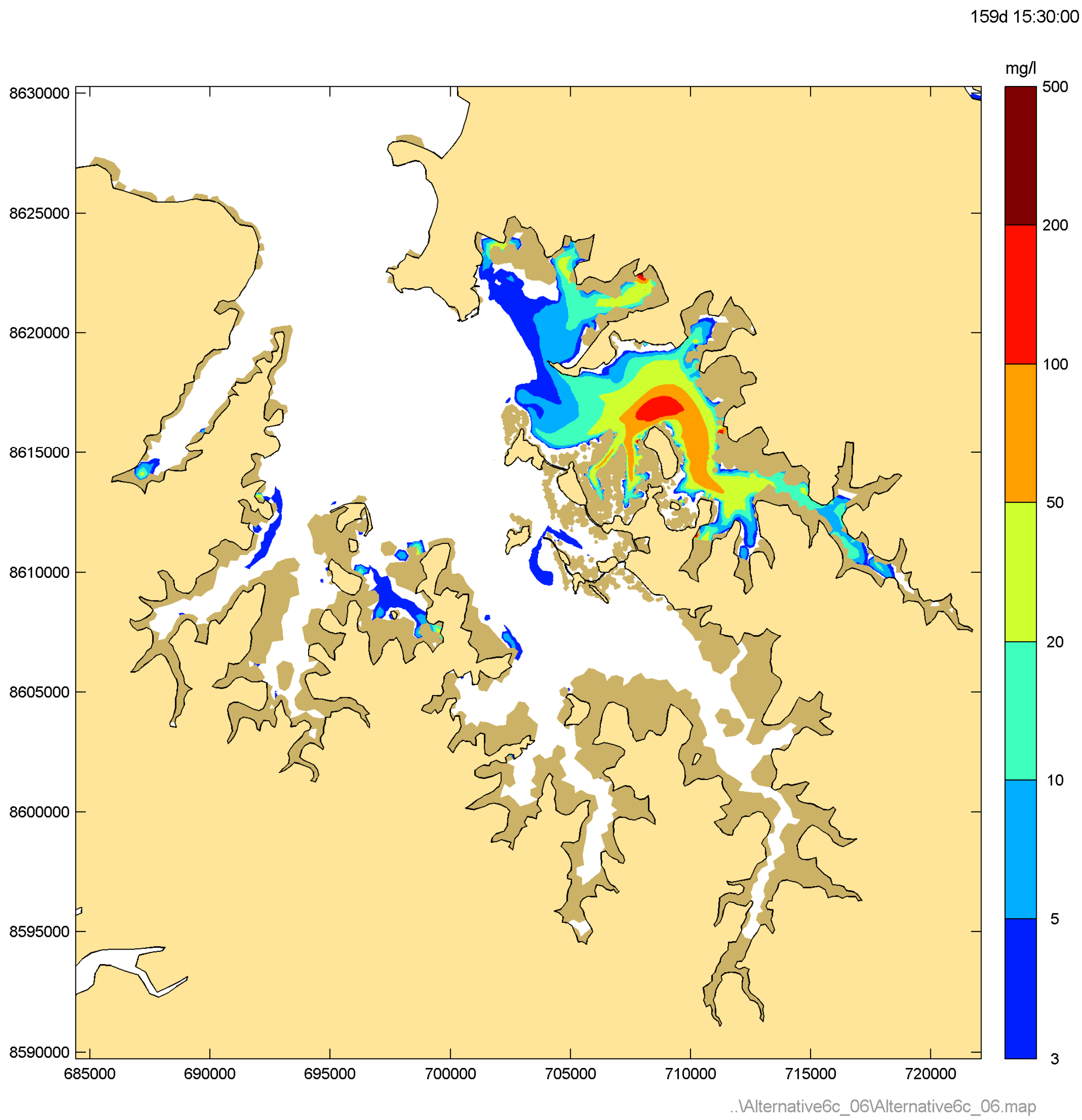


Figure 67 Instantaneous suspended sediment concentrations during Phase 6 peak flood – Spring tide (cutter-suction dredger activity)

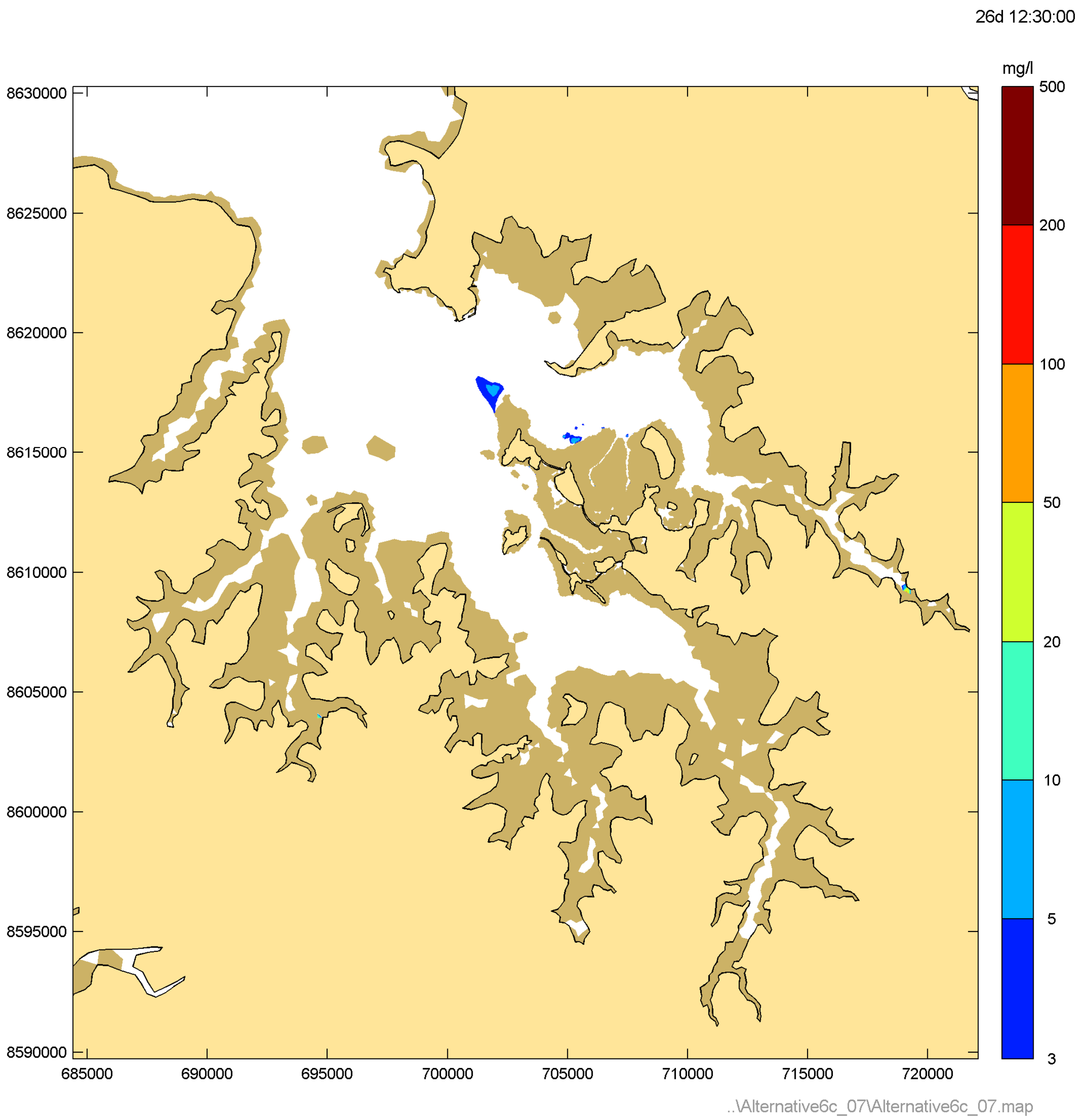


Figure 68 Instantaneous suspended sediment concentrations during Phase 7 peak ebb – Neap tide

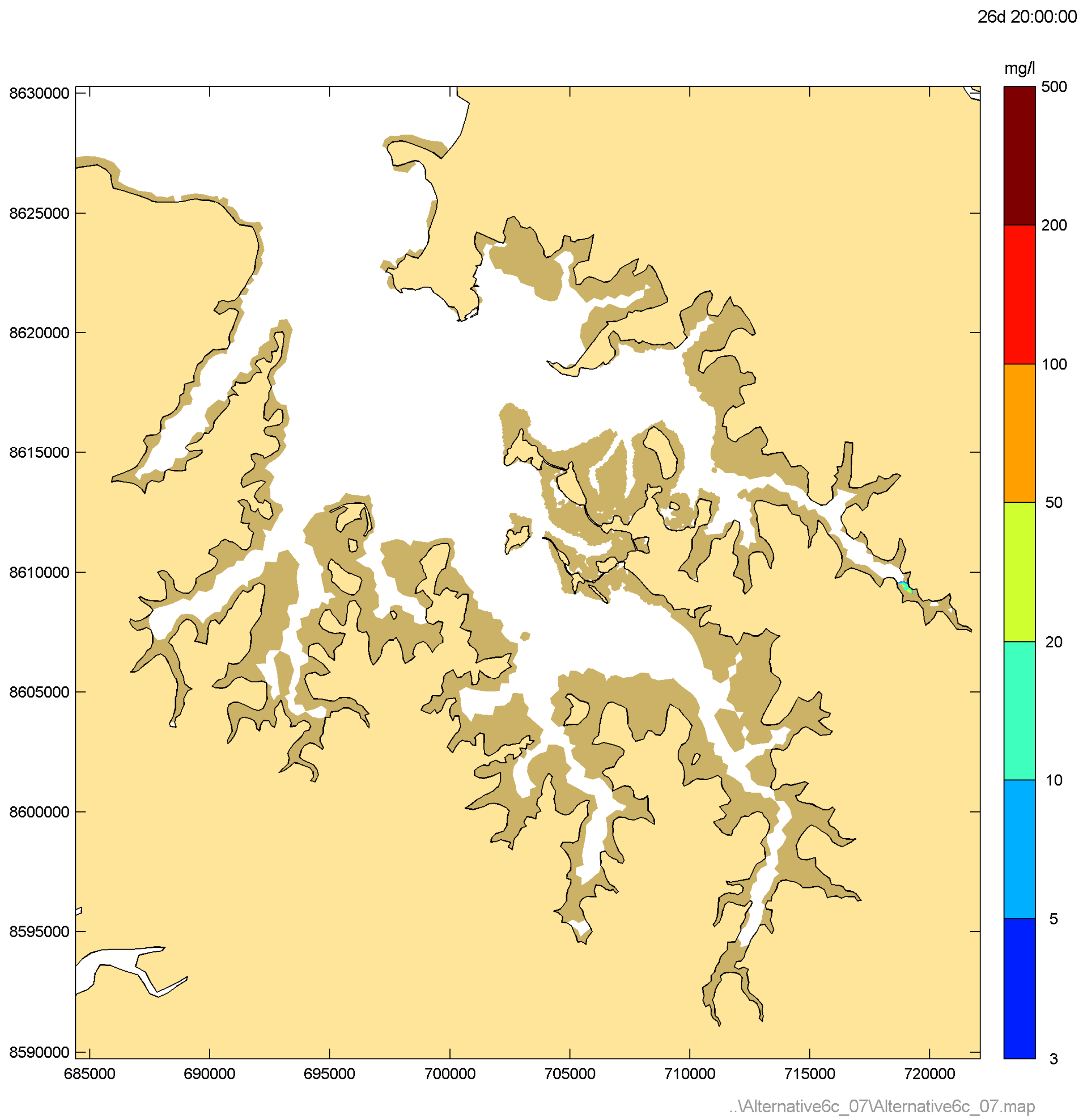


Figure 69 Instantaneous suspended sediment concentrations during Phase 7 peak flood – Neap tide

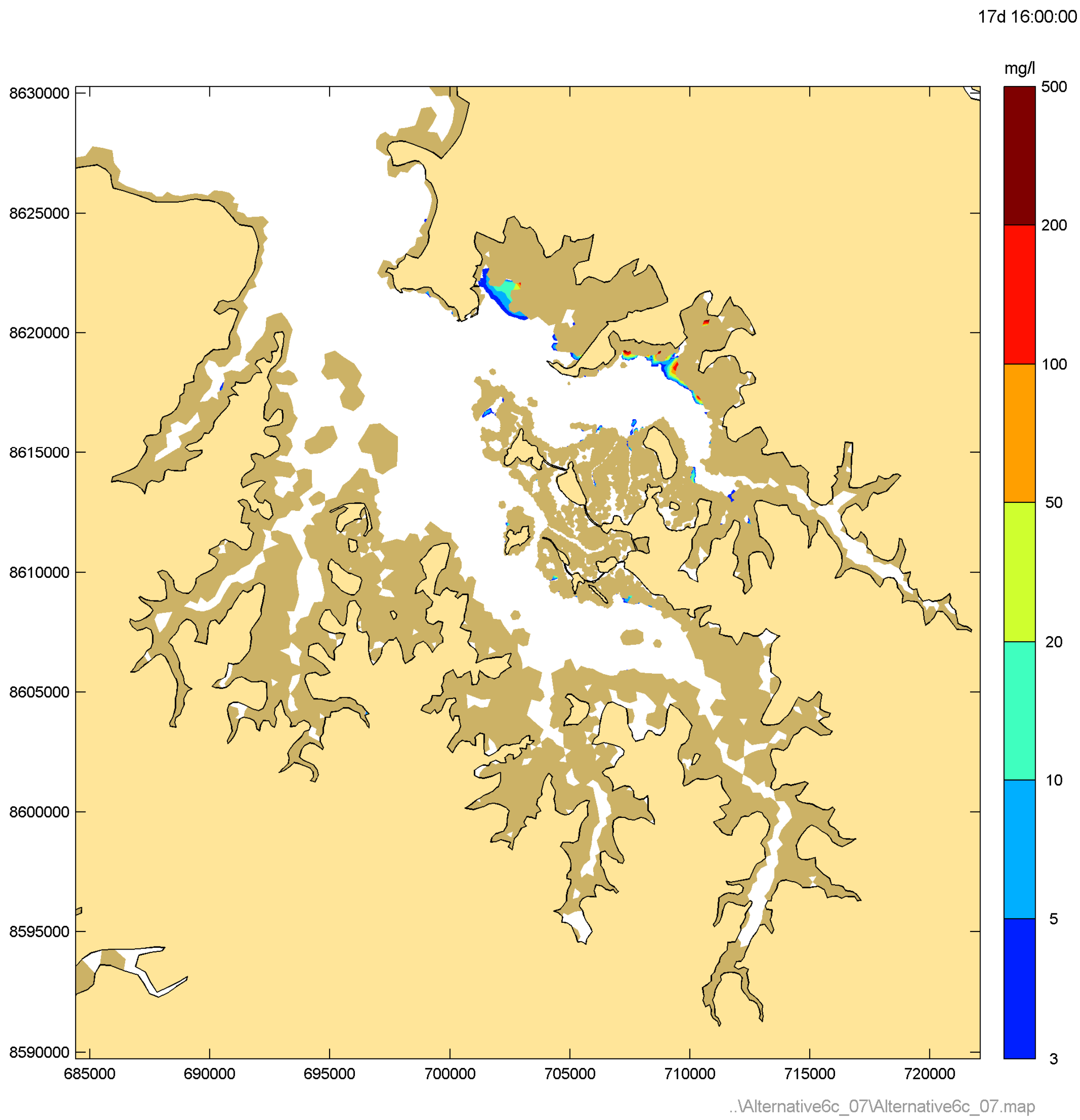


Figure 70 Instantaneous suspended sediment concentrations during Phase 7 peak ebb – Spring tide

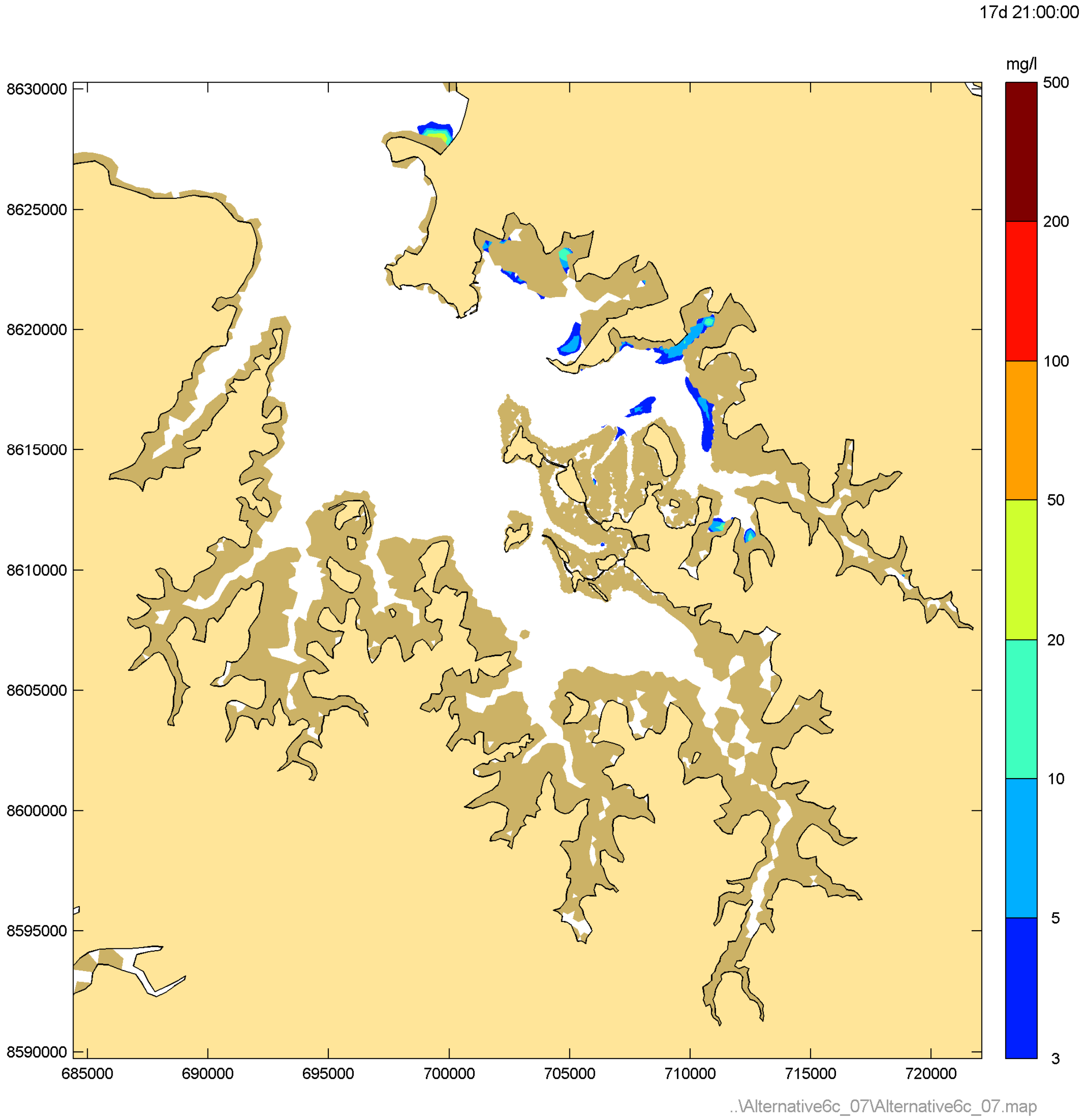


Figure 71 Instantaneous suspended sediment concentrations during Phase 7 peak flood – Spring tide

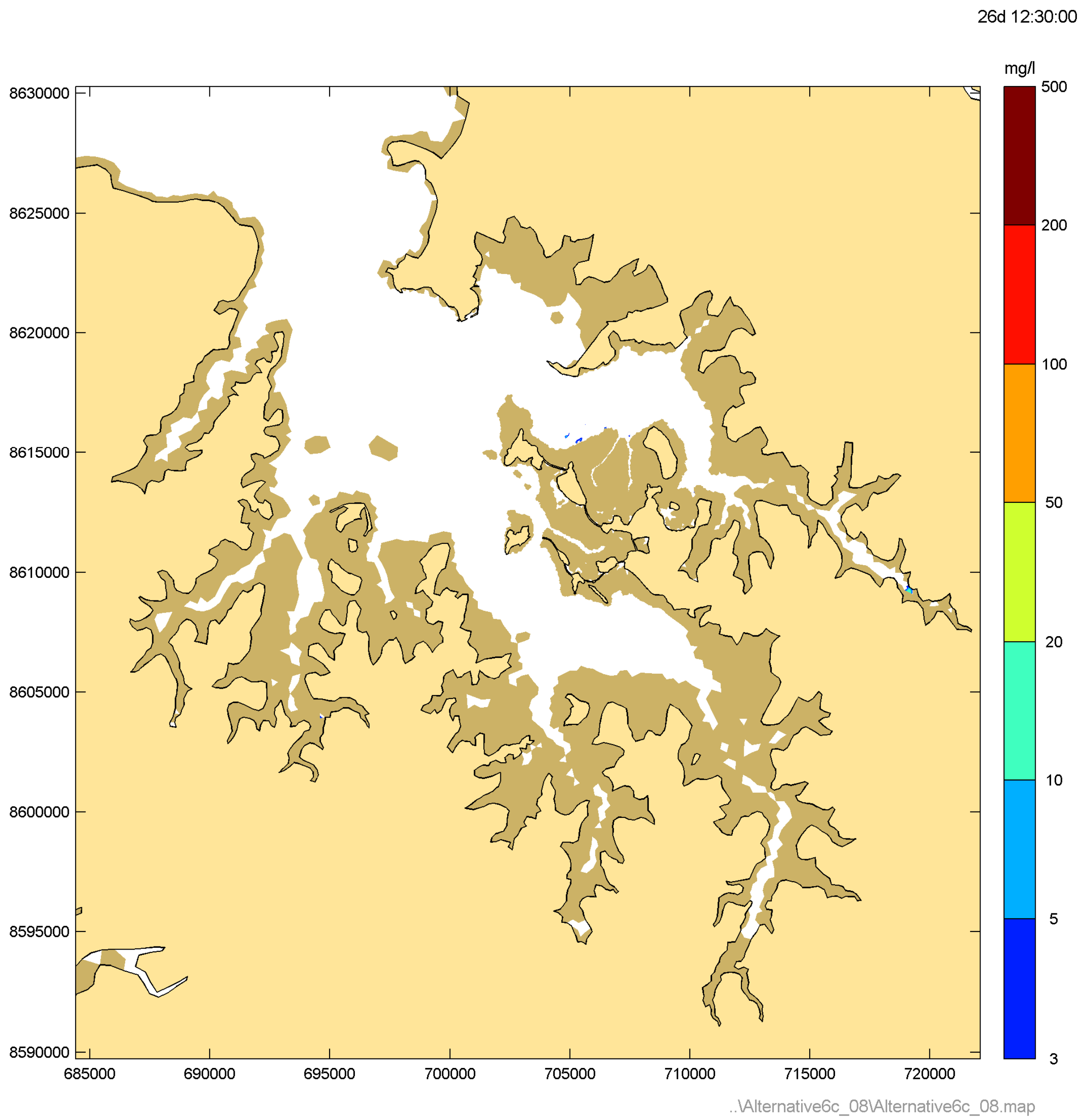


Figure 72 Instantaneous suspended sediment concentrations during Phase 8 peak ebb – Neap tide

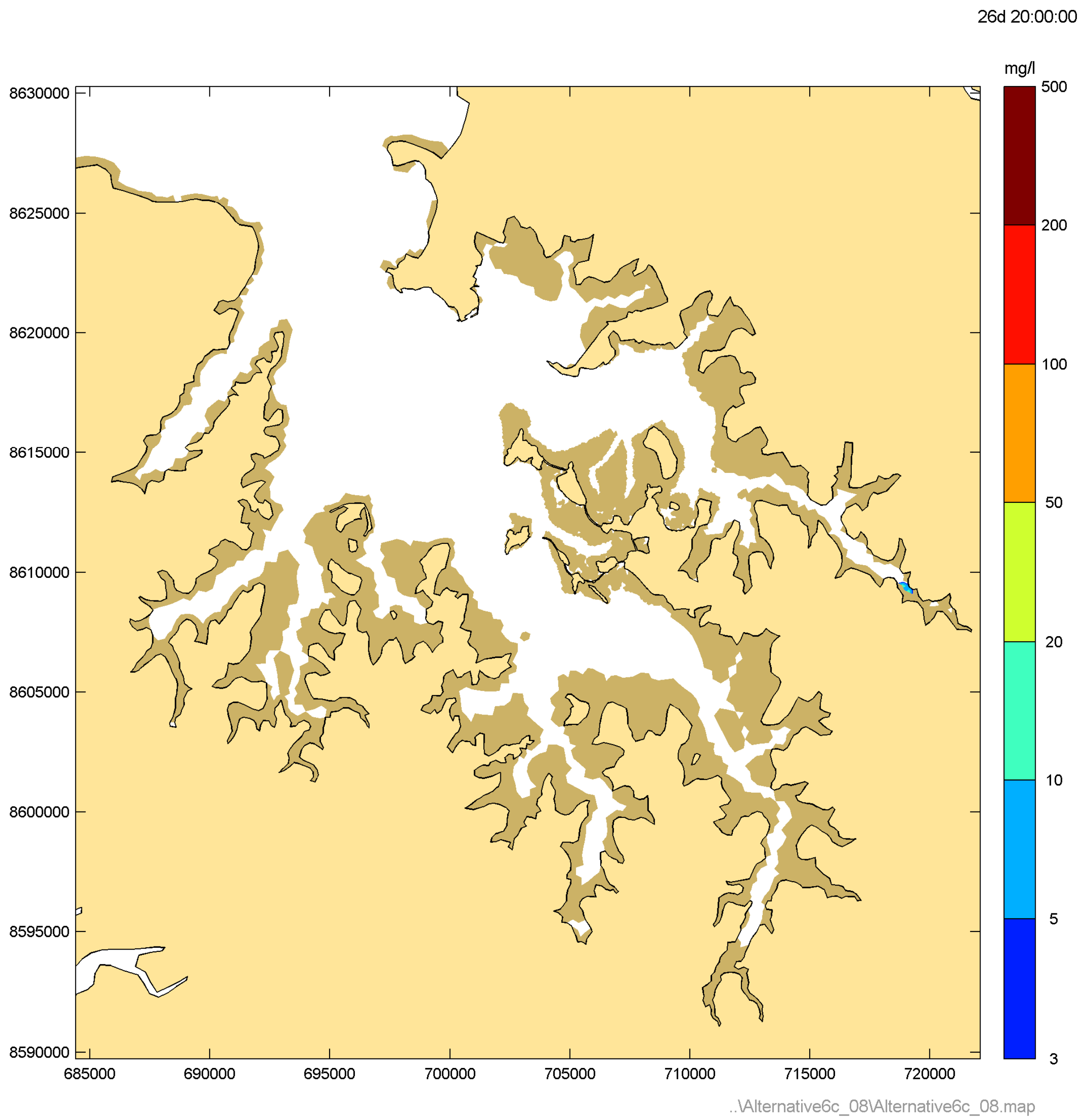


Figure 73 Instantaneous suspended sediment concentrations during Phase 8 peak flood – Neap tide

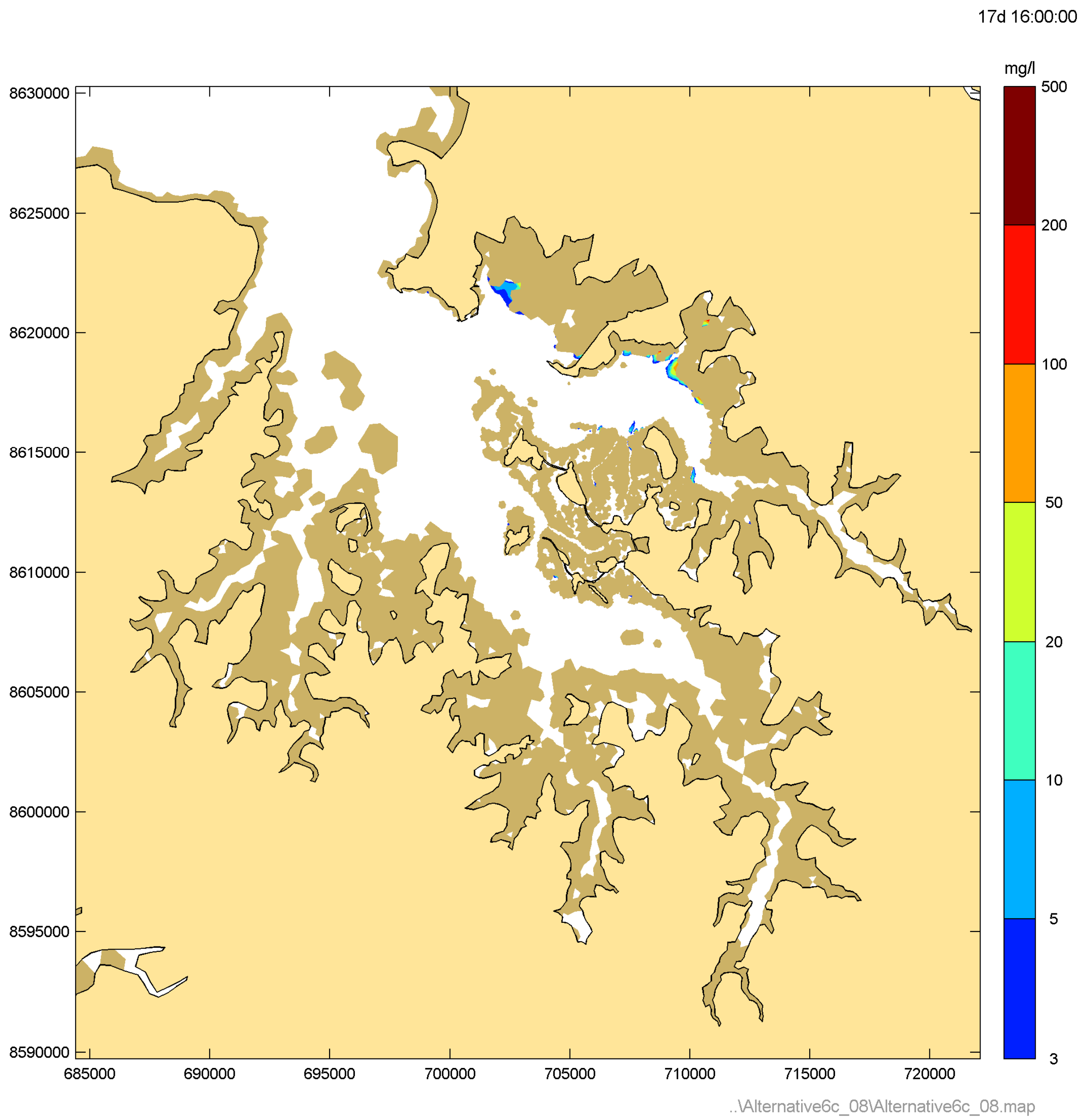


Figure 74 Instantaneous suspended sediment concentrations during Phase 8 peak ebb – Spring tide

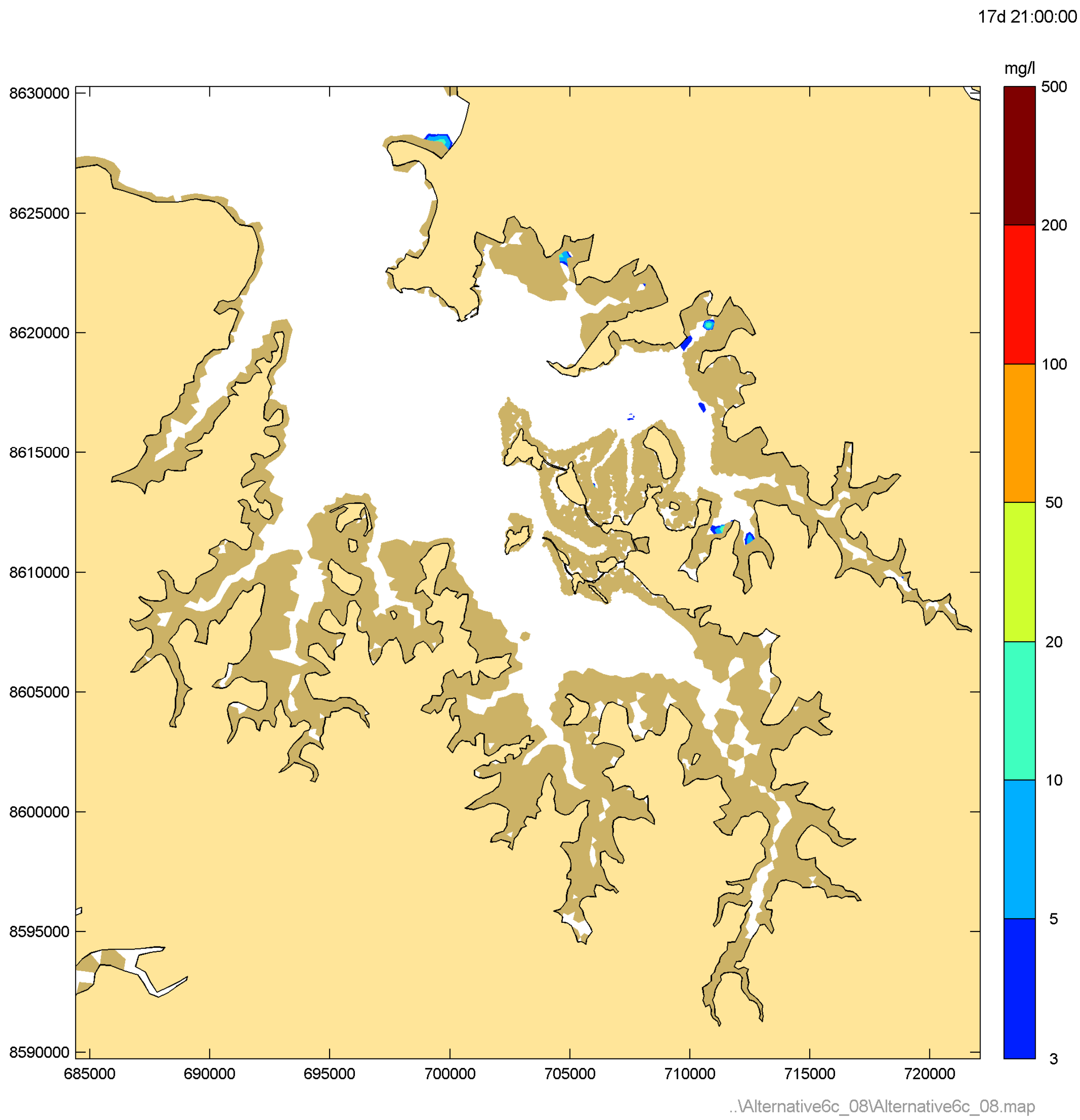


Figure 75 Instantaneous suspended sediment concentrations during Phase 8 peak flood – Spring tide

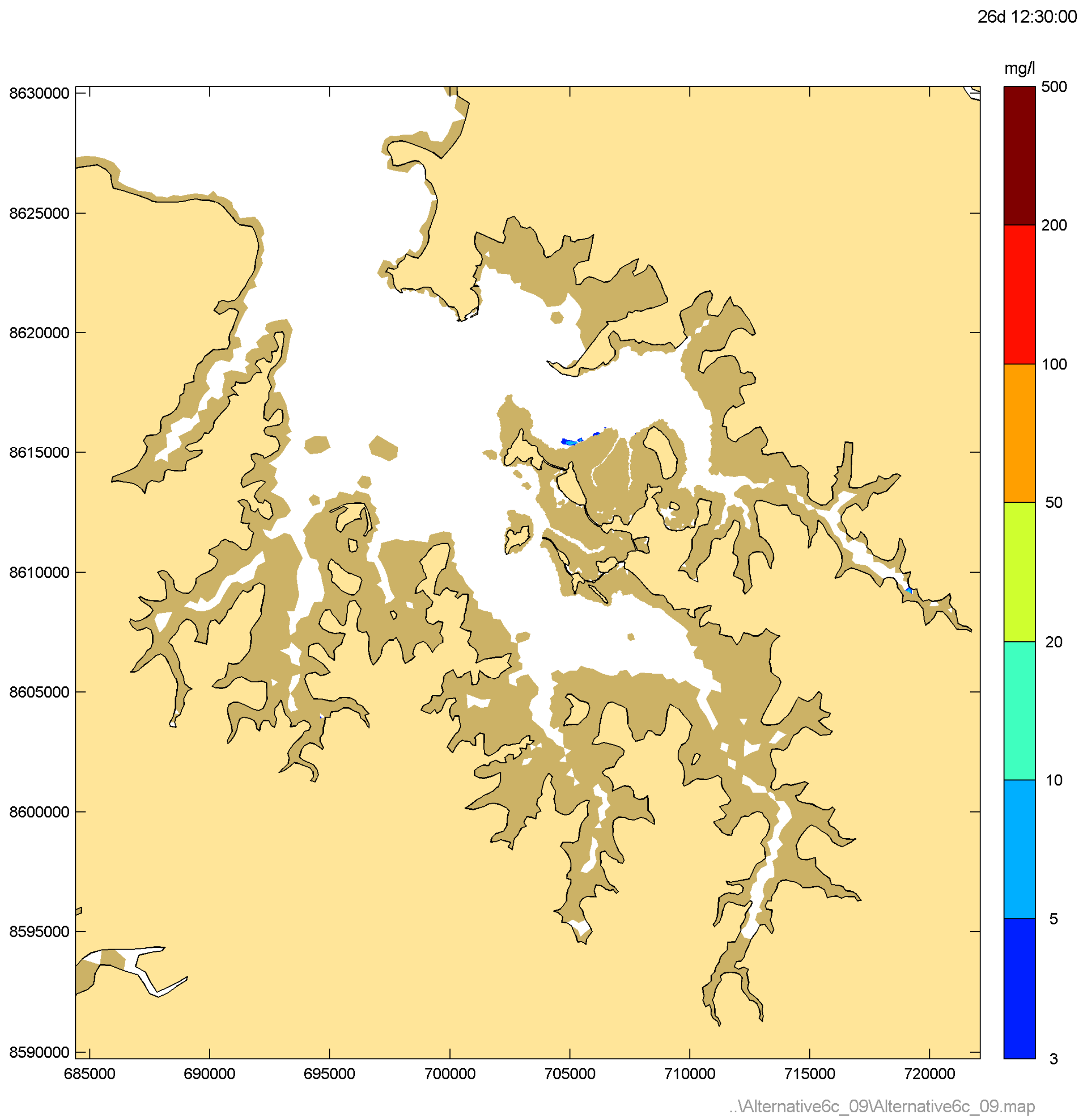


Figure 76 Instantaneous suspended sediment concentrations during Phase 9 peak ebb – Neap tide

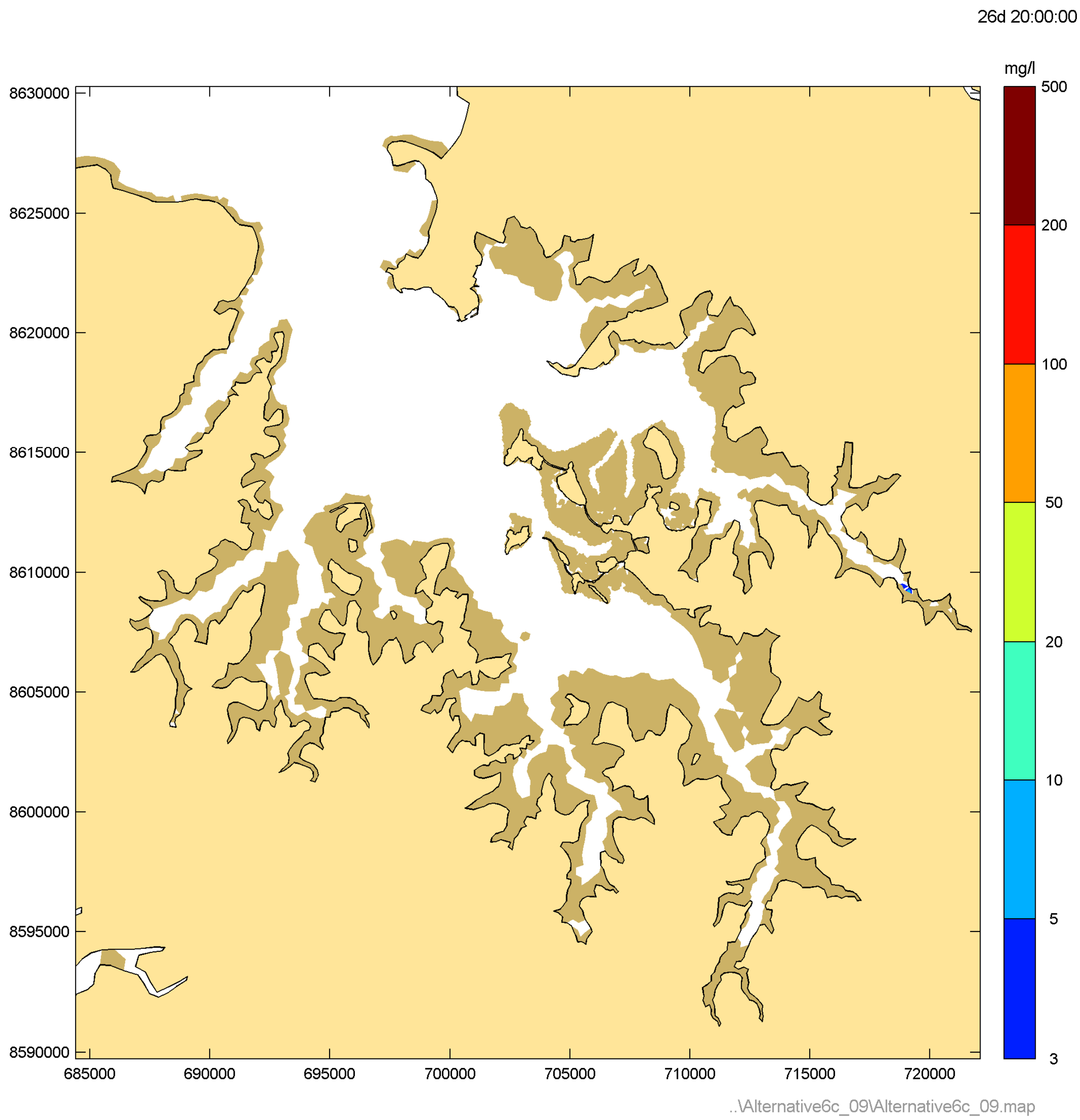


Figure 77 Instantaneous suspended sediment concentrations during Phase 9 peak flood – Neap tide

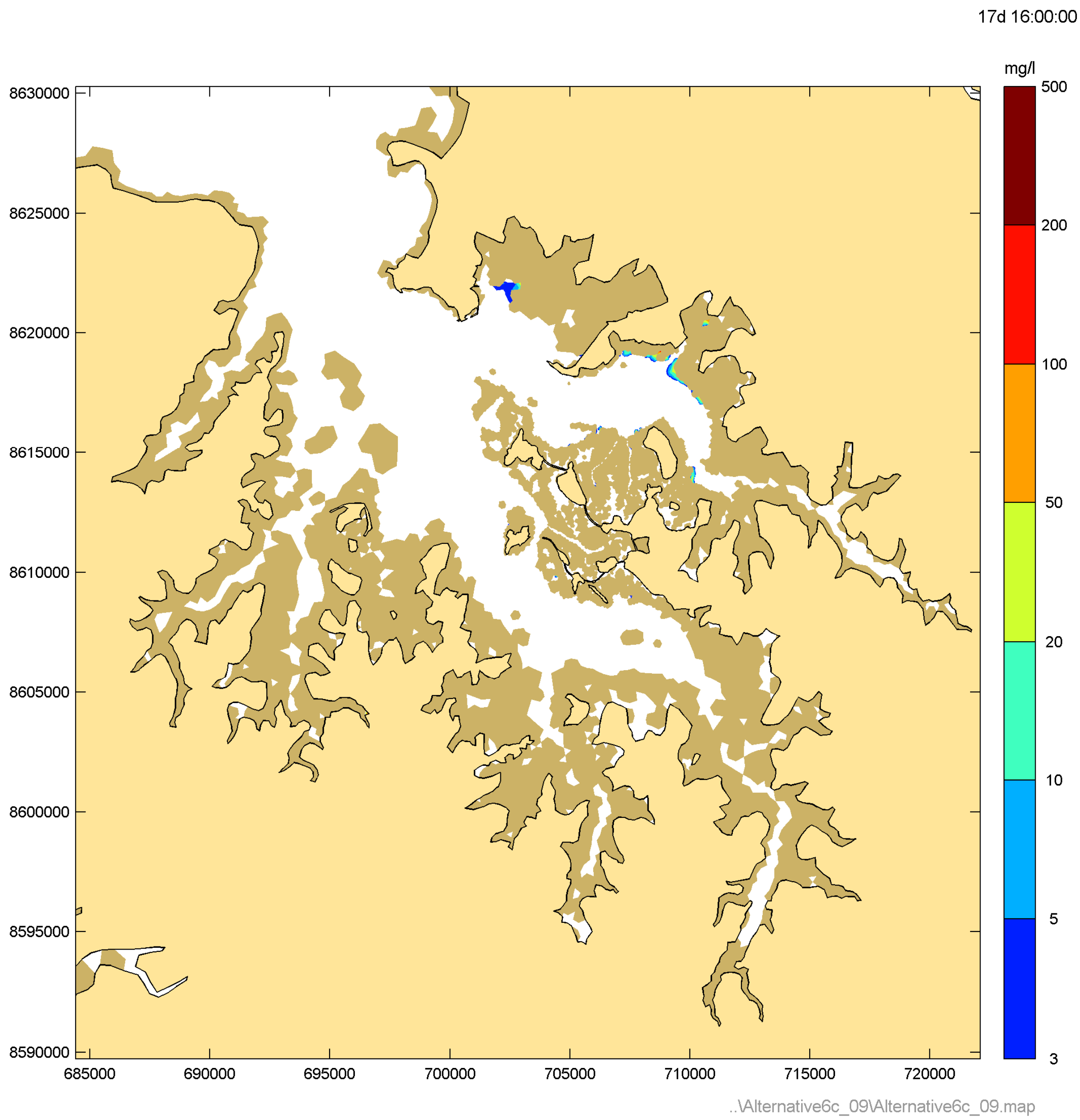


Figure 78 Instantaneous suspended sediment concentrations during Phase 9 peak ebb – Spring tide

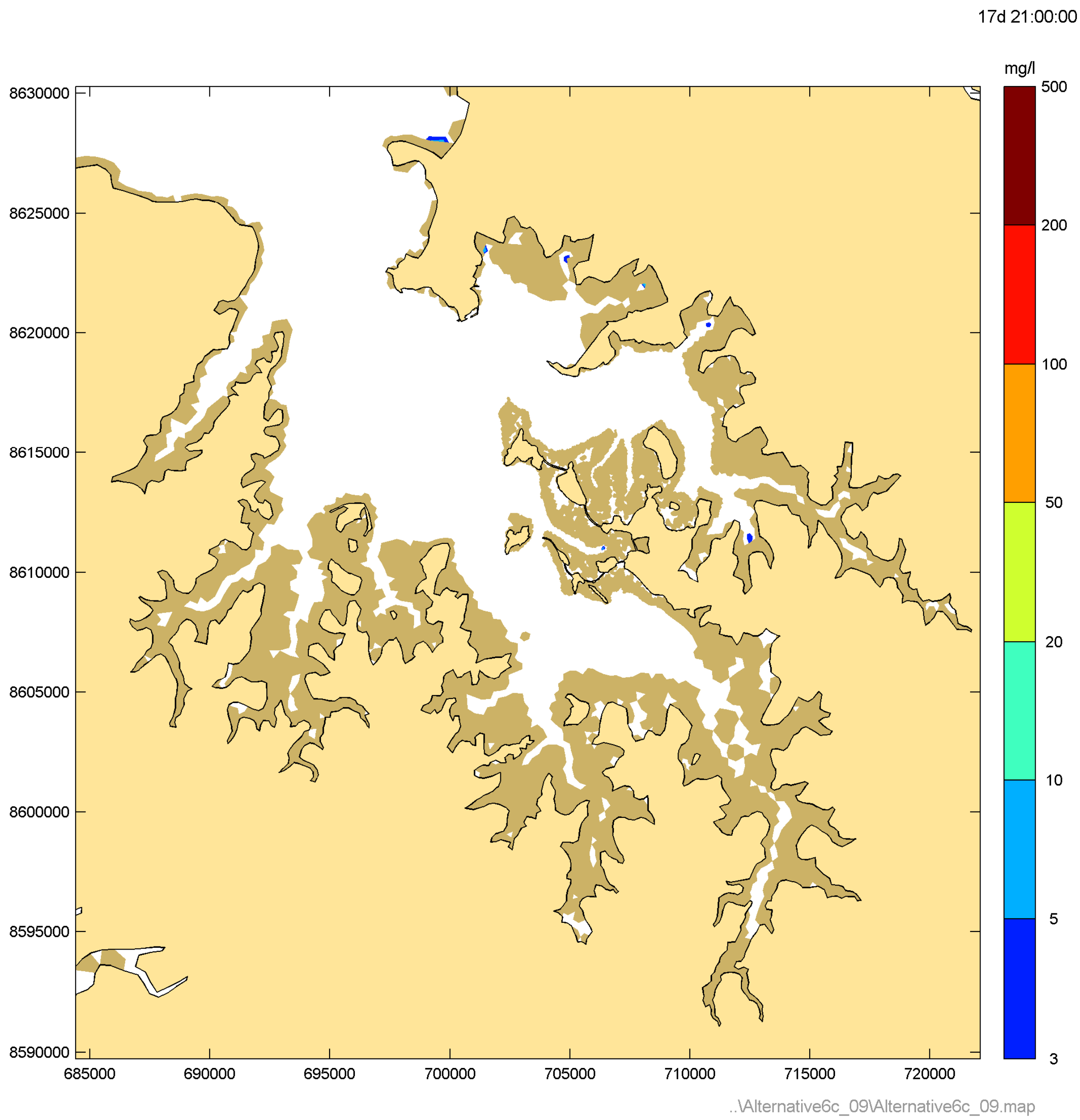


Figure 79 Instantaneous suspended sediment concentrations during Phase 9 peak flood – Spring tide

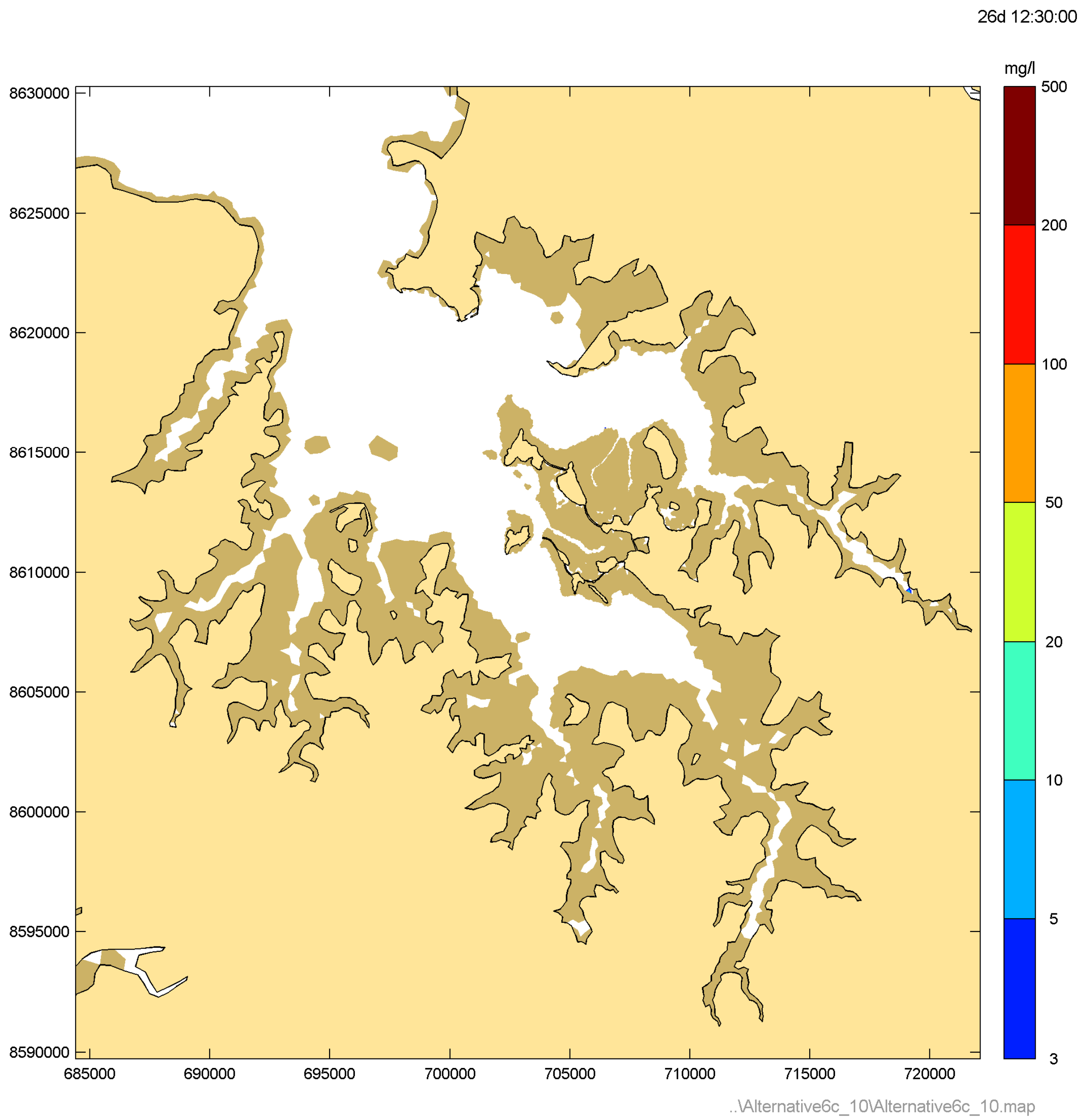


Figure 80 Instantaneous suspended sediment concentrations during Phase 10 peak ebb – Neap tide

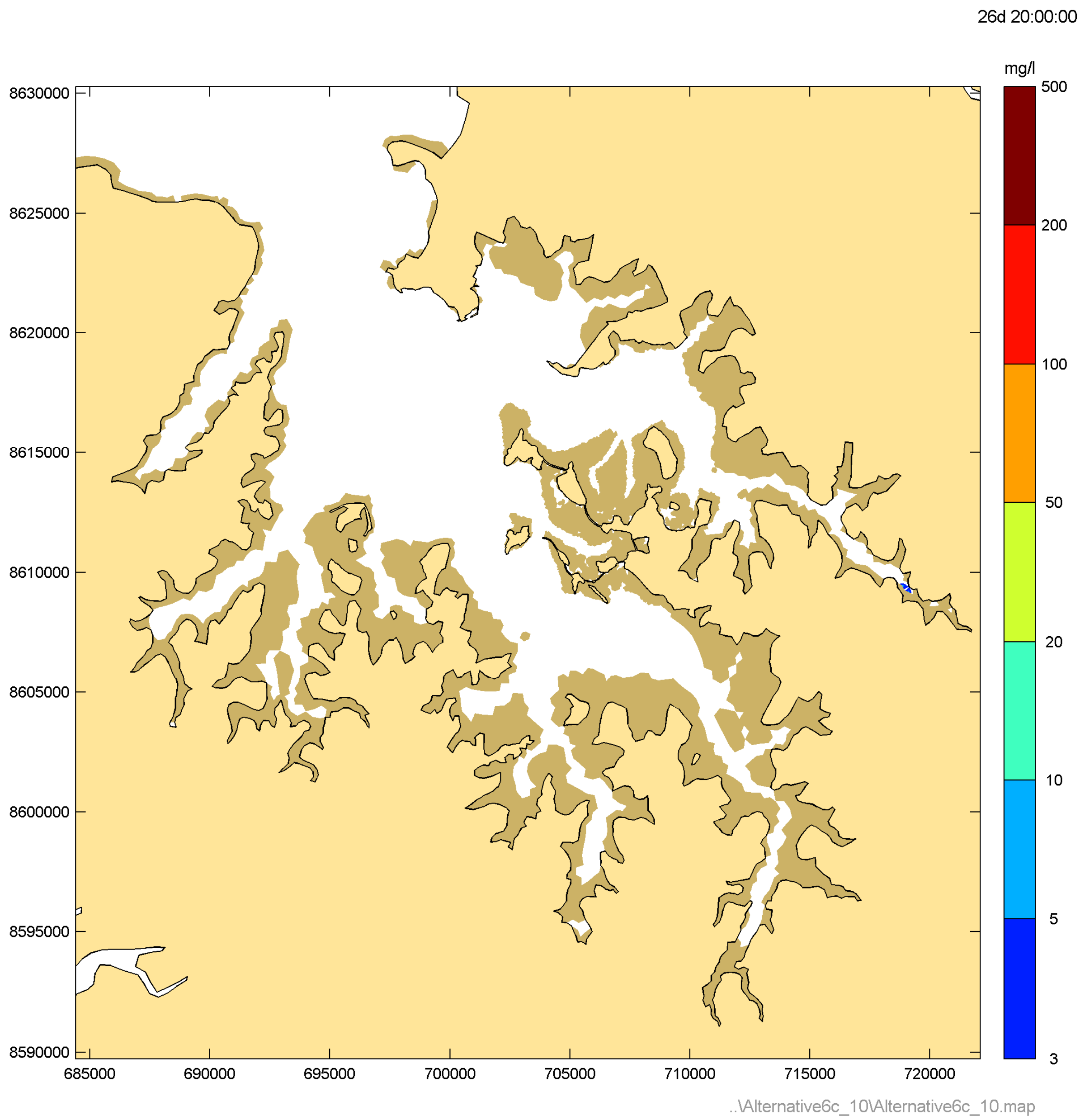


Figure 81 **Instantaneous suspended sediment concentrations during Phase 10 peak flood – Neap tide**

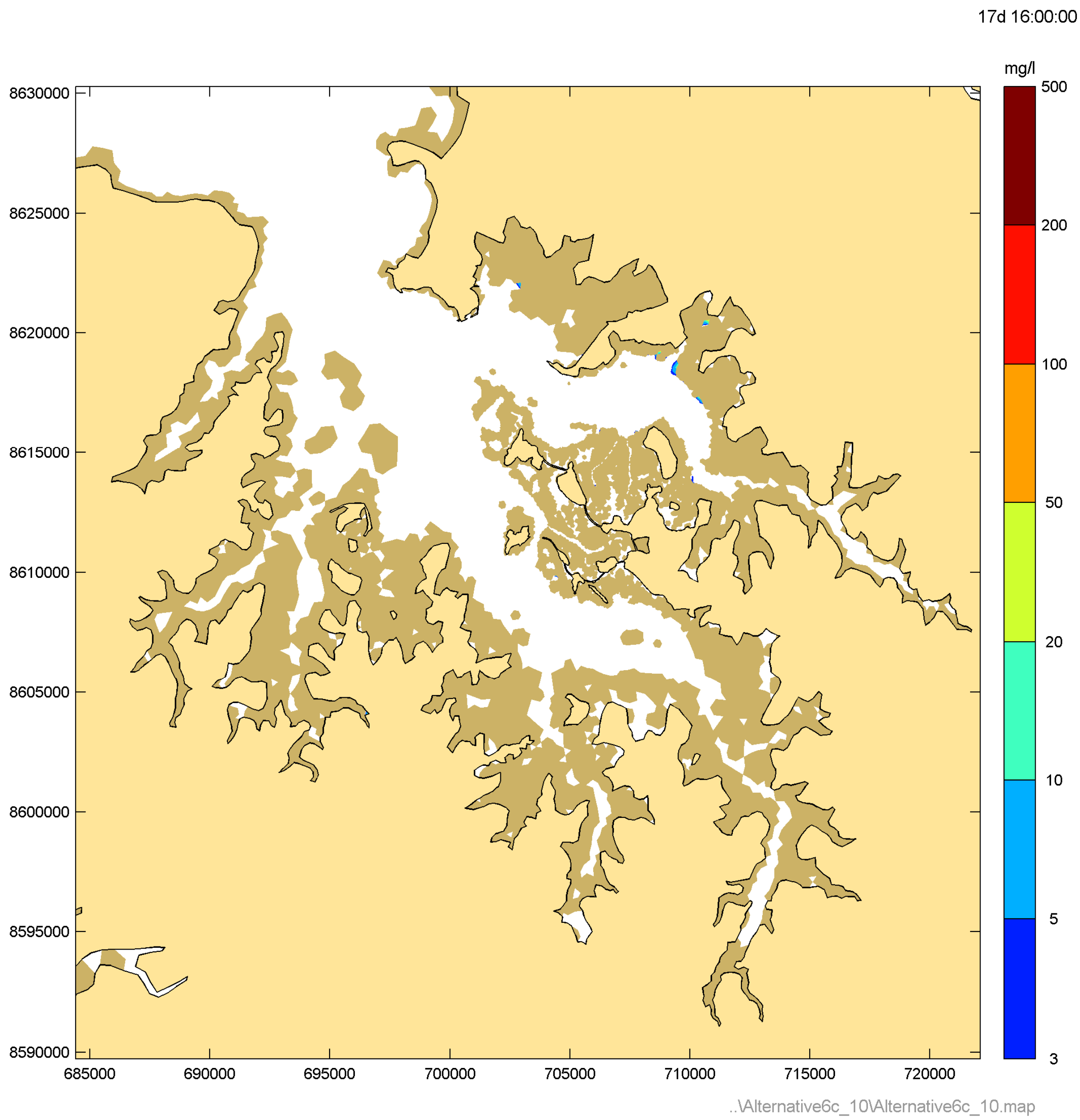


Figure 82 Instantaneous suspended sediment concentrations during Phase 10 peak ebb – Spring tide

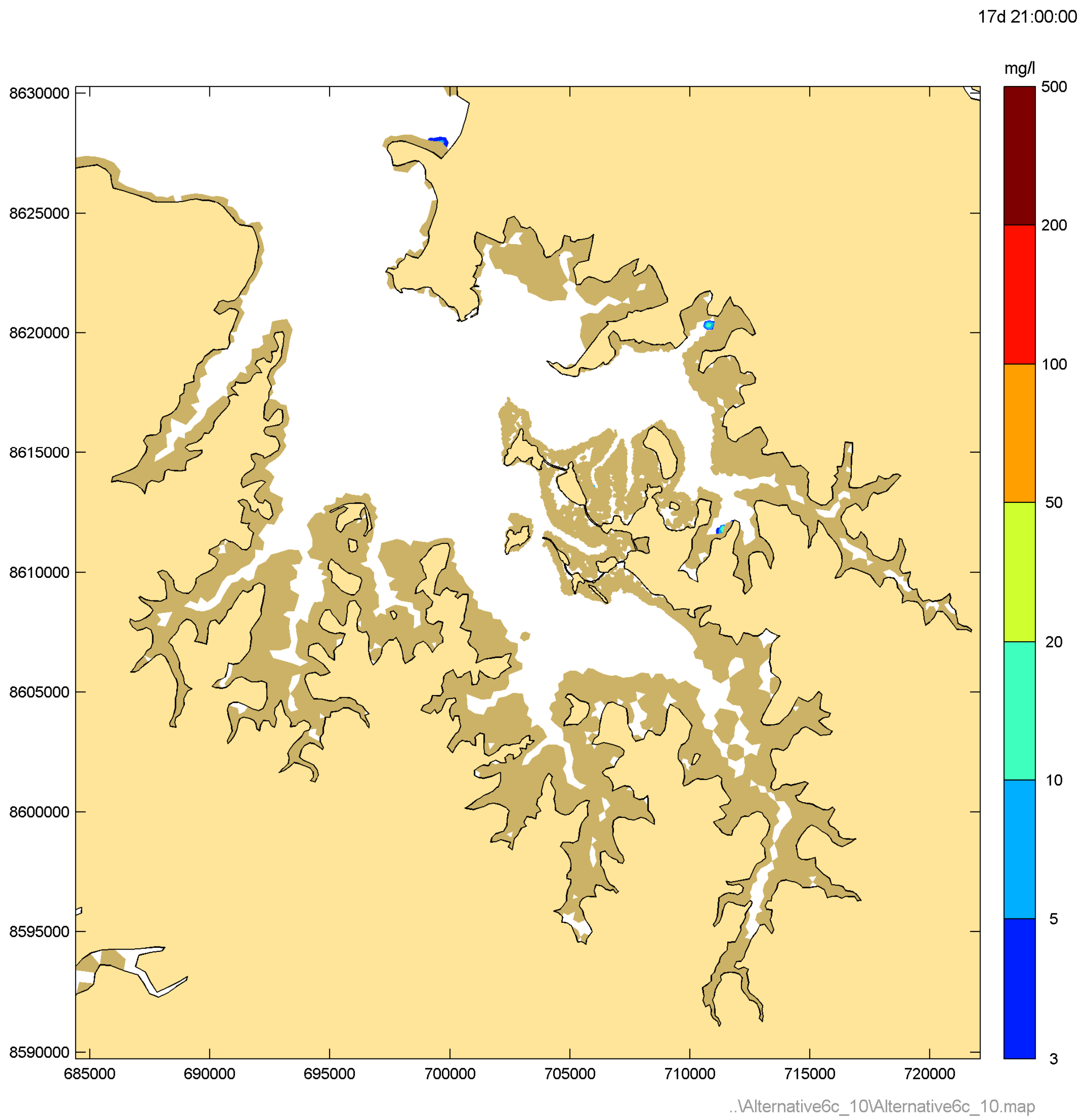


Figure 83 Instantaneous suspended sediment concentrations during Phase 10 peak flood – Spring tide

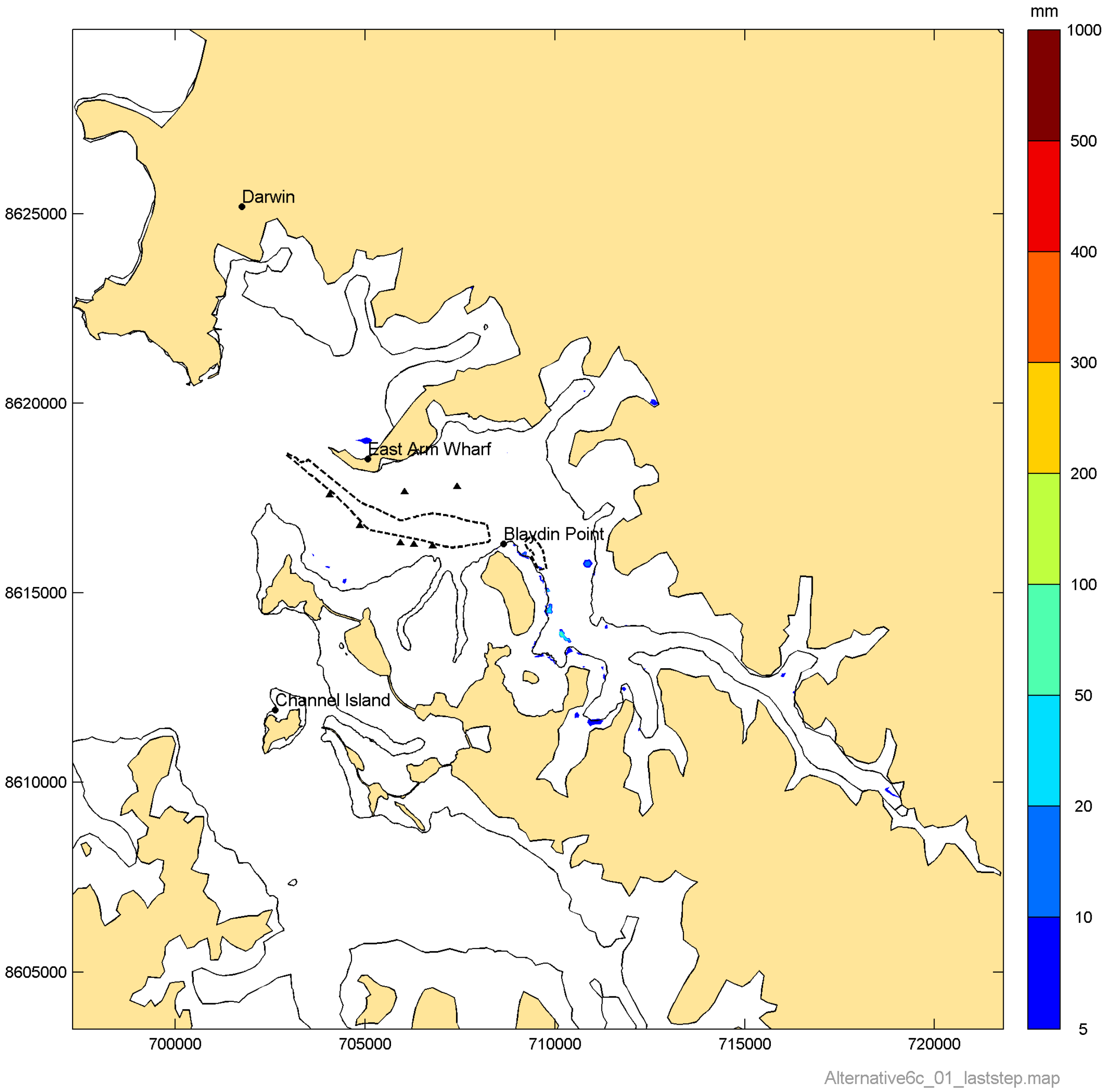


Figure 84 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 1

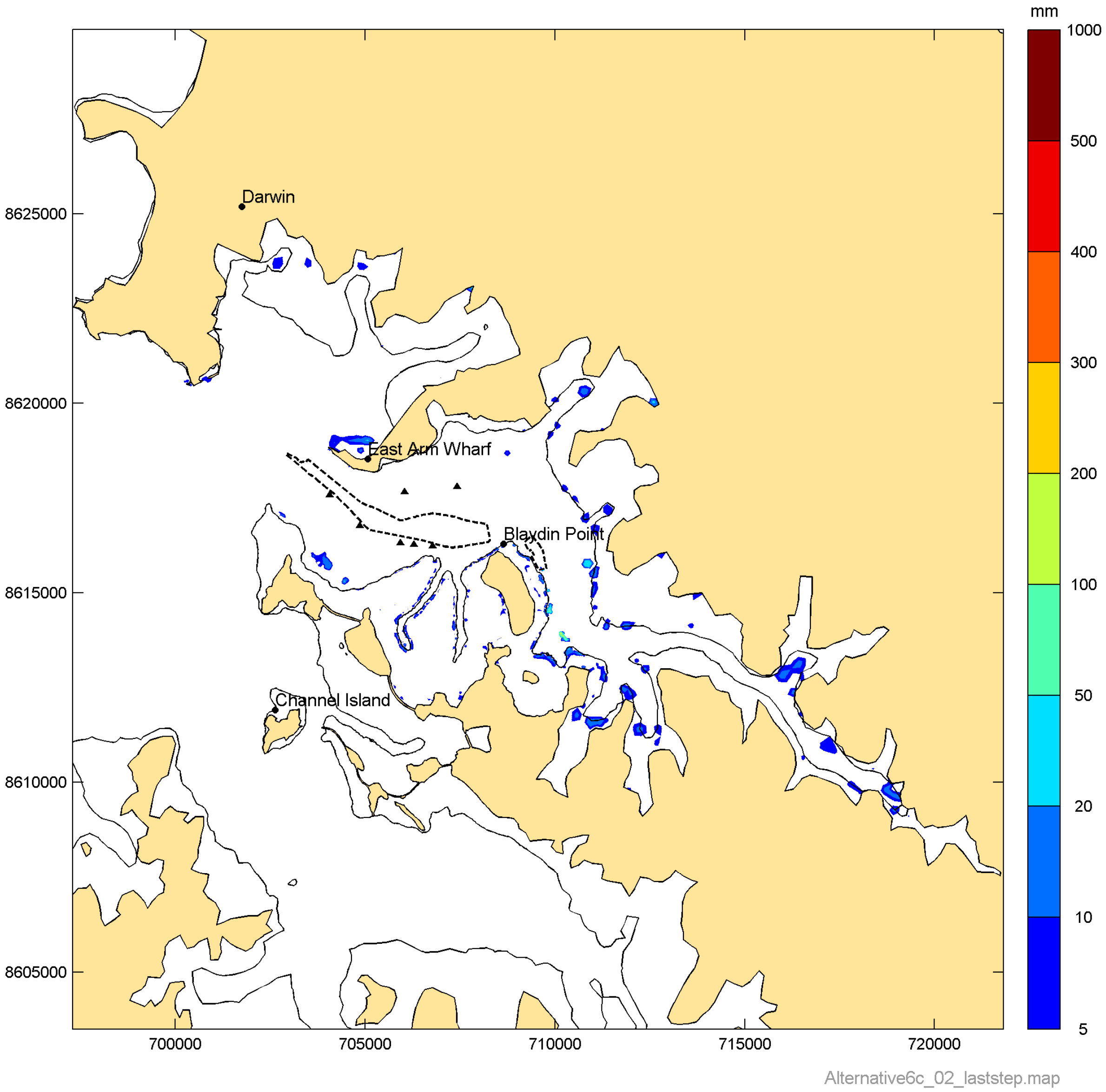


Figure 85 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 2

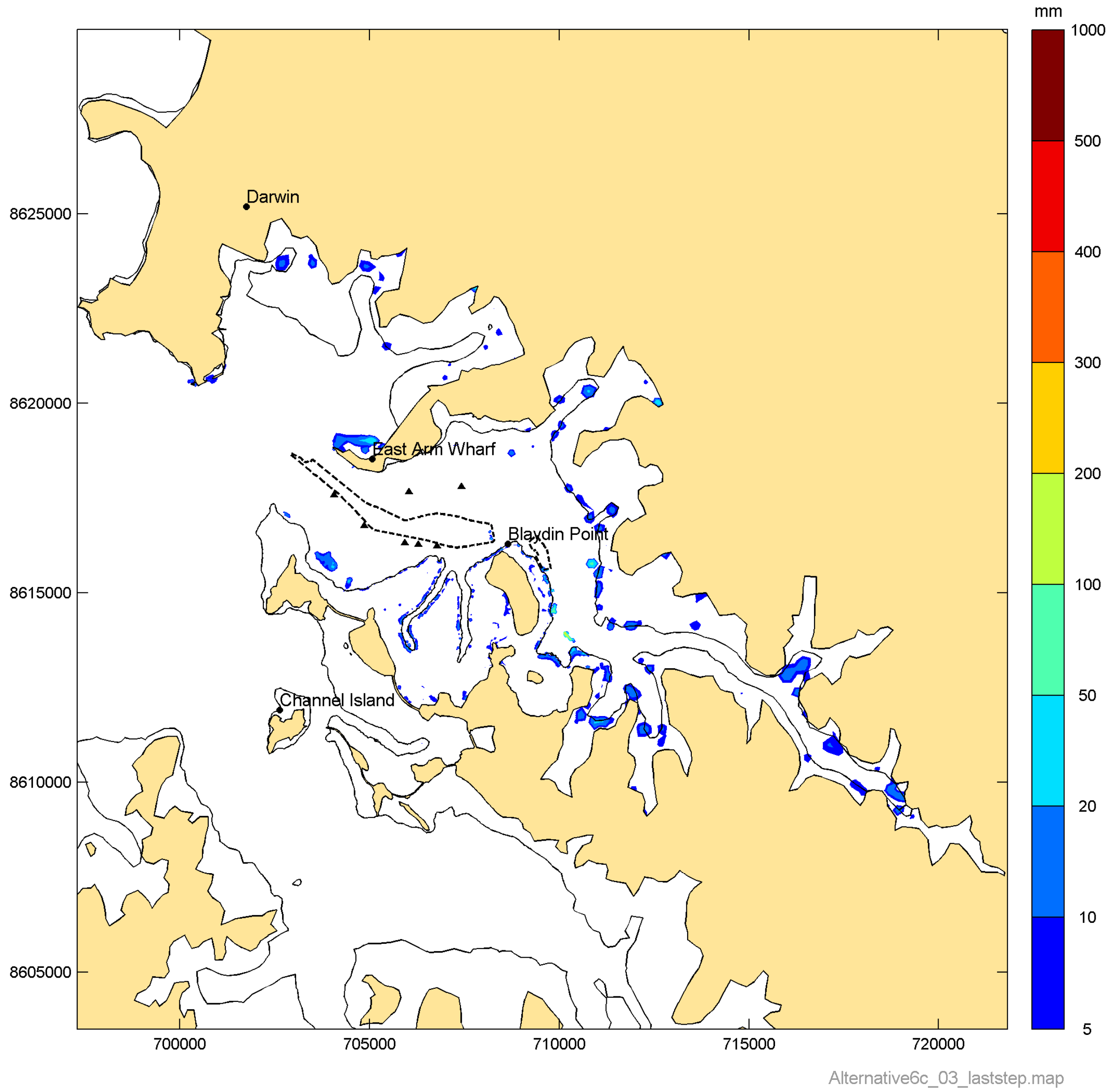


Figure 86 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 3

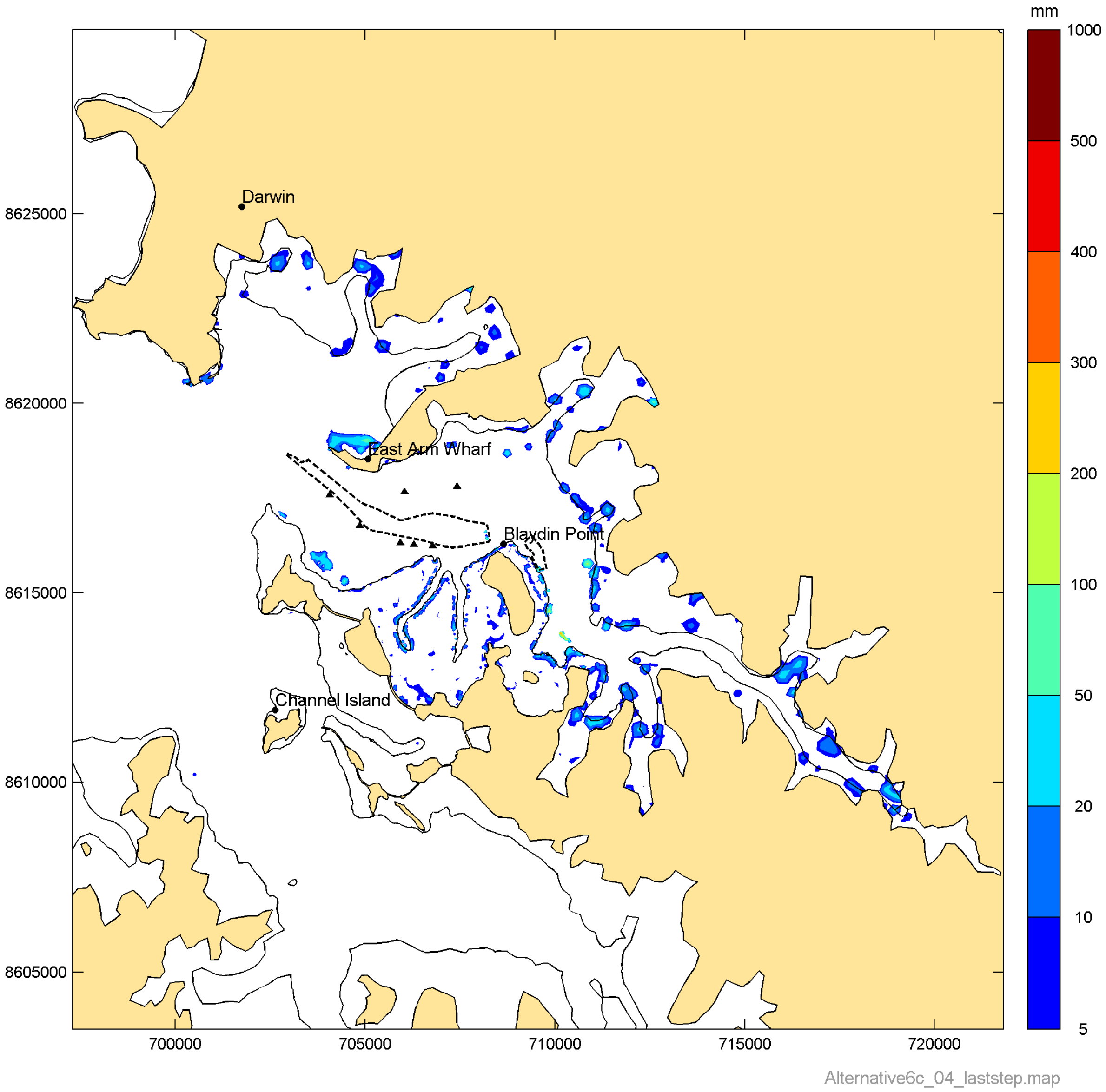


Figure 87 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 4

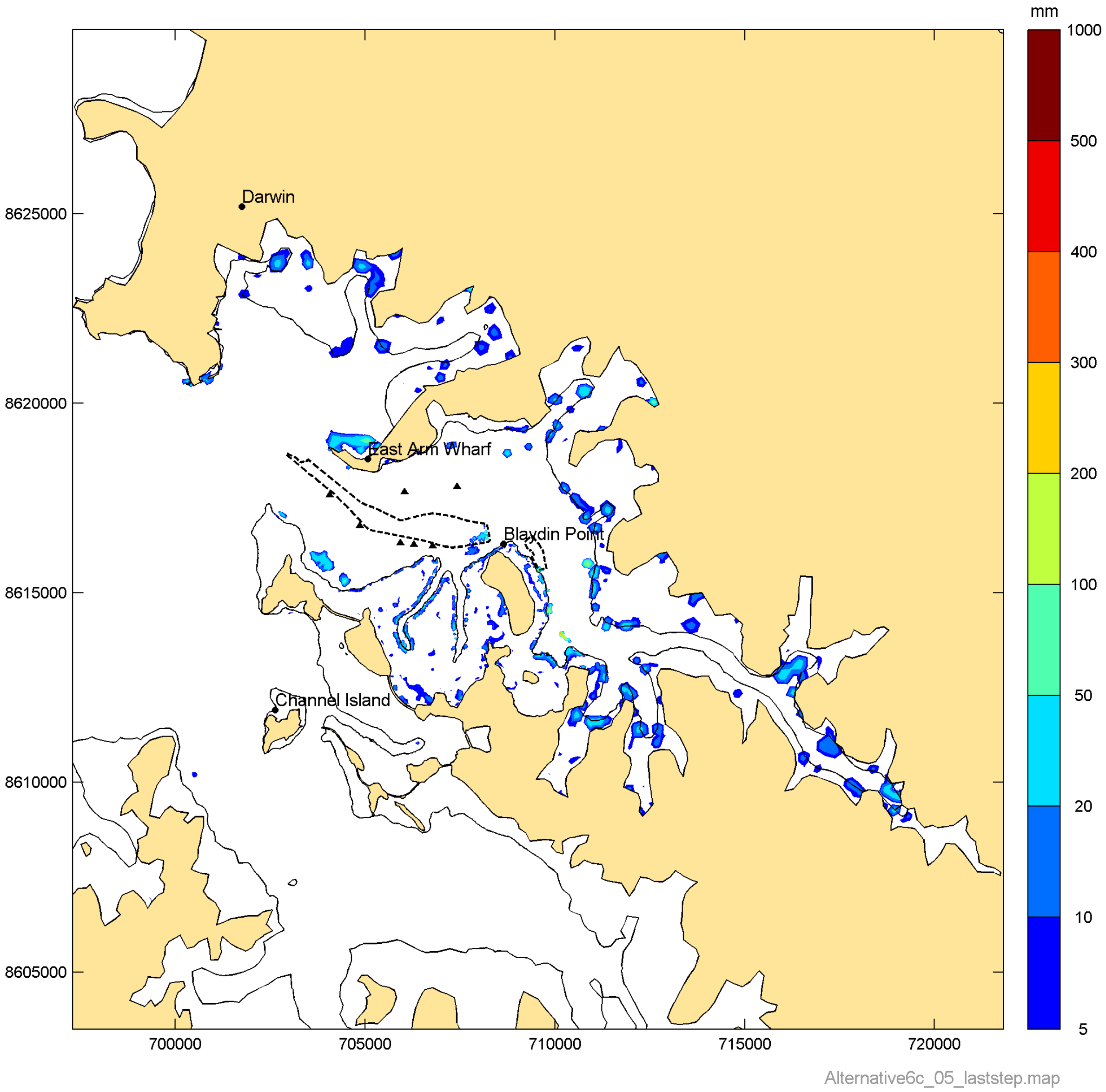


Figure 88 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 5

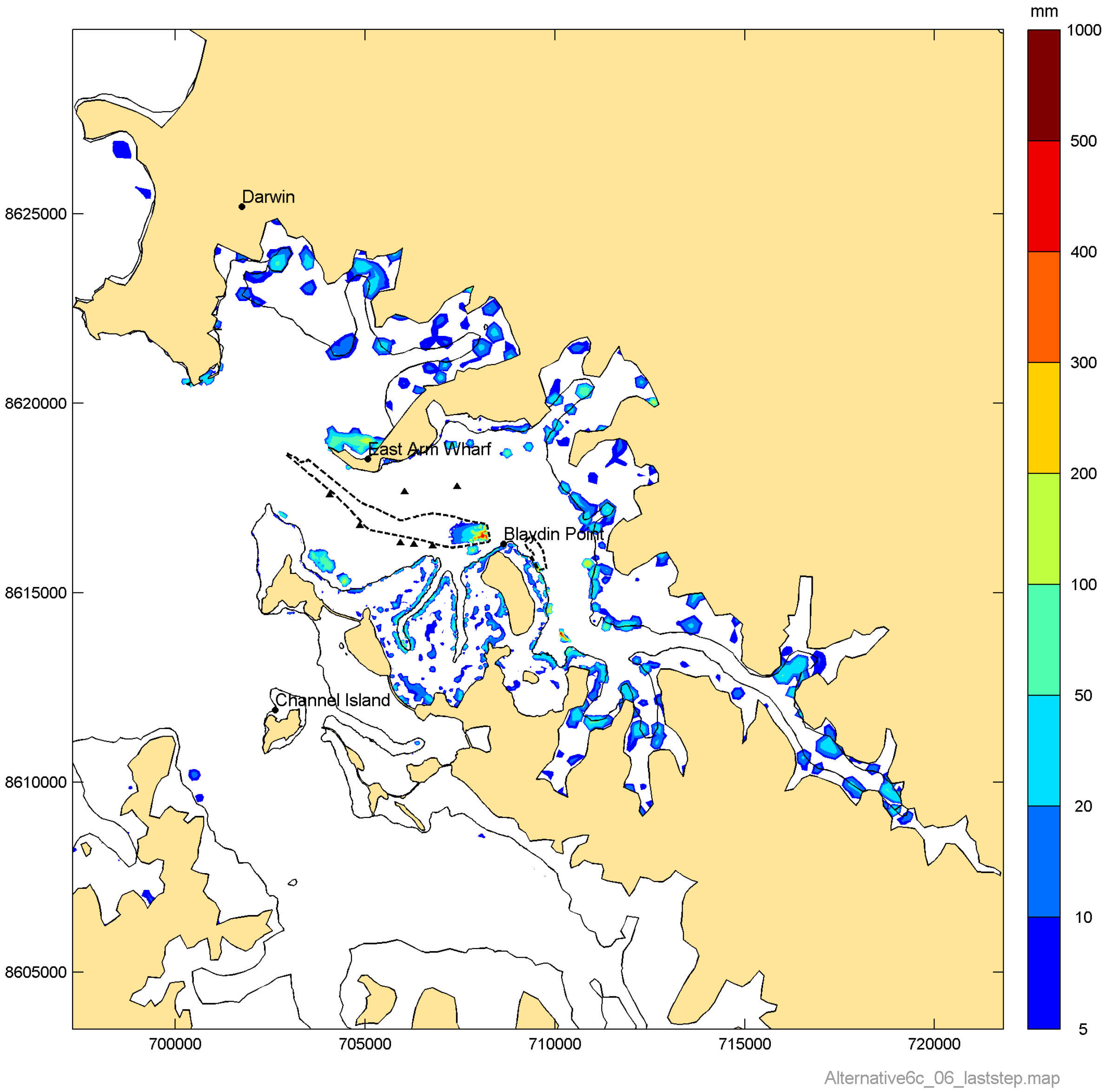


Figure 89 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 6

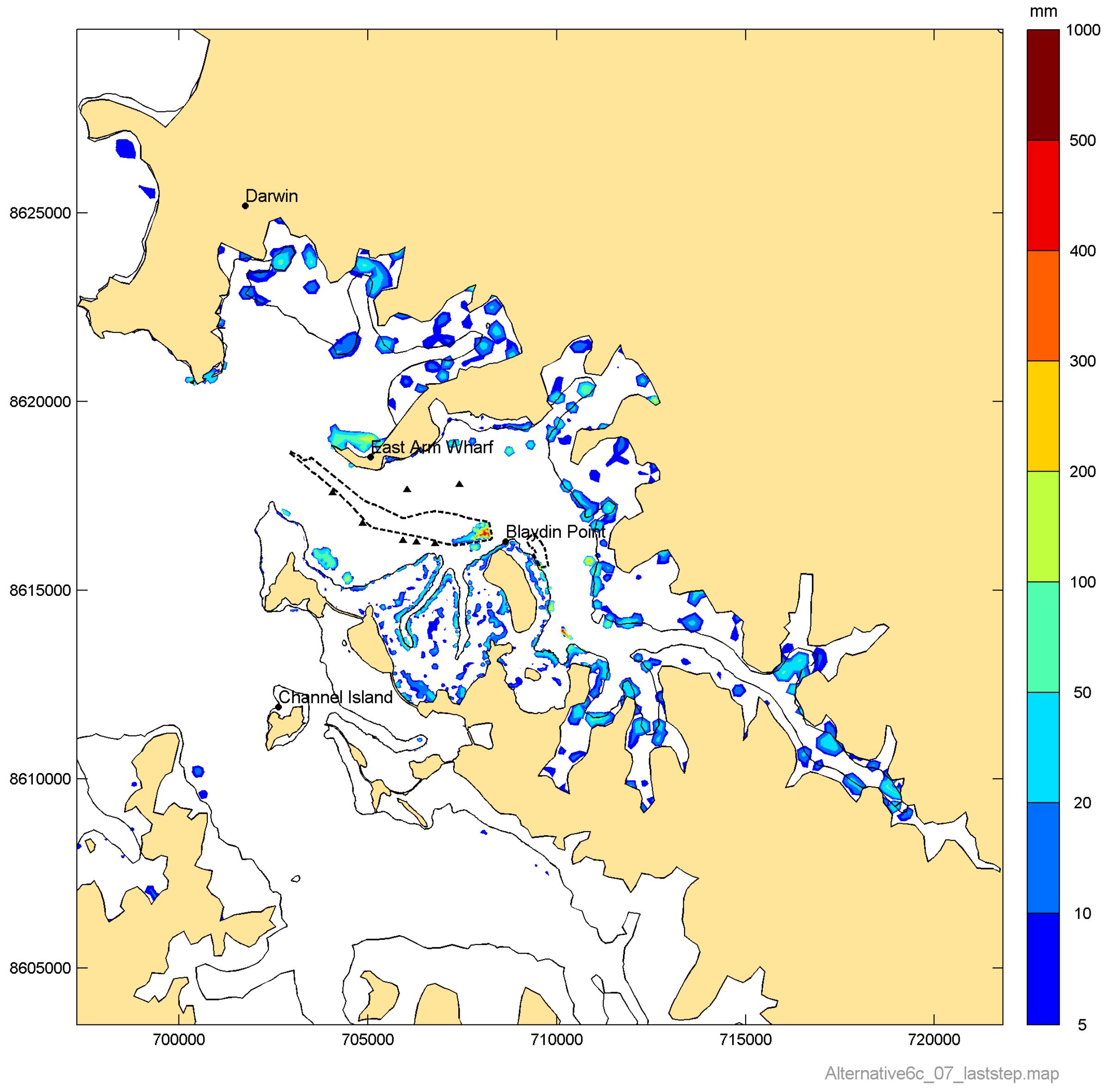


Figure 90 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 7

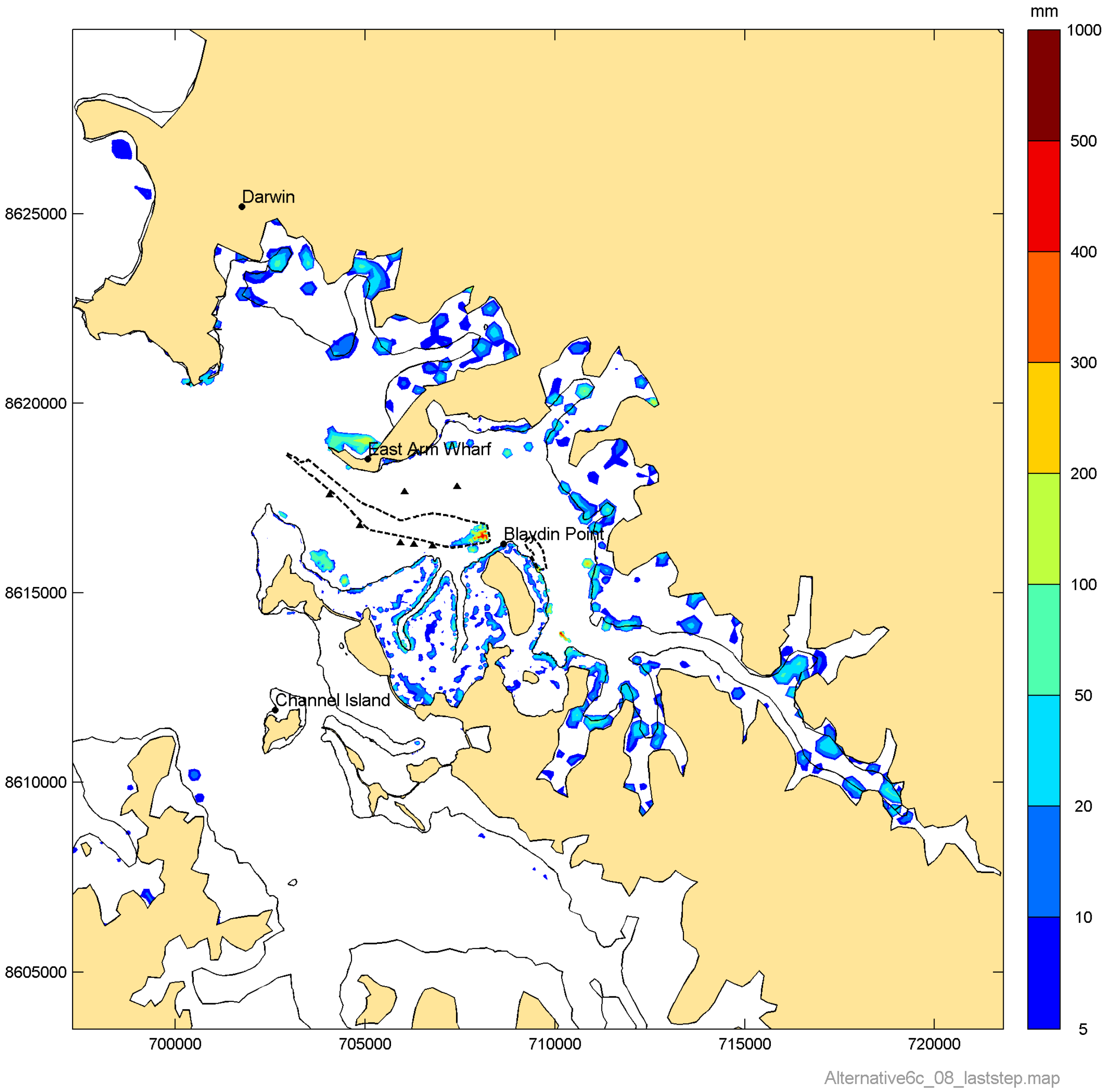


Figure 91 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 8

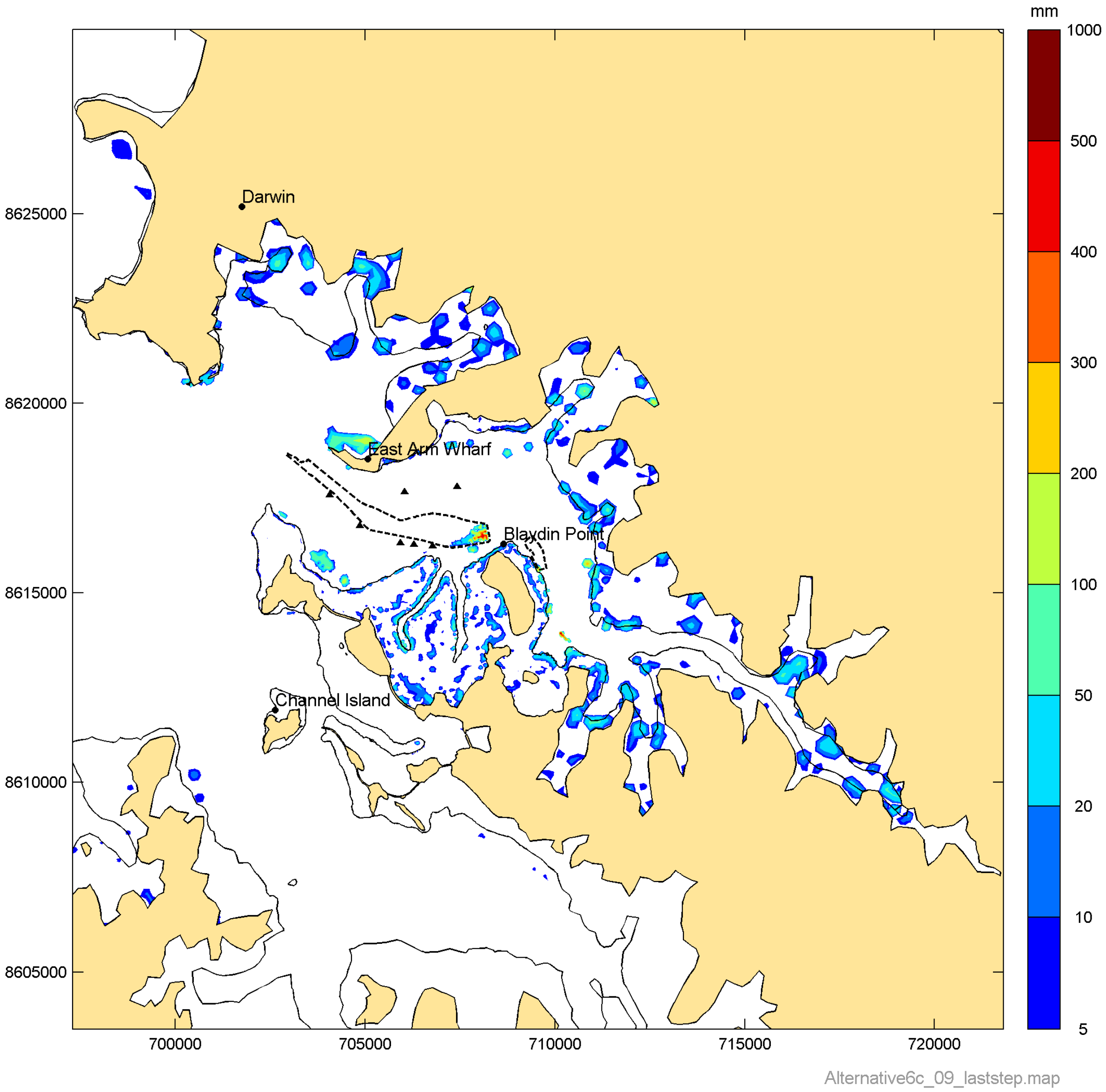


Figure 92 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 9

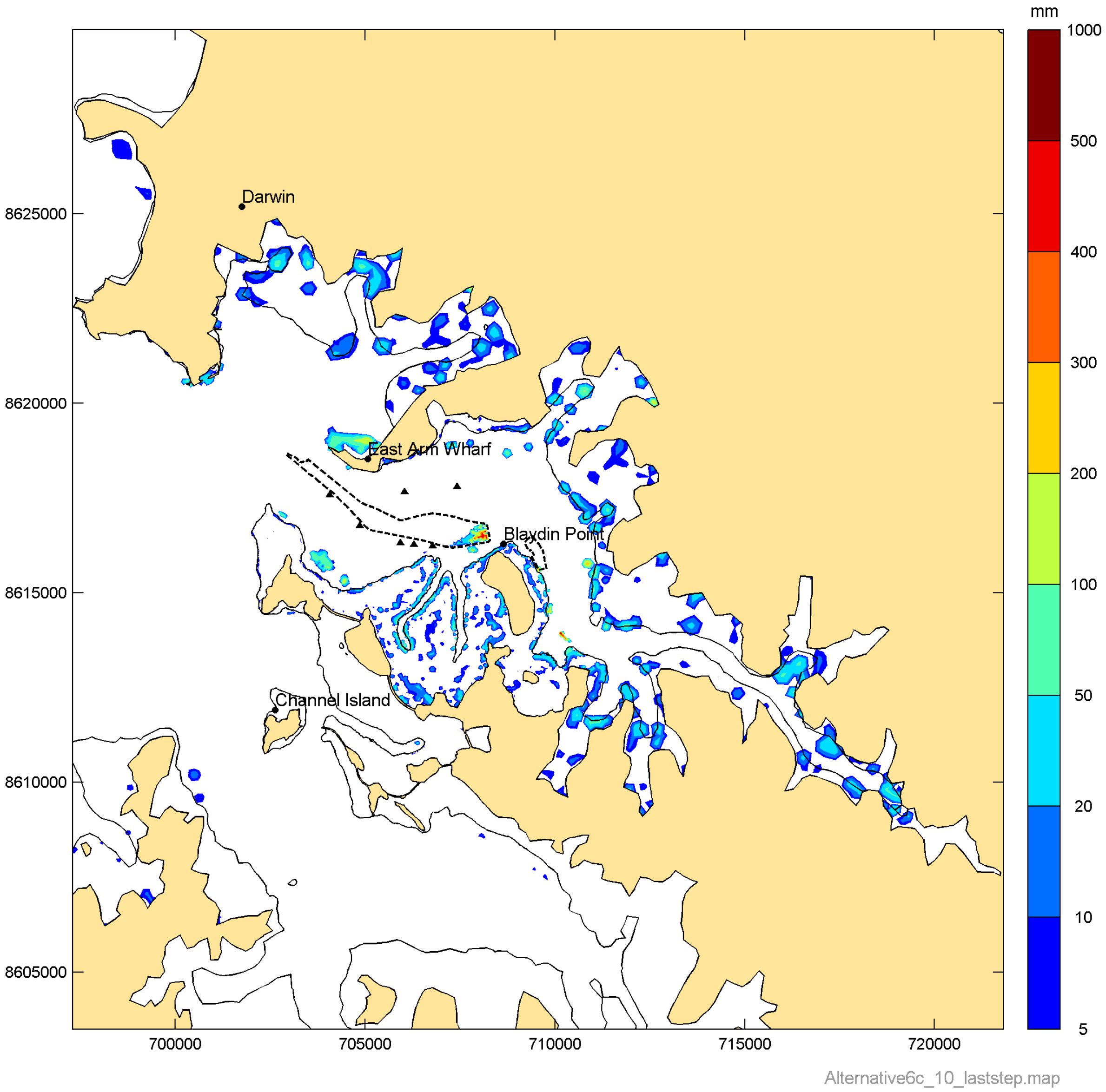


Figure 93 Simulated depth of fine sediment accretion in the East Arm at the end of Phase 10

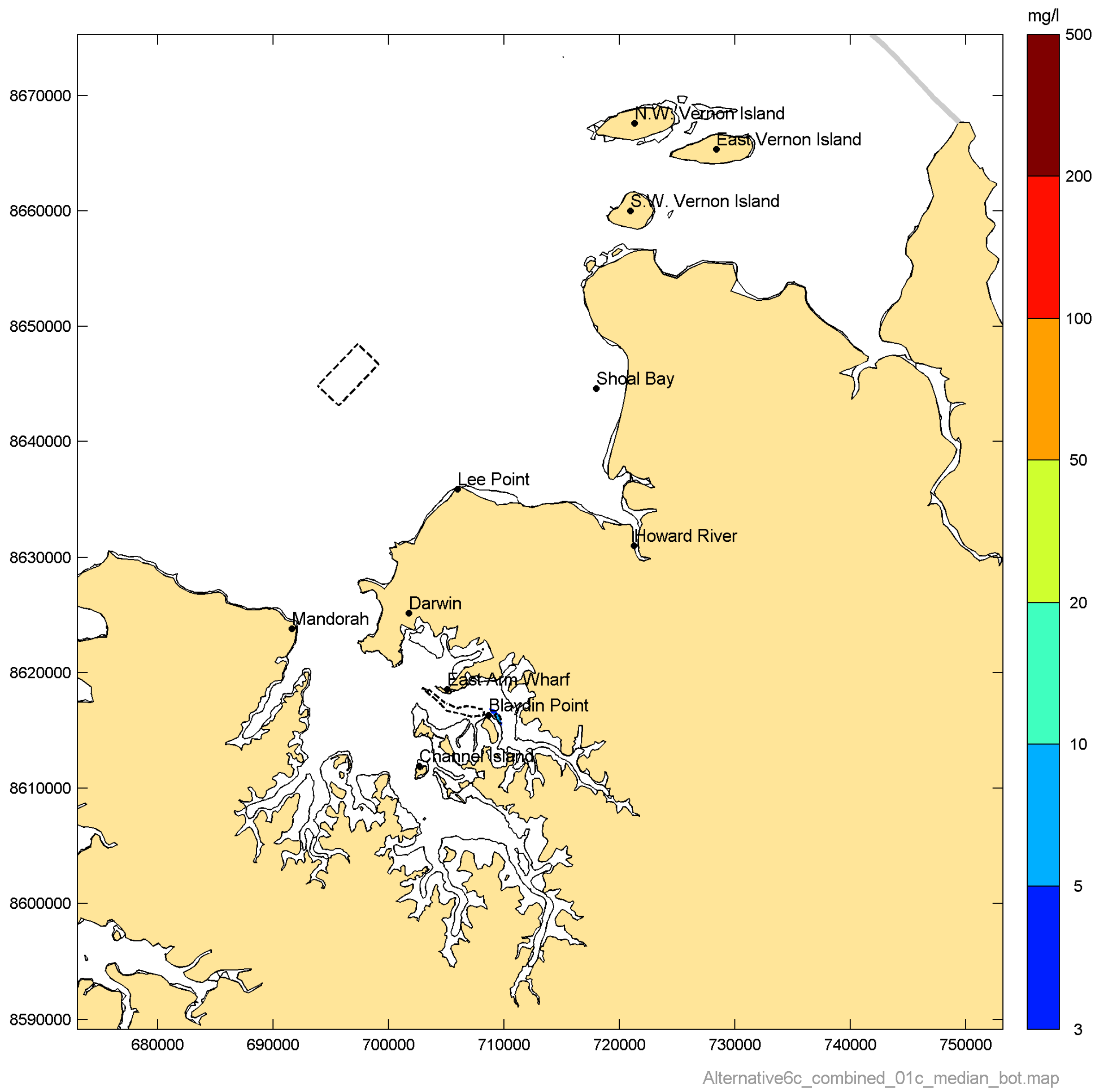


Figure 94 Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 1

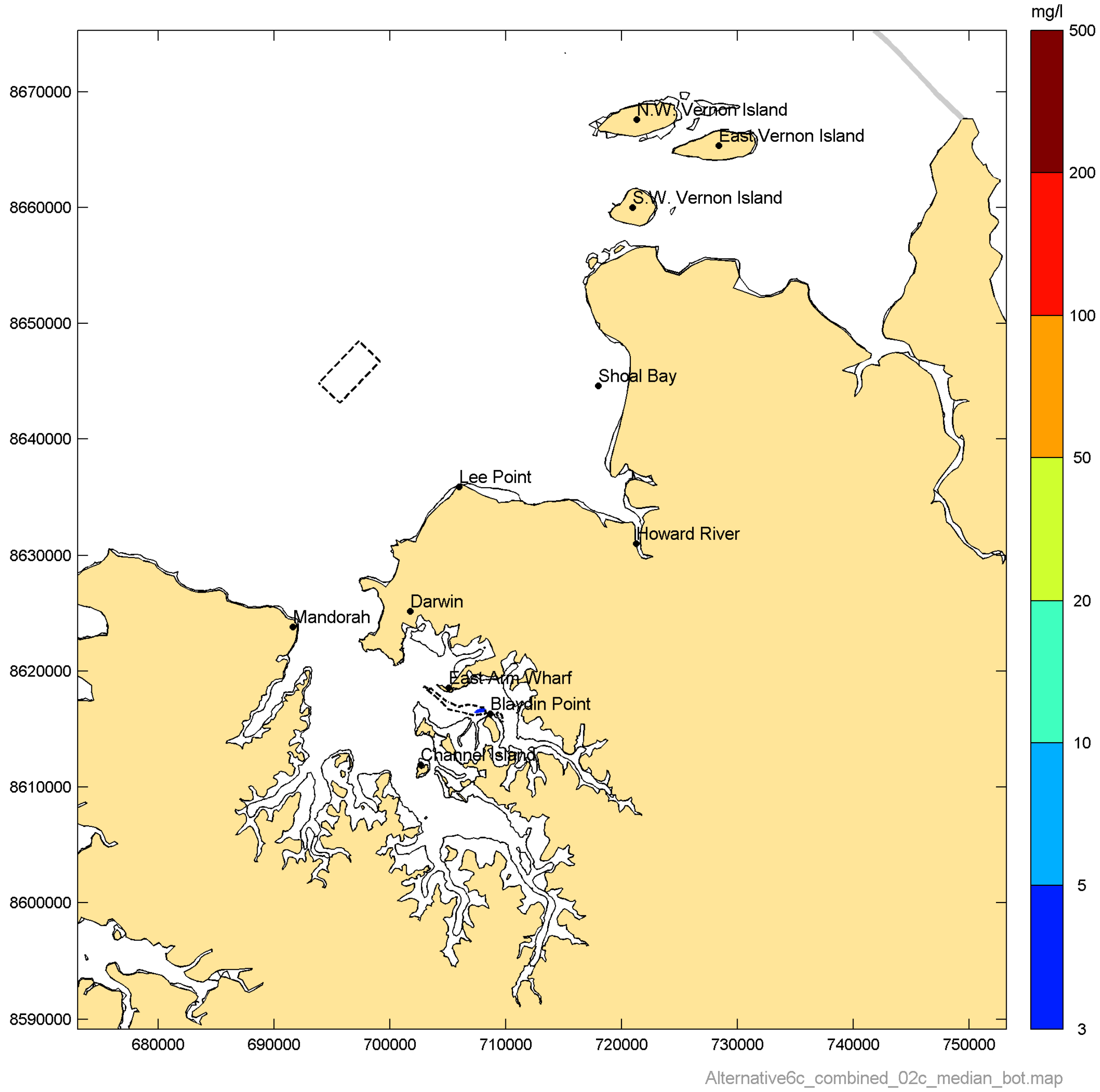


Figure 95 **Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 2**

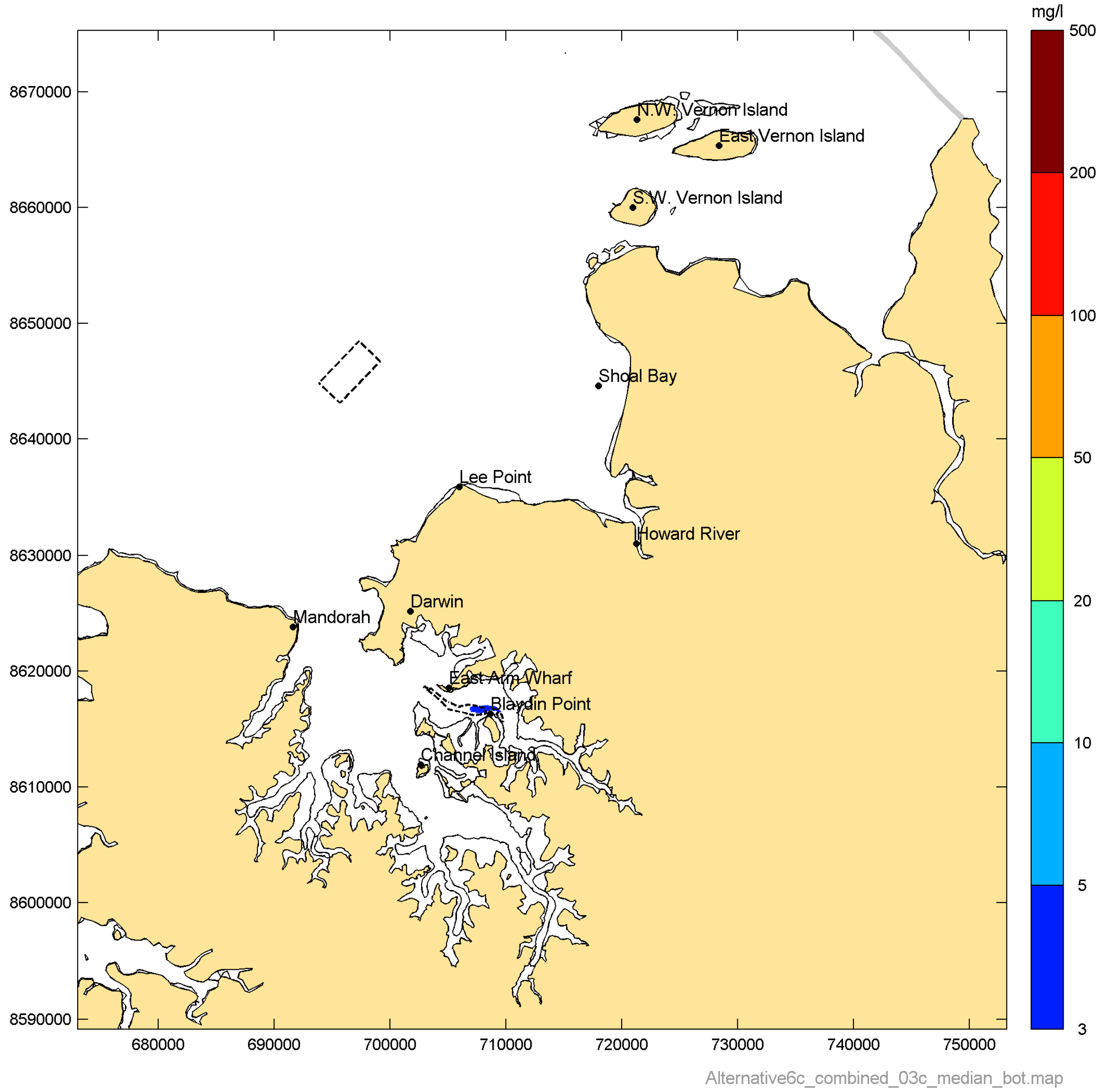


Figure 96 Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 3

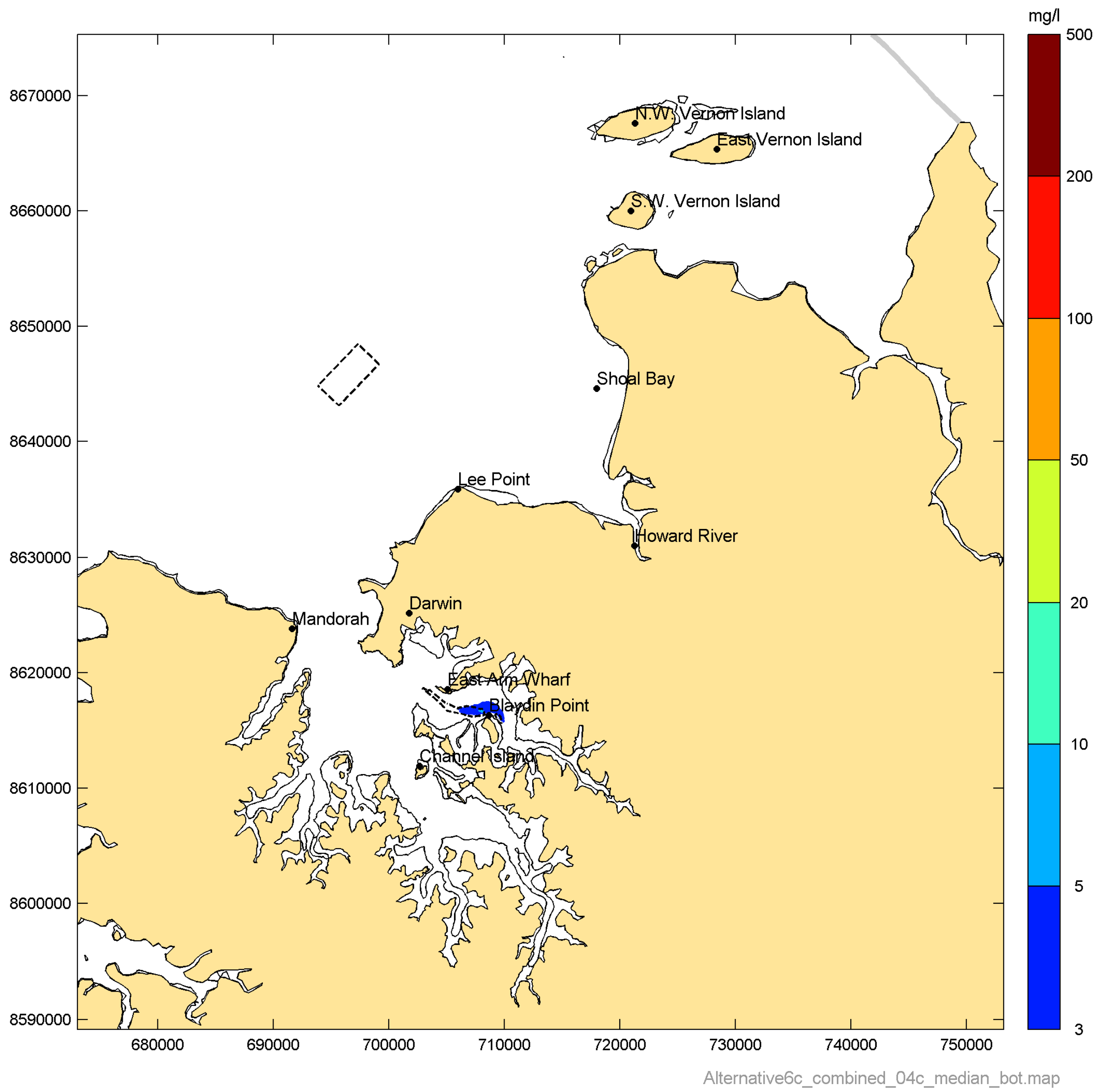


Figure 97 **Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 4**

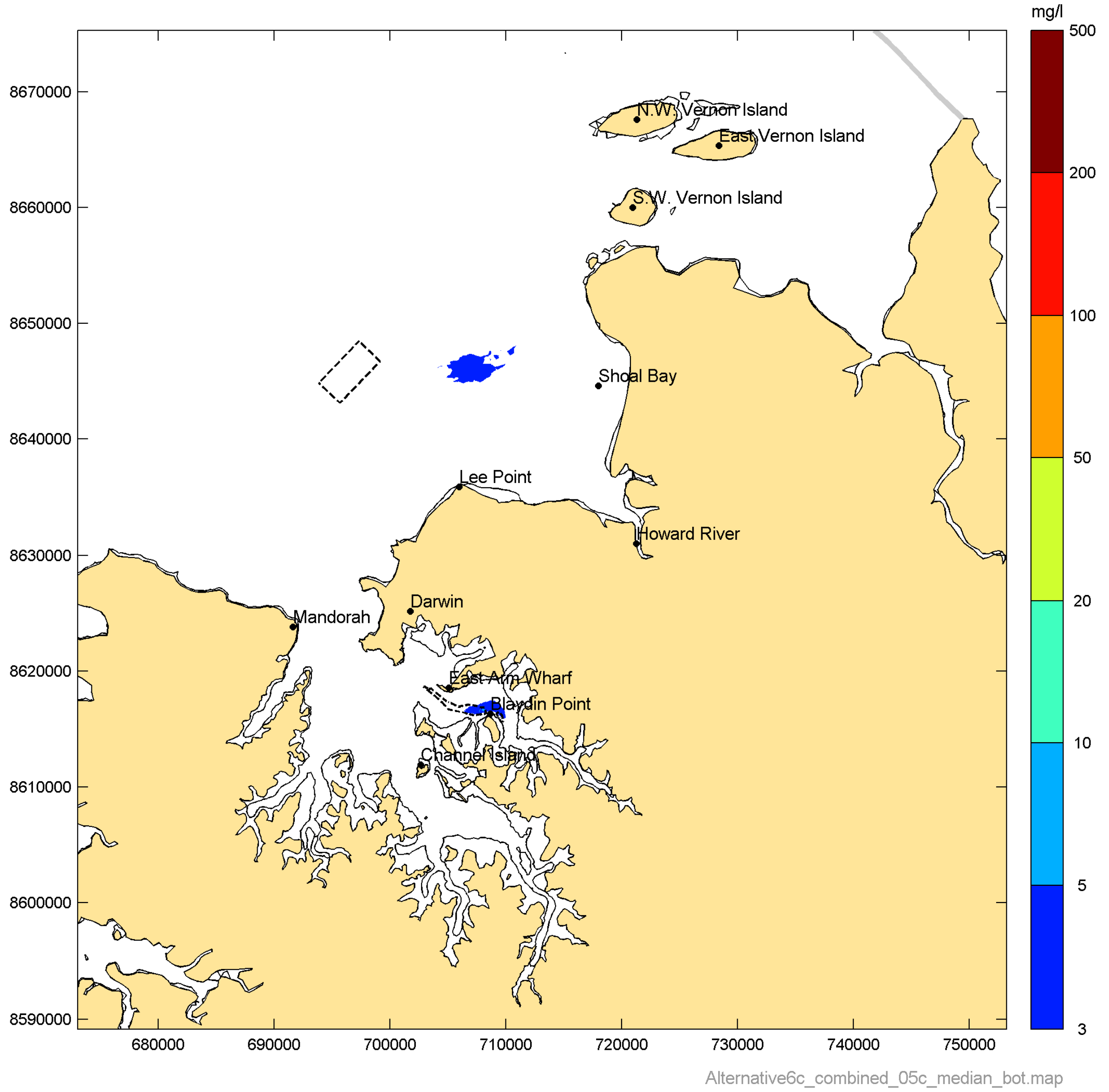


Figure 98 **Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 5**

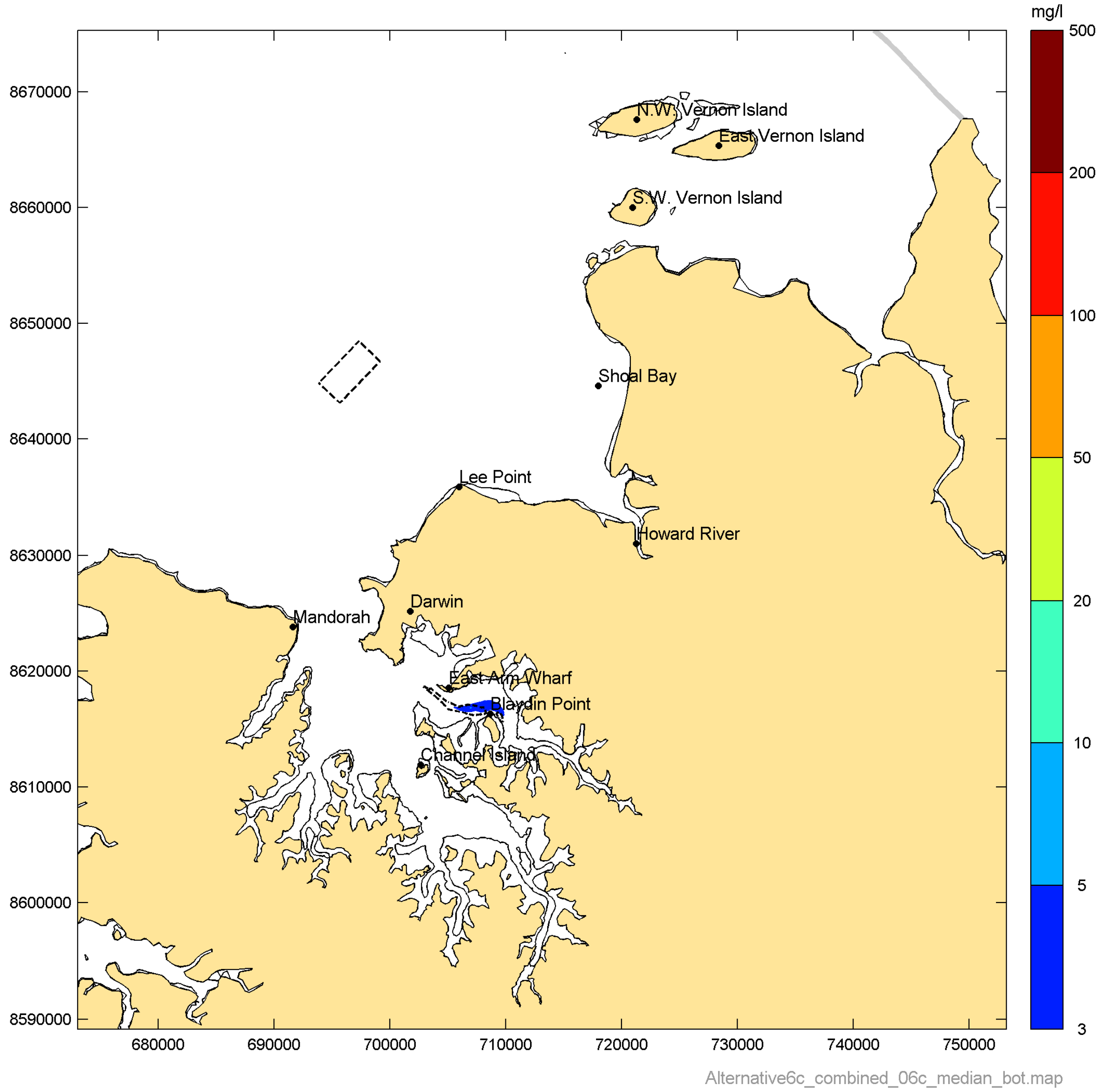
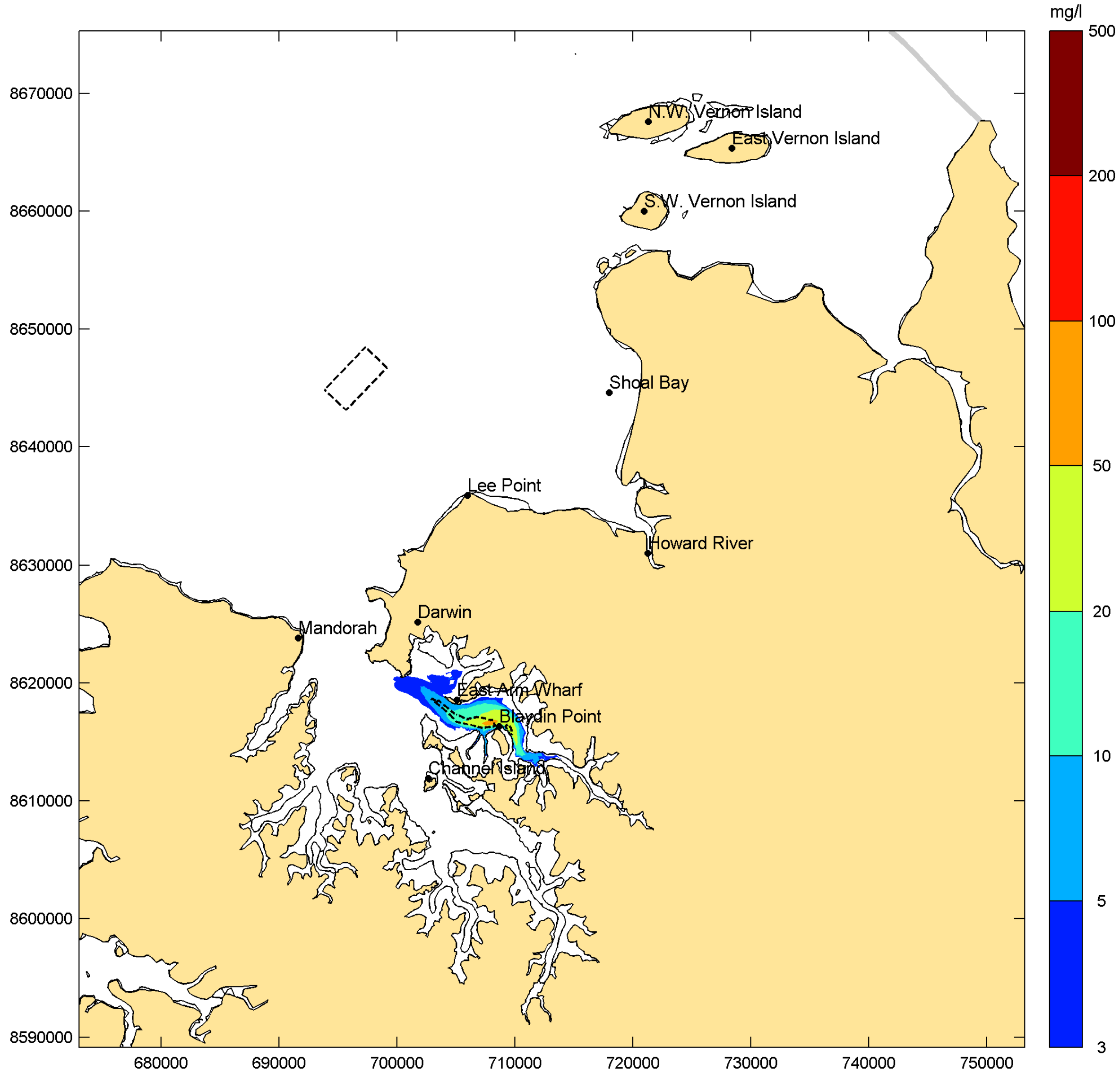


Figure 99 **Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 6**



v-uk.local\ebr4470$\model\PLUME_MODELLING\Delwaq\Median_concentrations\Alternative6c_combined_06c_median_intensive_bot.map

Figure 100 Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 6 – cutter-suction dredger activity

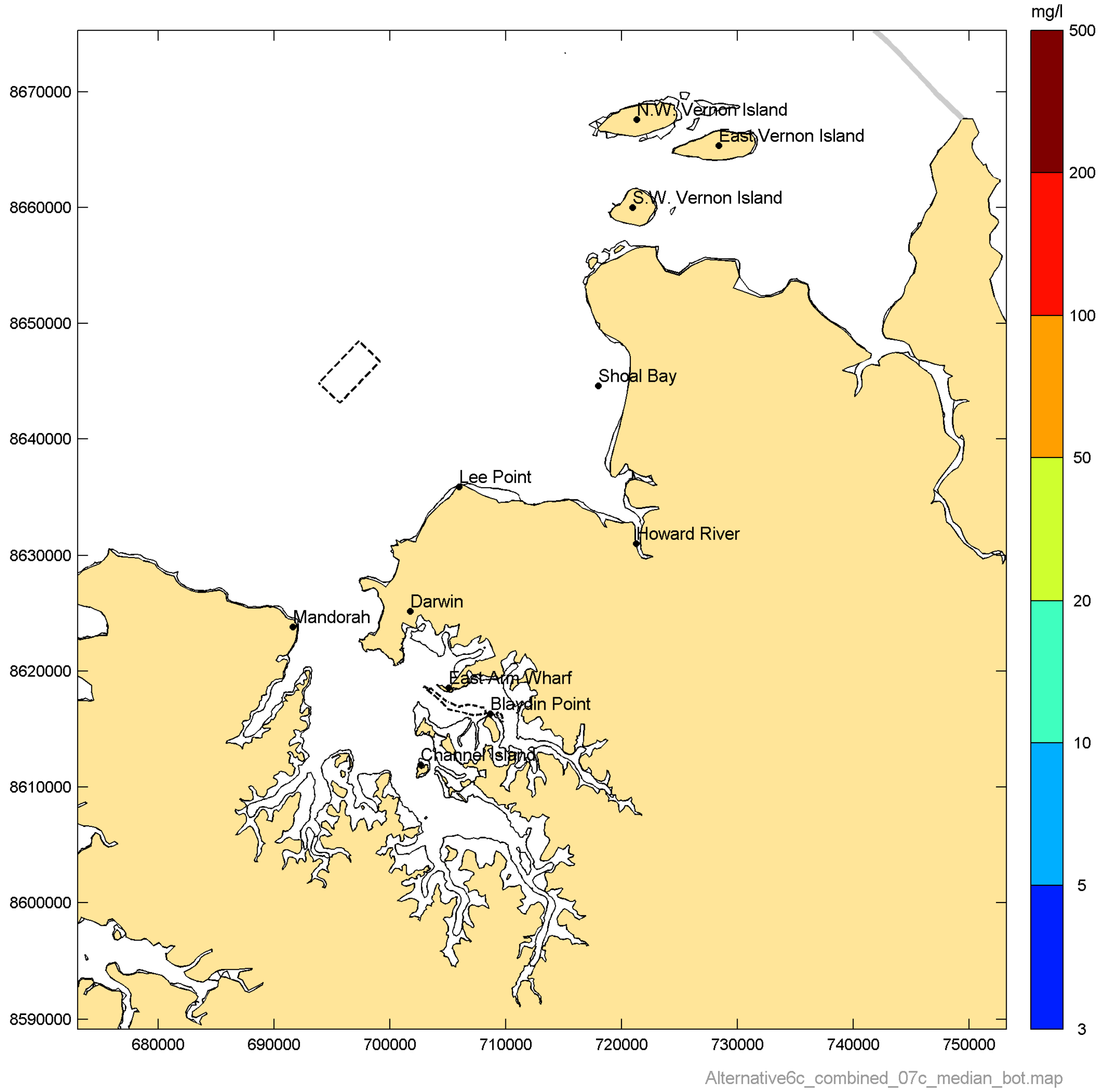


Figure 101 Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 7

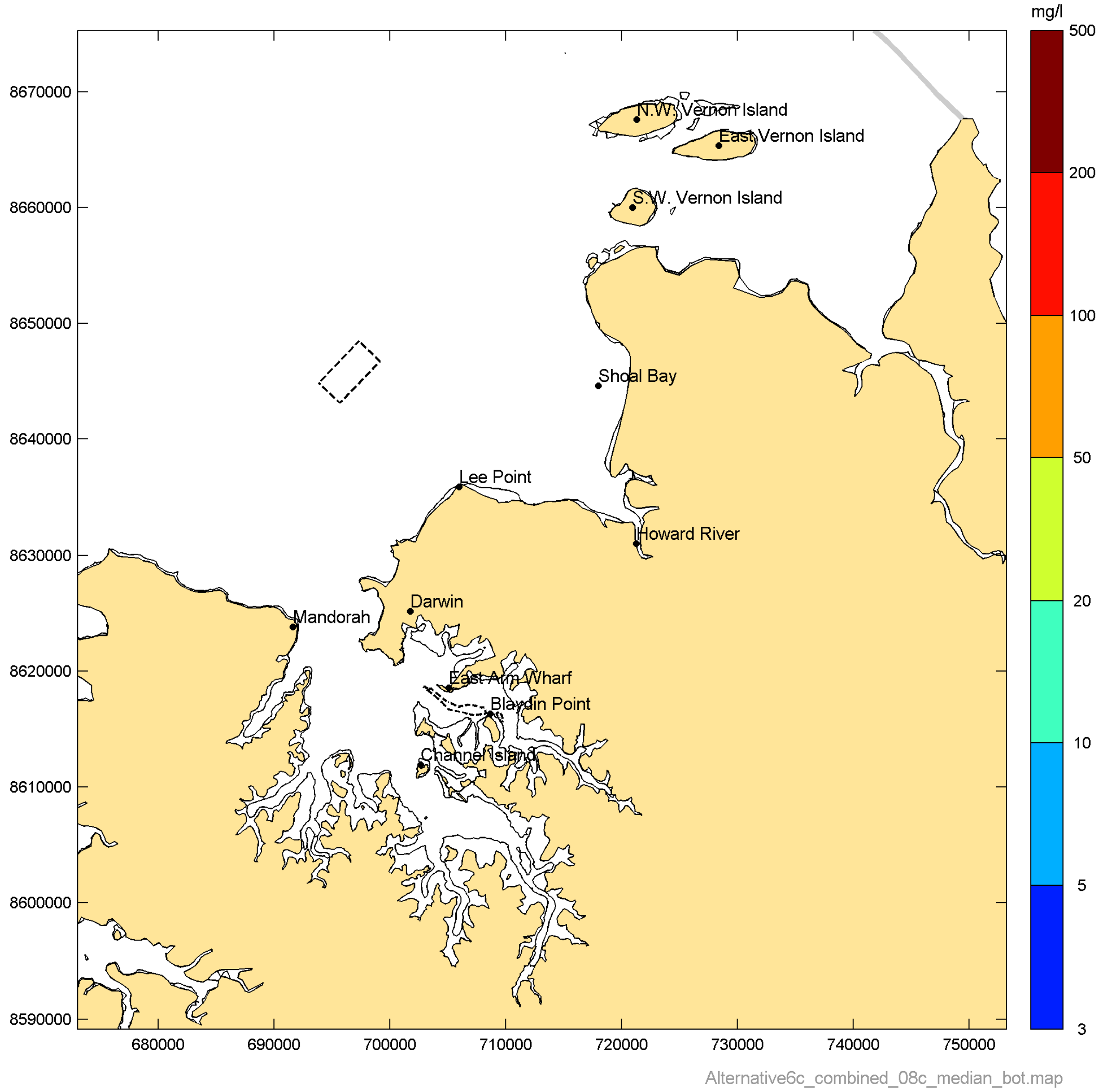


Figure 102 Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 8

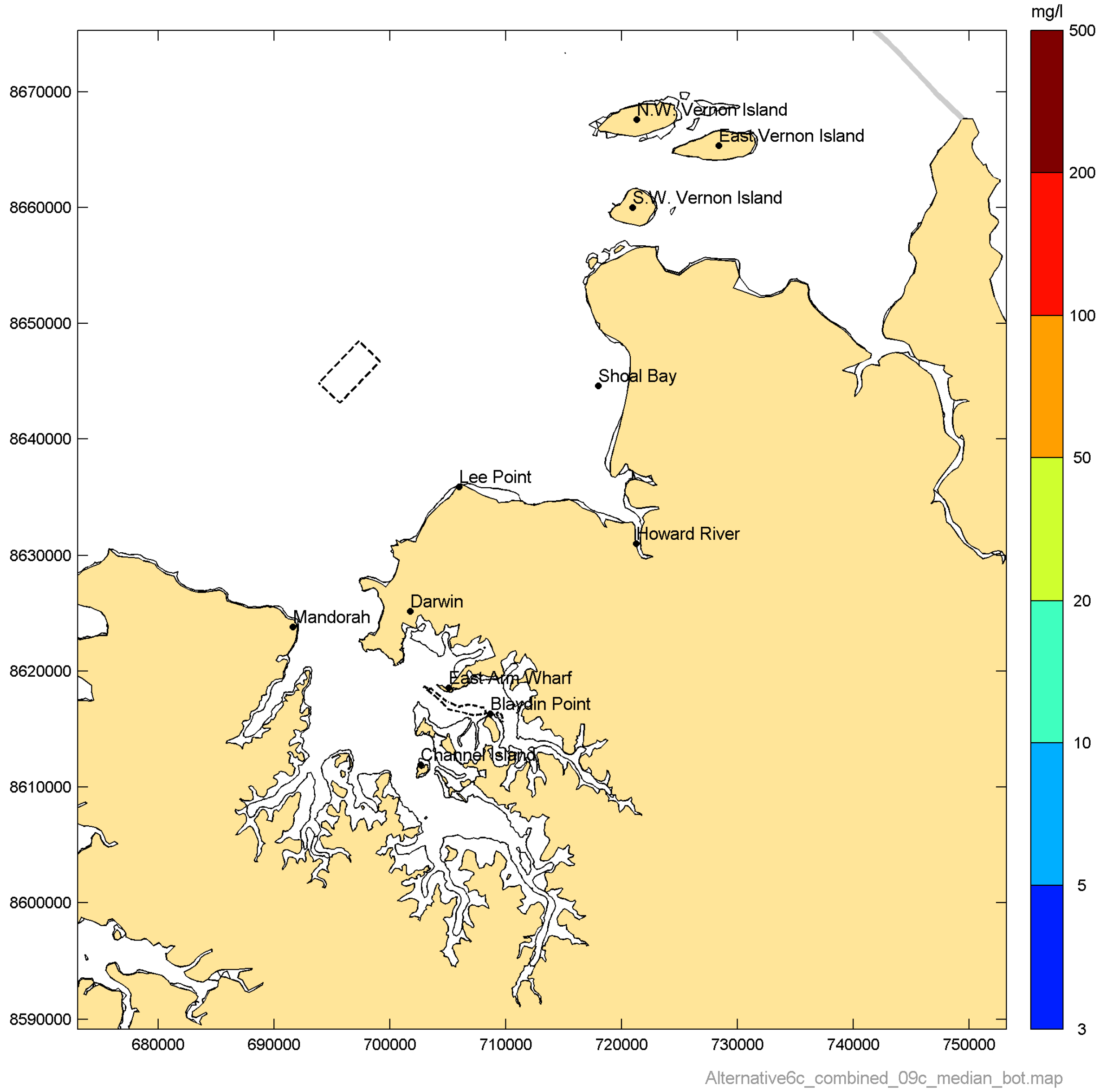


Figure 103 Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 9

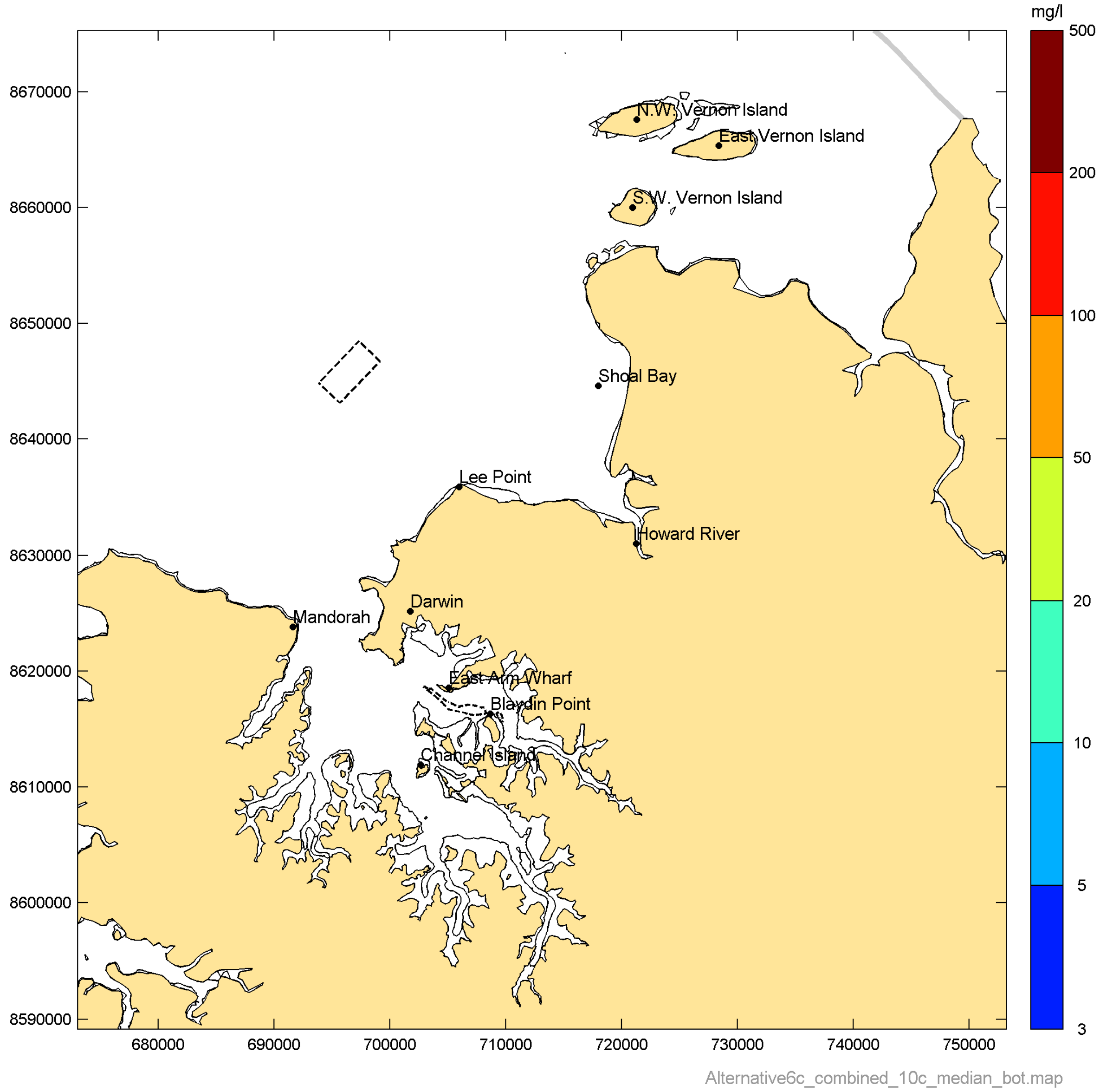


Figure 104 Simulated median suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 10

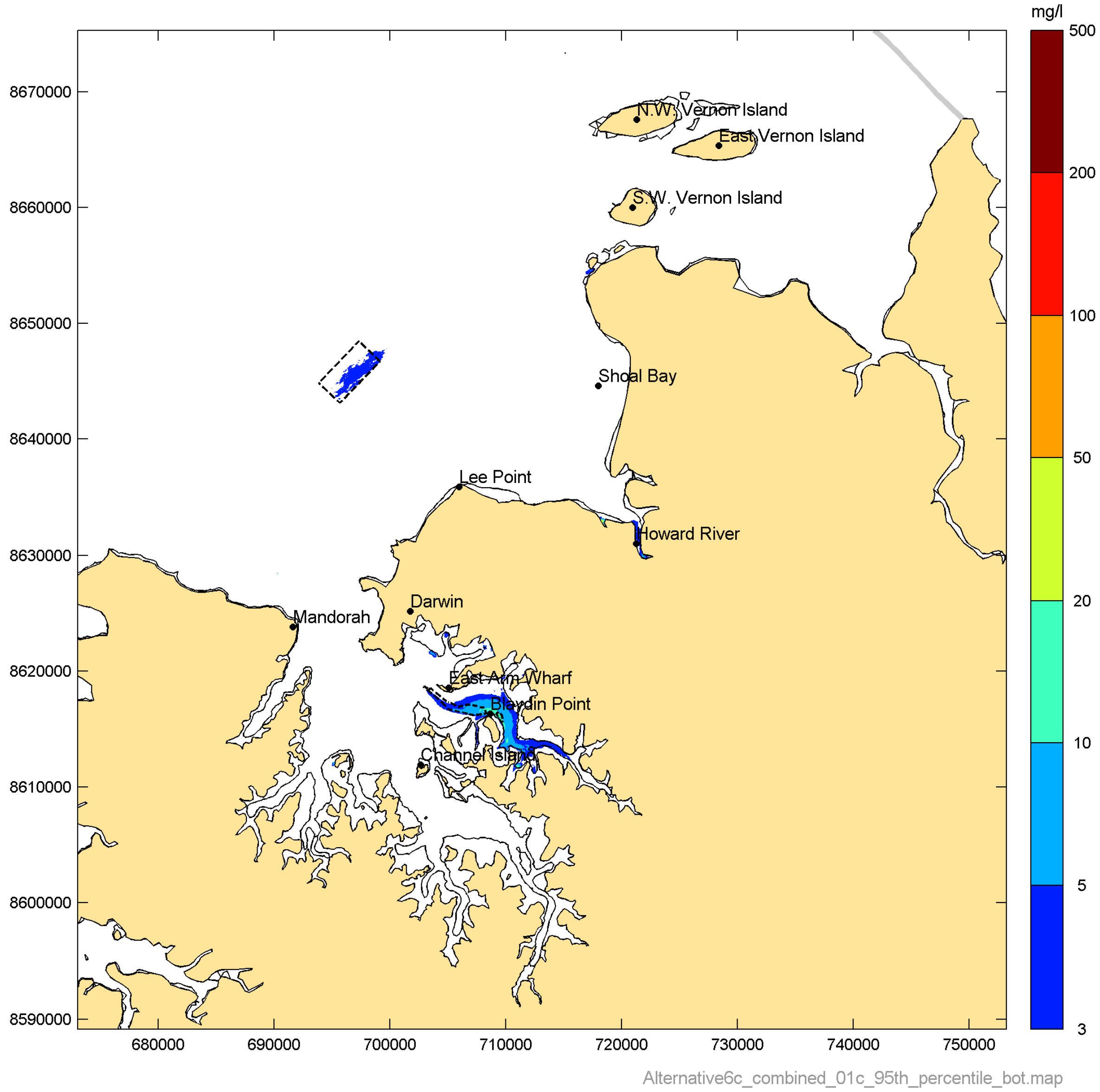


Figure 105 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 1

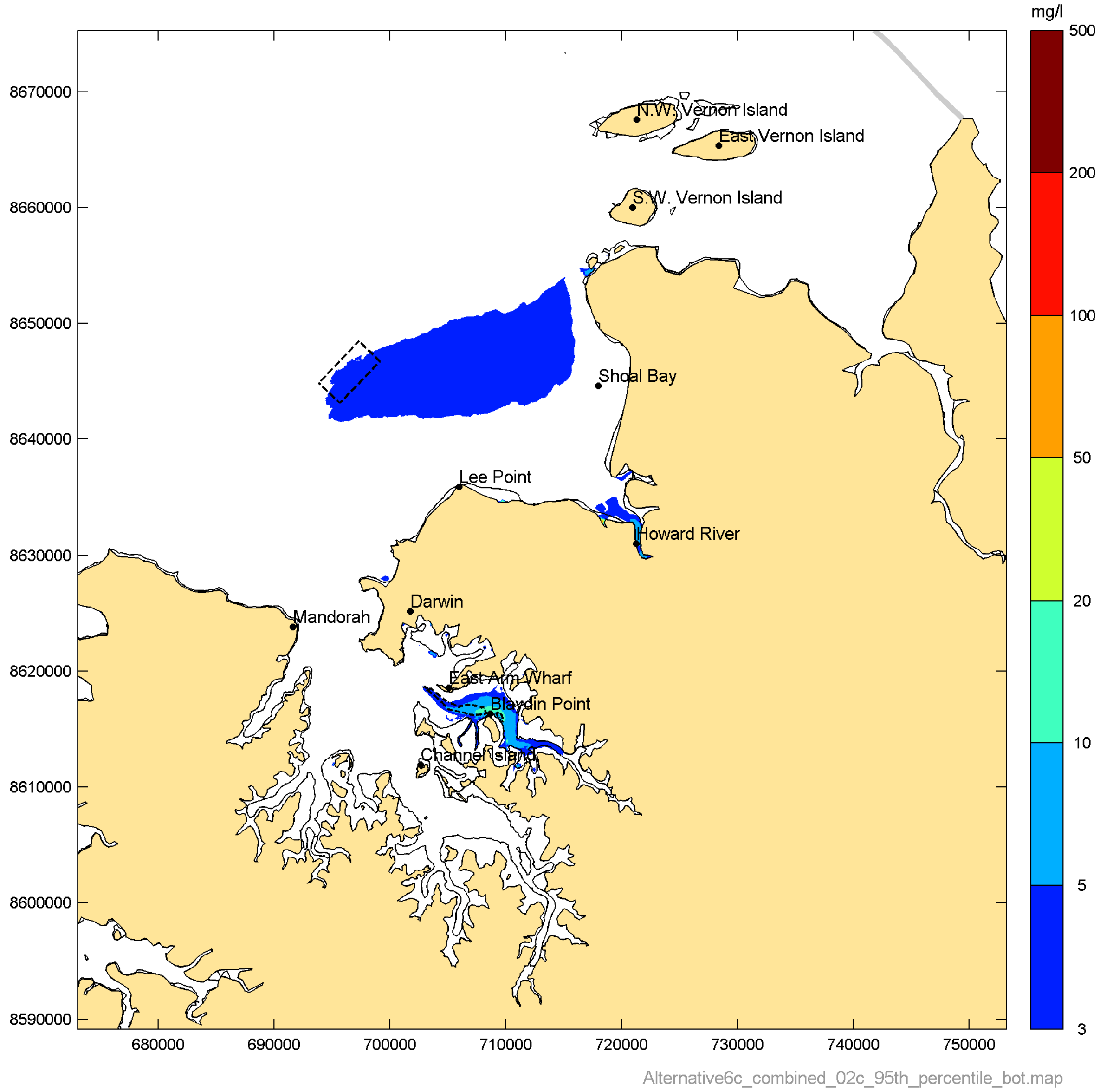


Figure 106 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 2

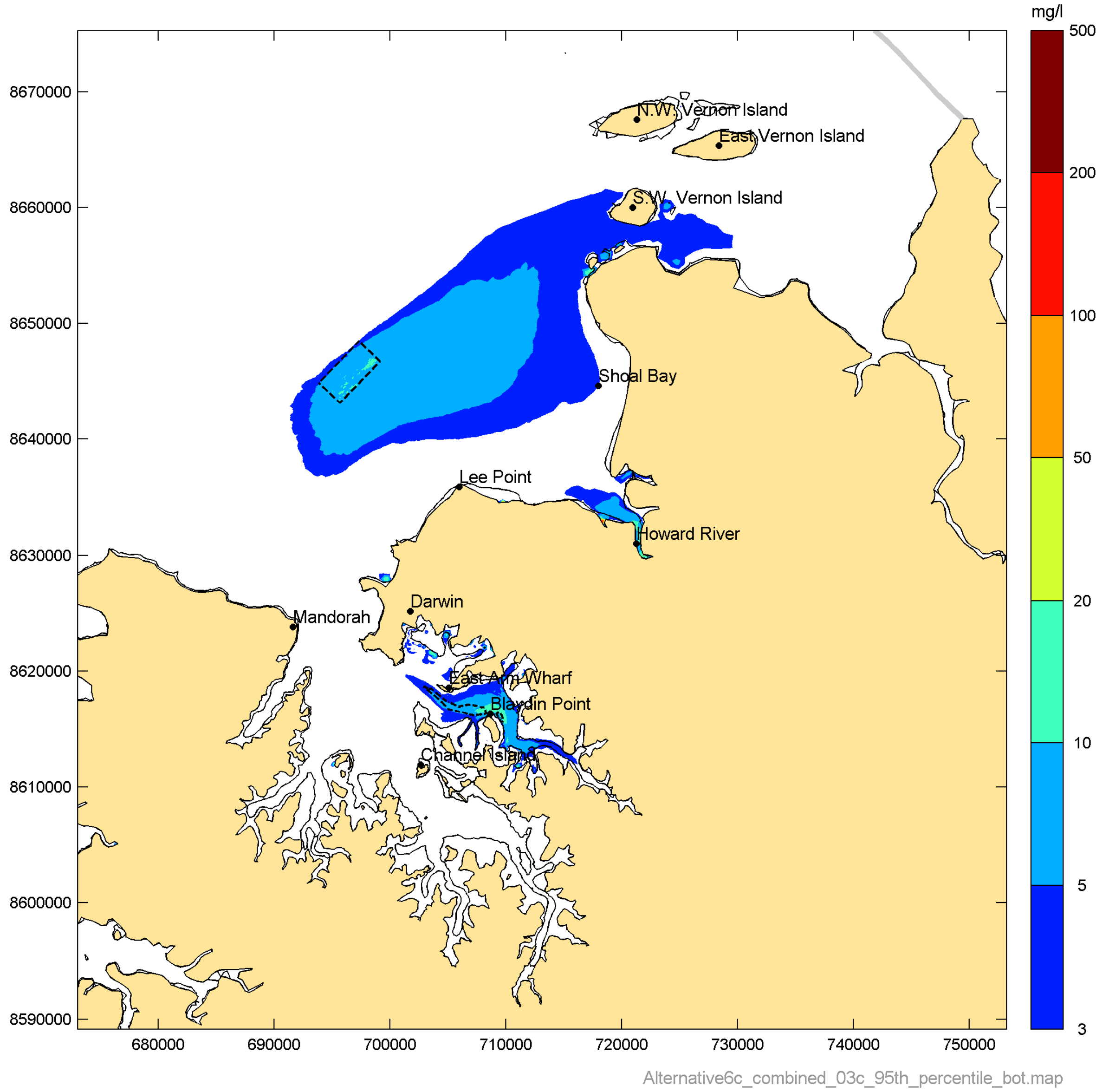


Figure 107 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 3

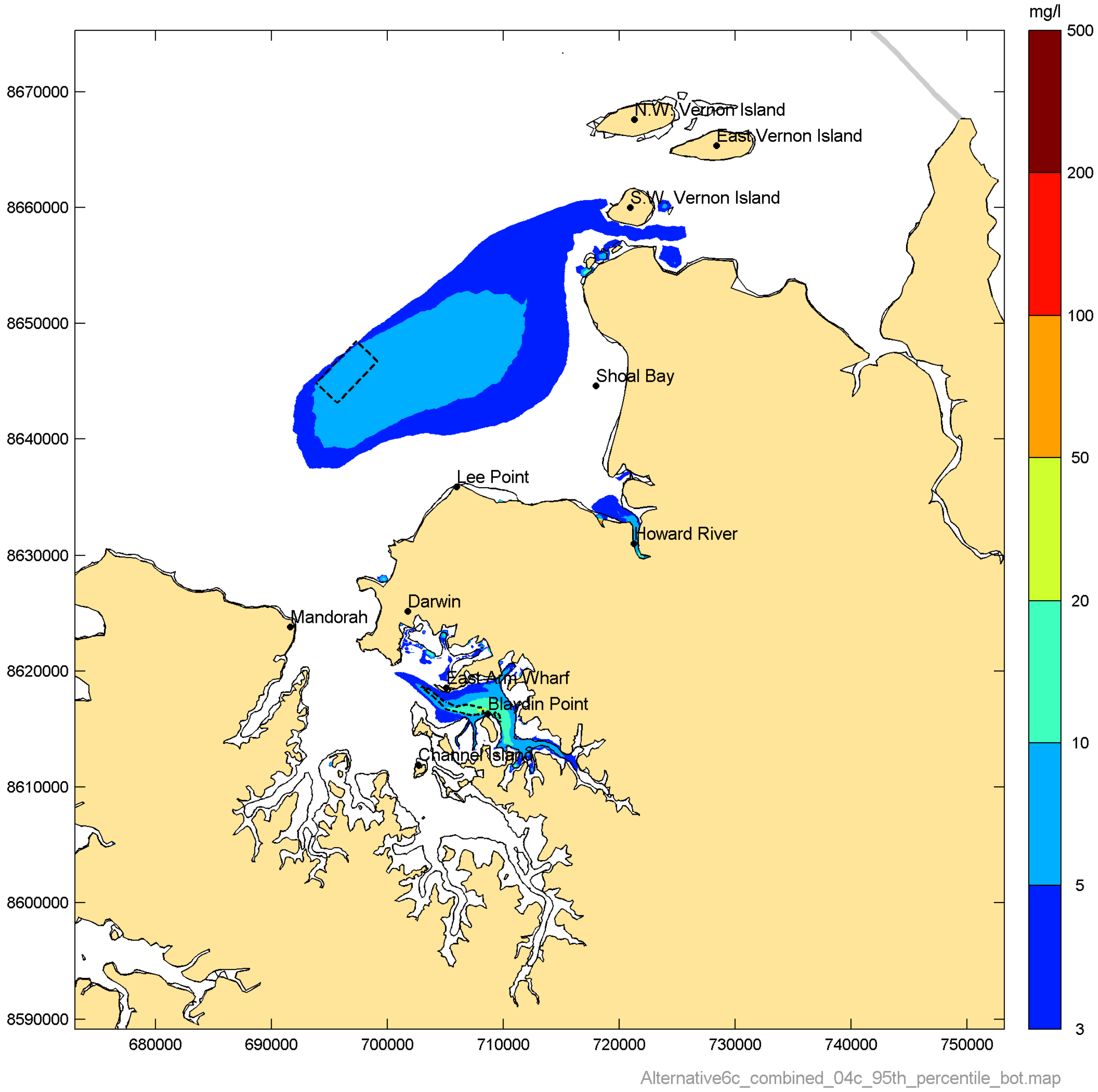


Figure 108 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 4

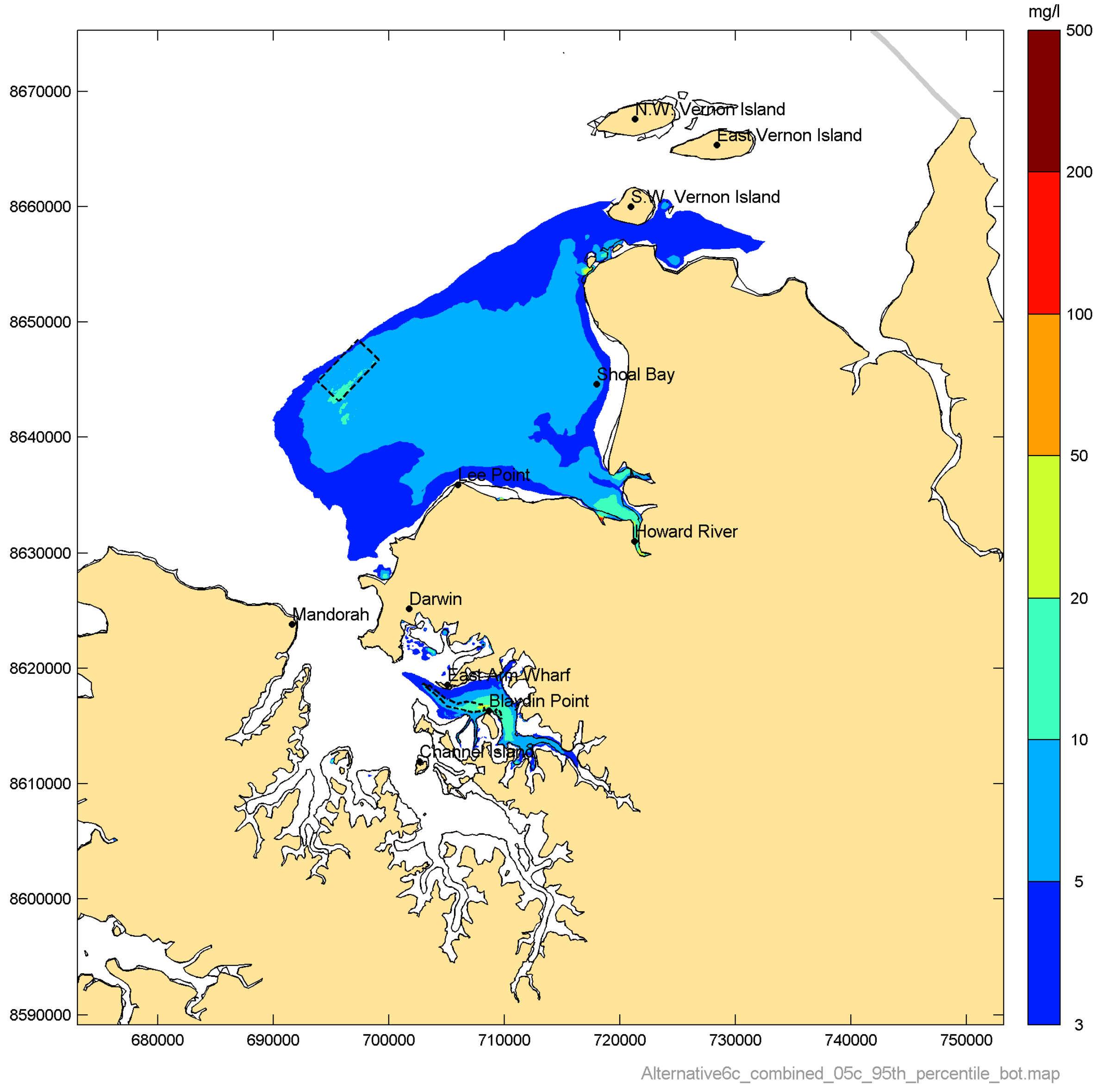


Figure 109 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 5

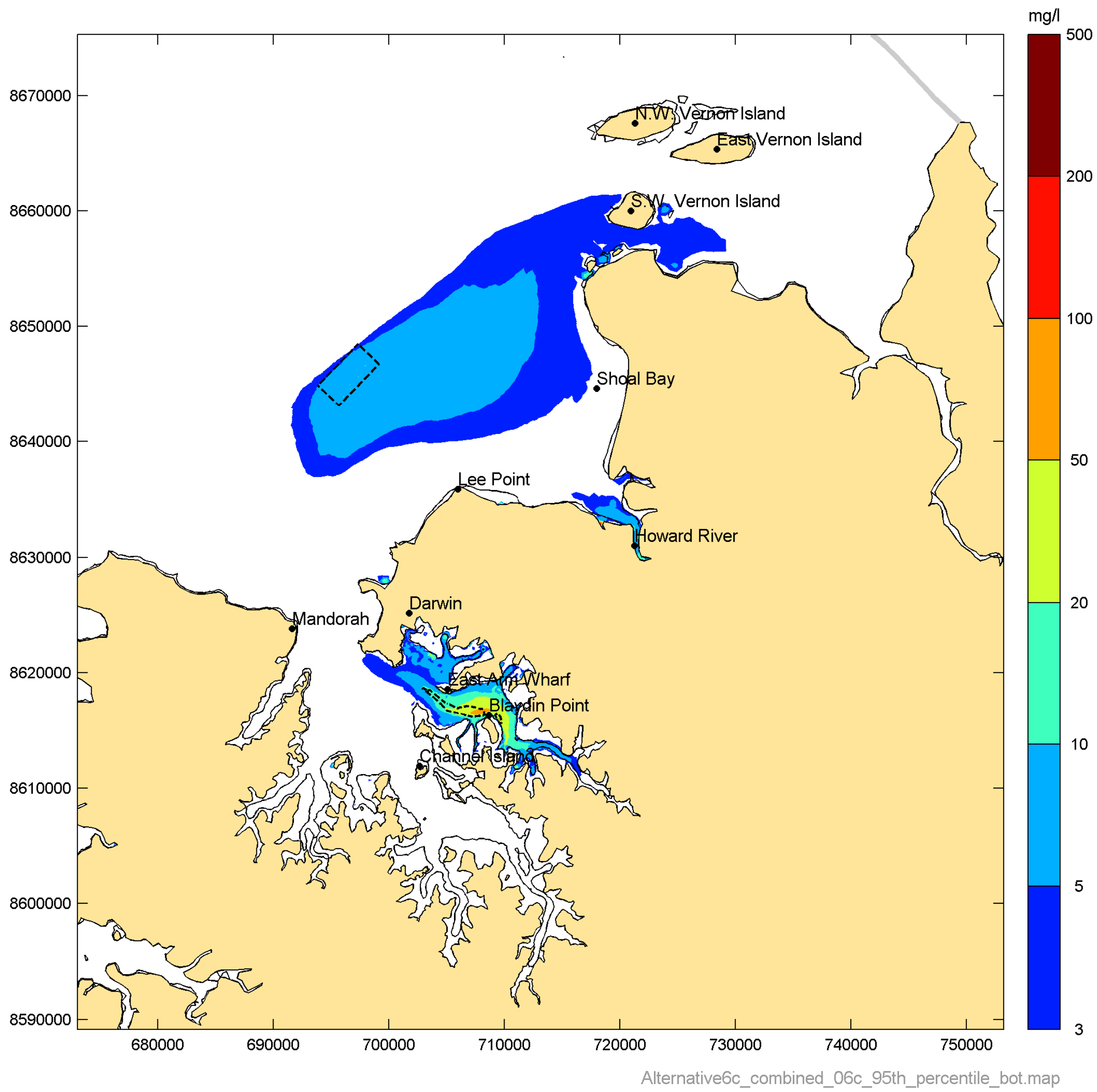


Figure 110 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 6

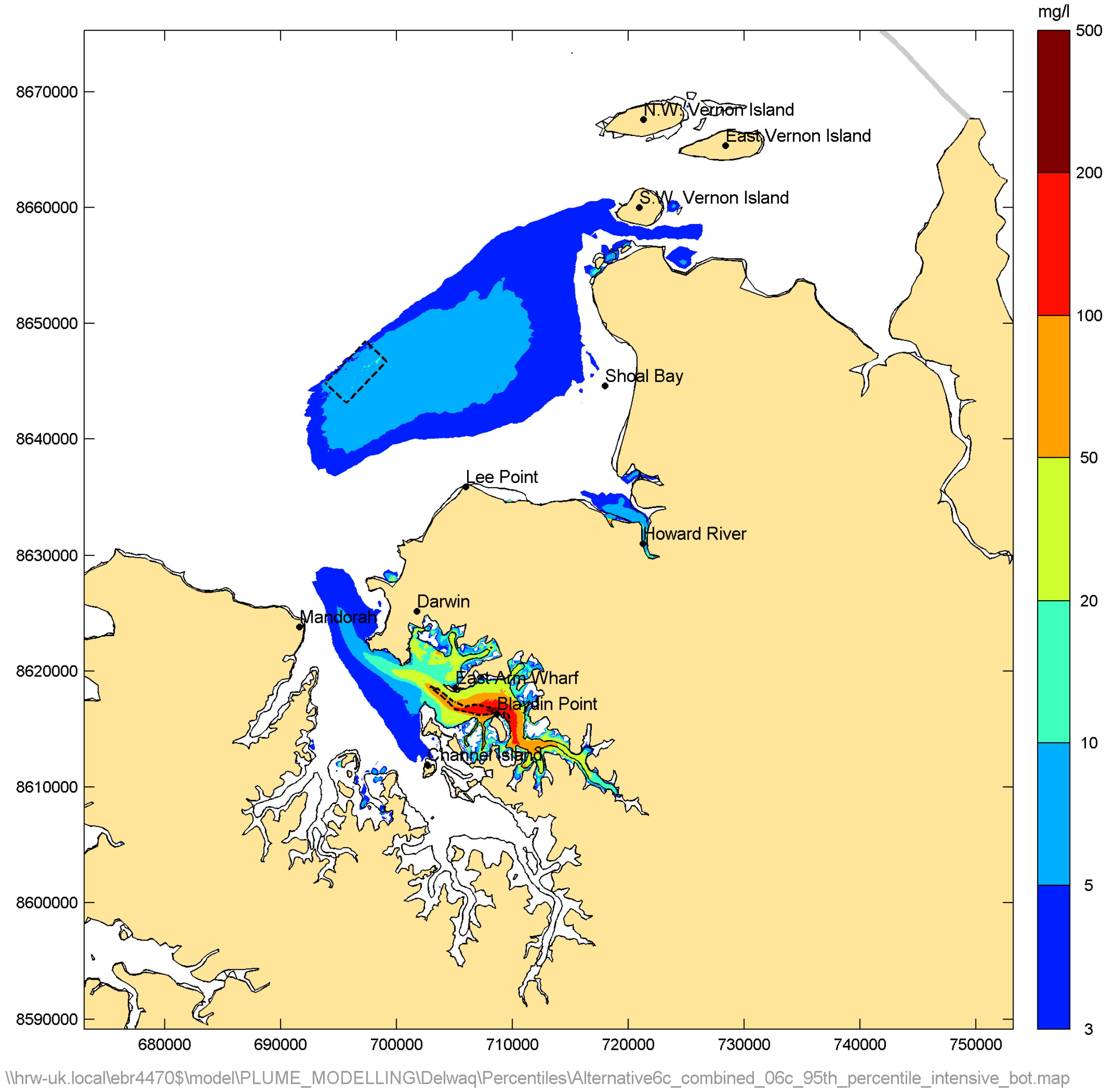


Figure 111 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 6 – cutter-suction dredger activity

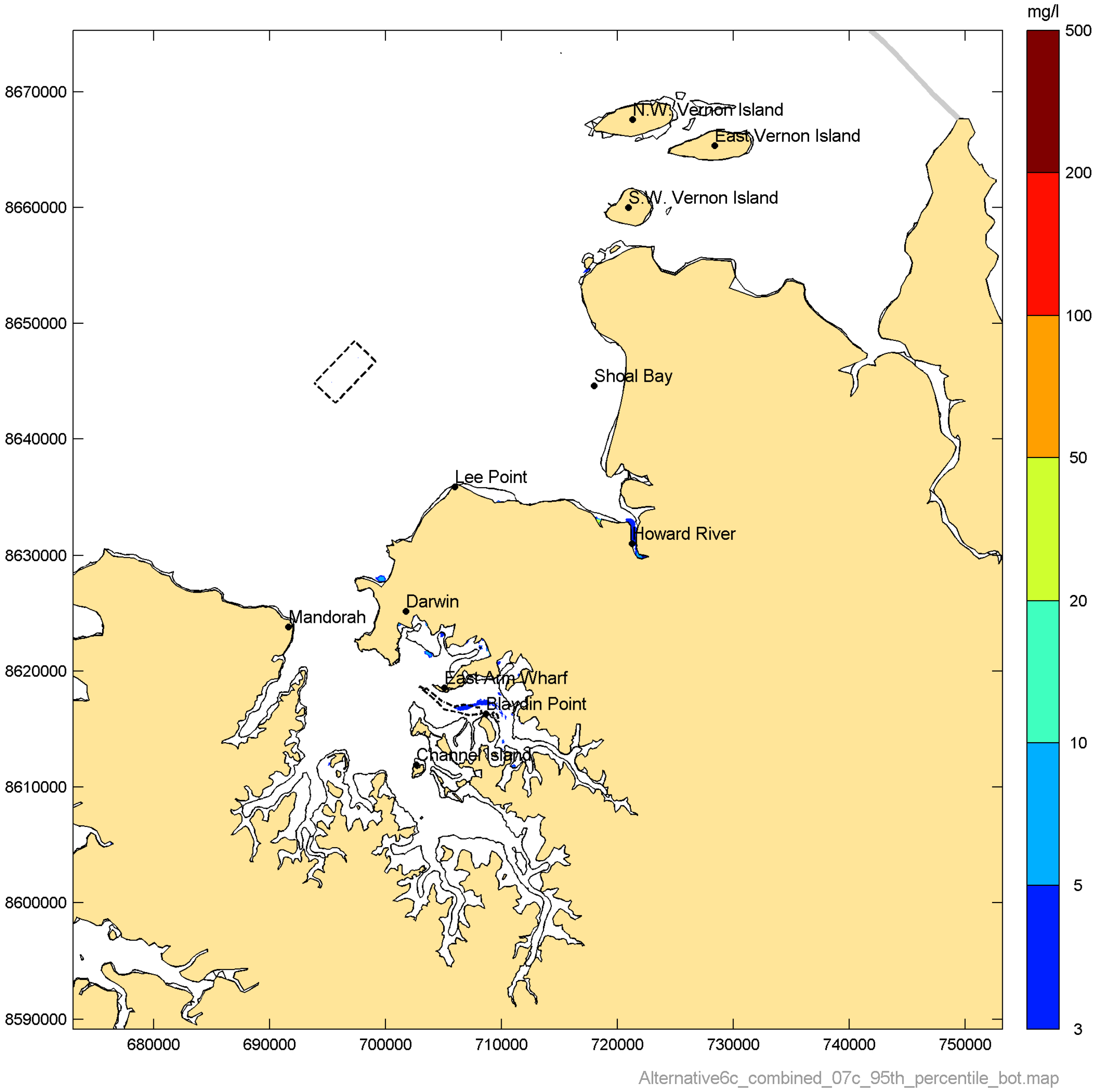


Figure 112 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 7

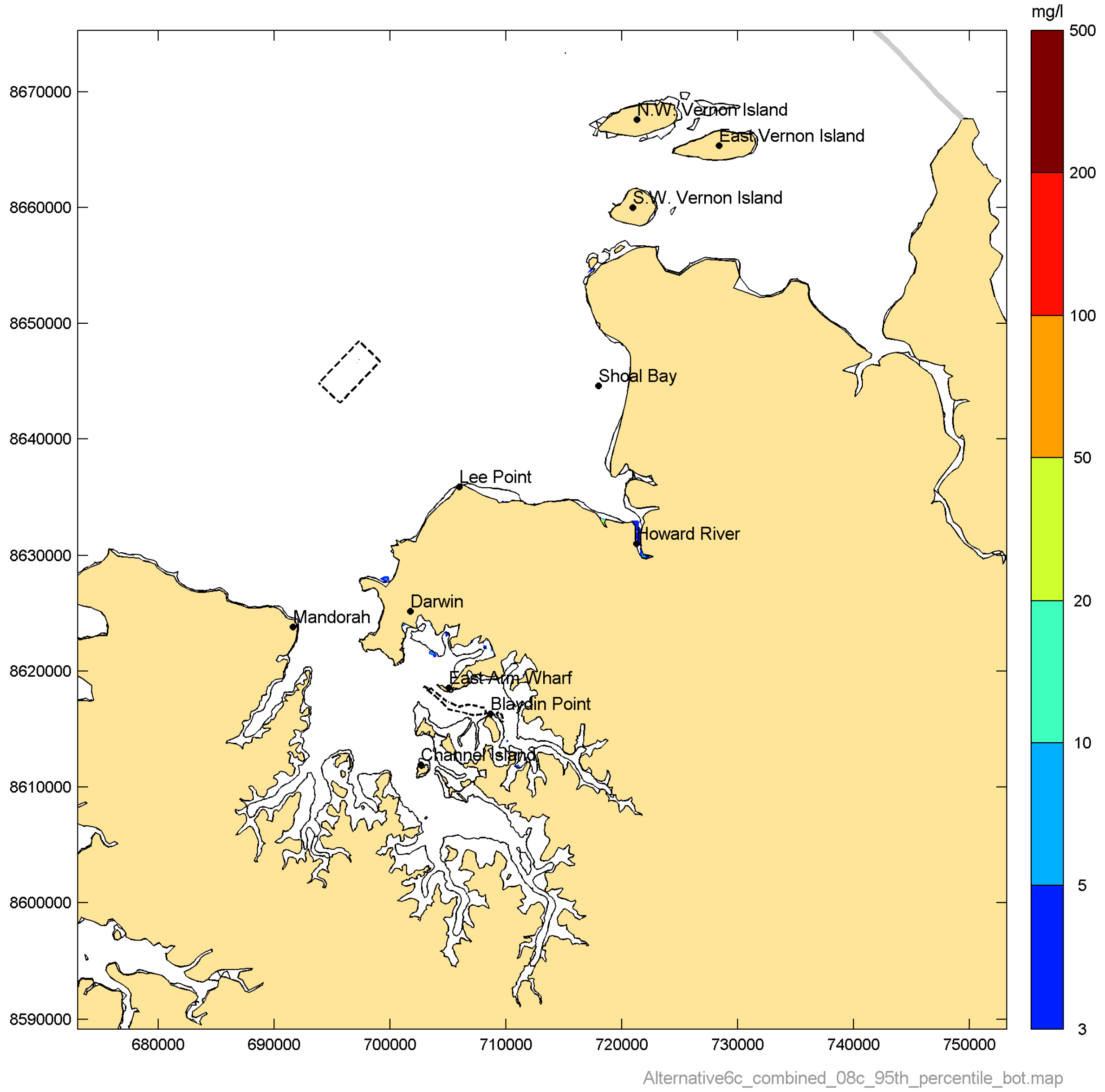


Figure 113 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 8

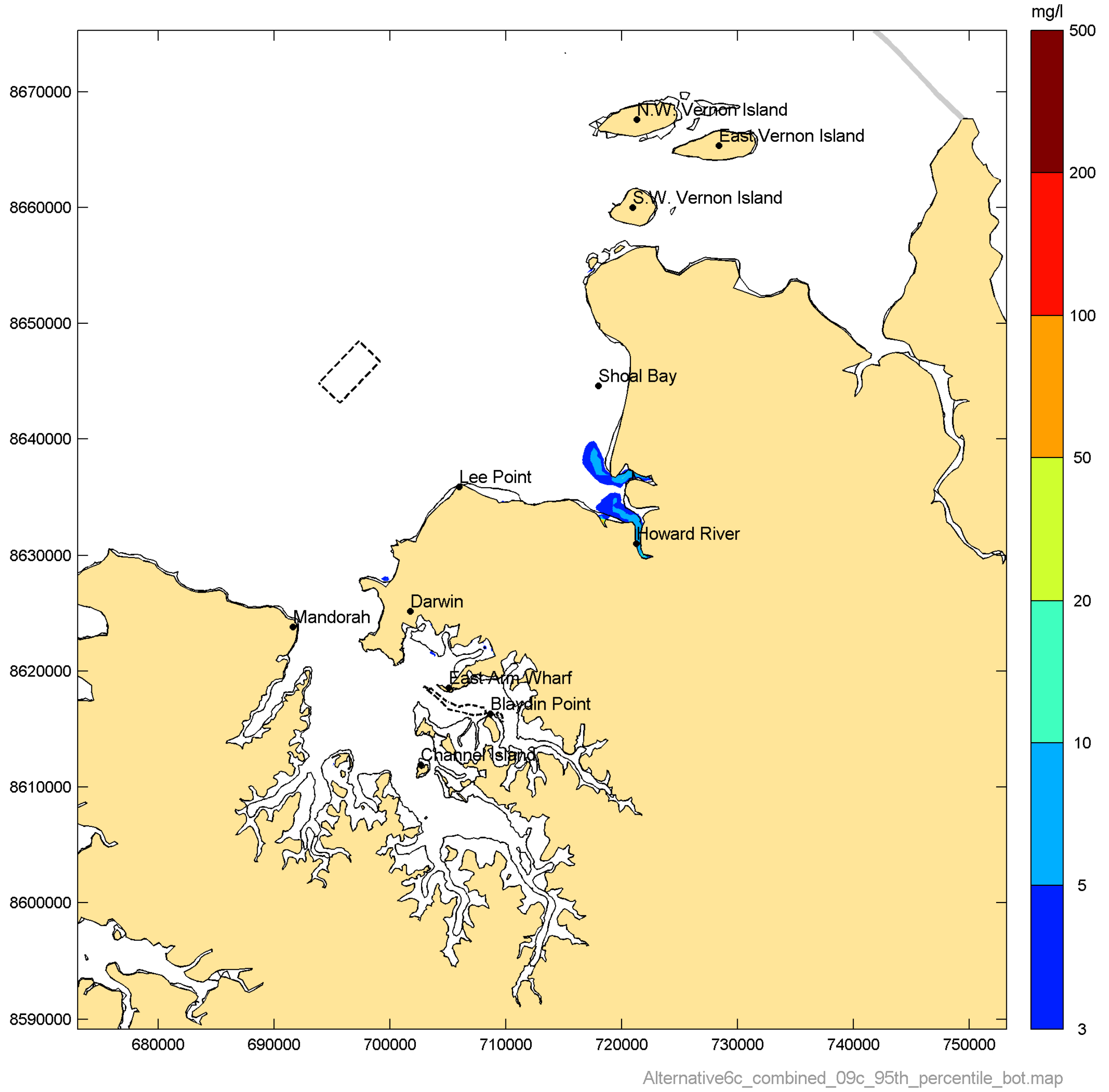


Figure 114 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 9

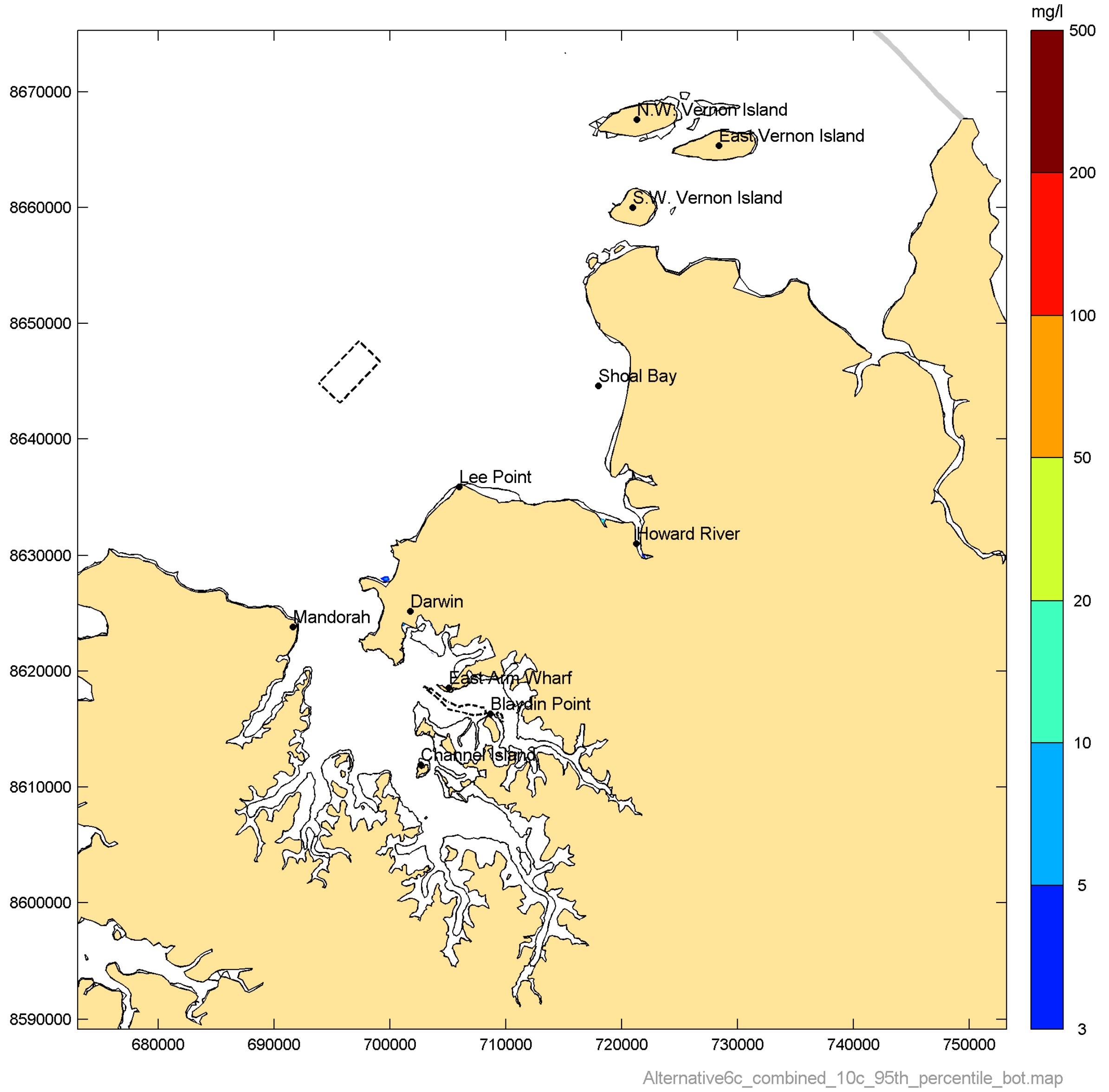


Figure 115 Simulated 95th percentile suspended sediment concentrations in the vicinity of Darwin Harbour for all dredging activities during Phase 10

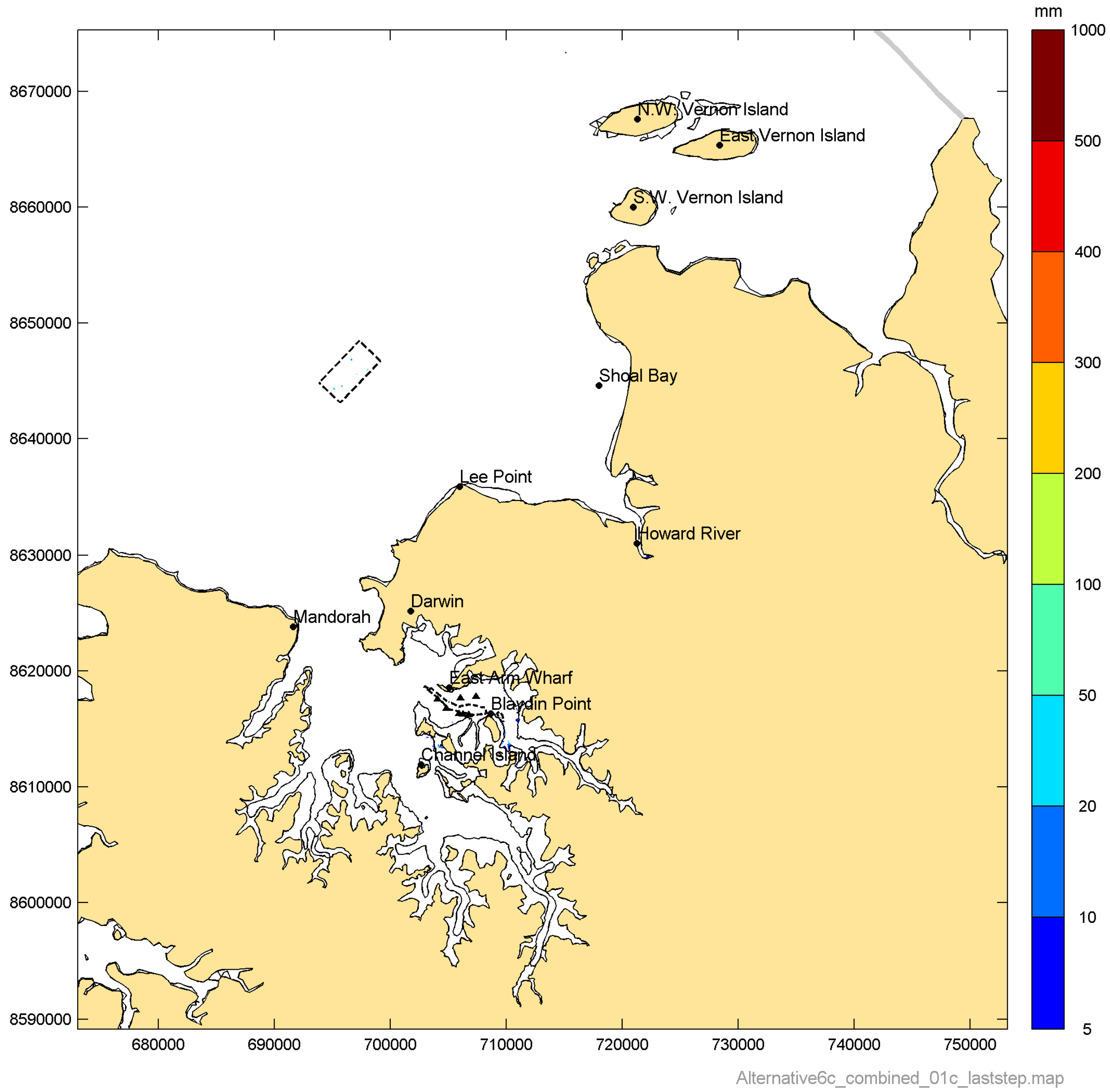


Figure 116 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 1

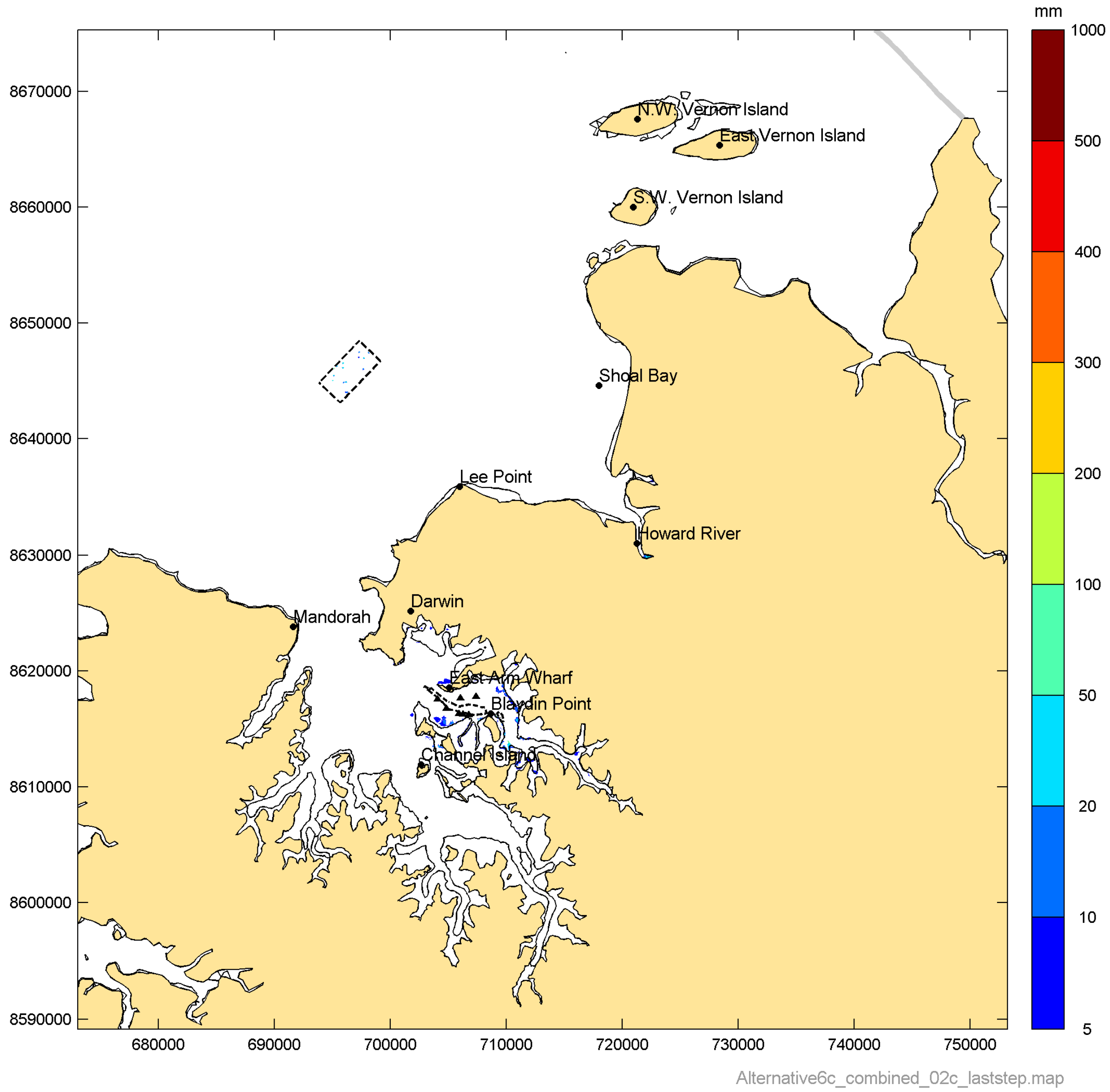


Figure 117 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 2

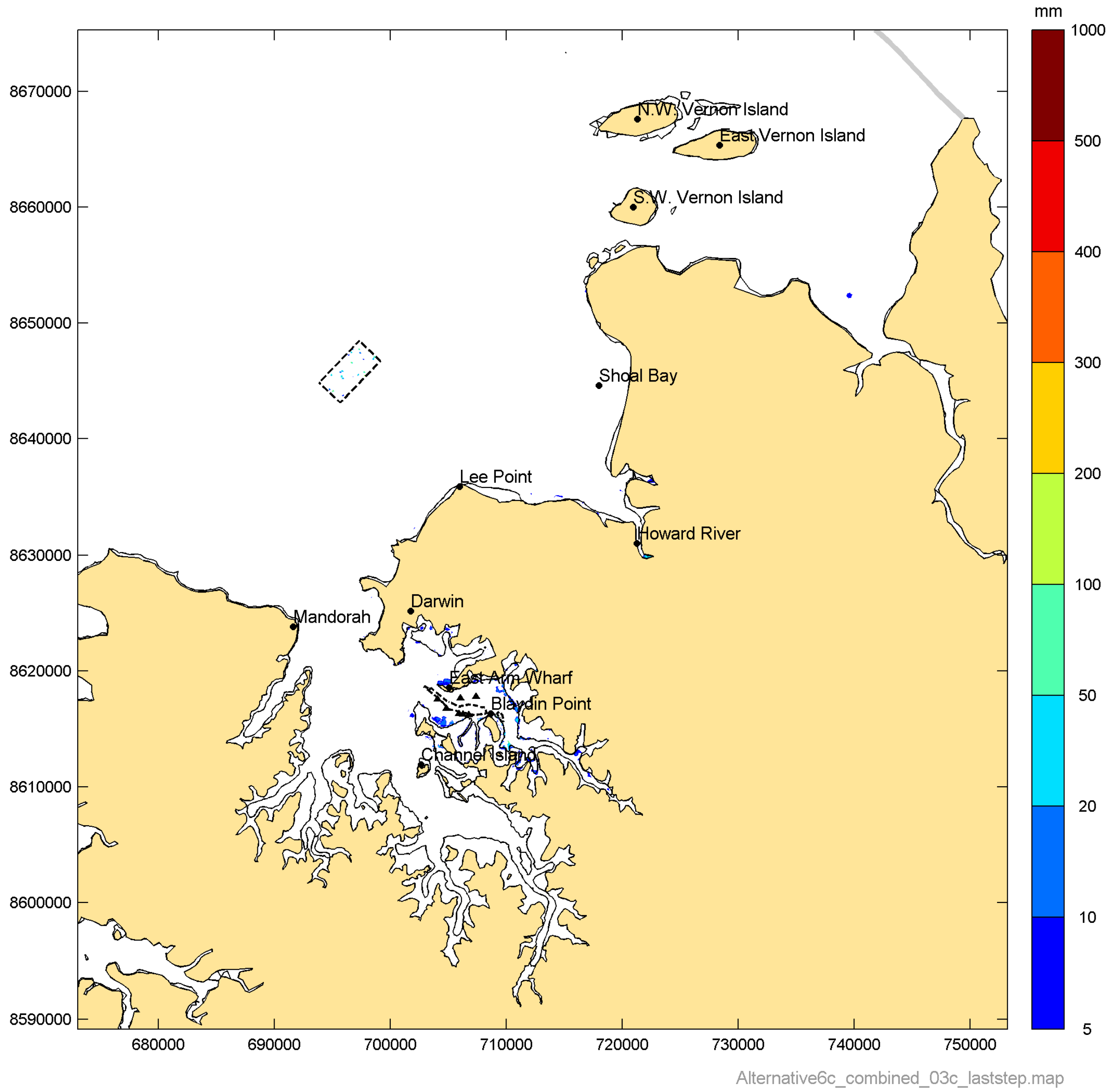


Figure 118 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 3

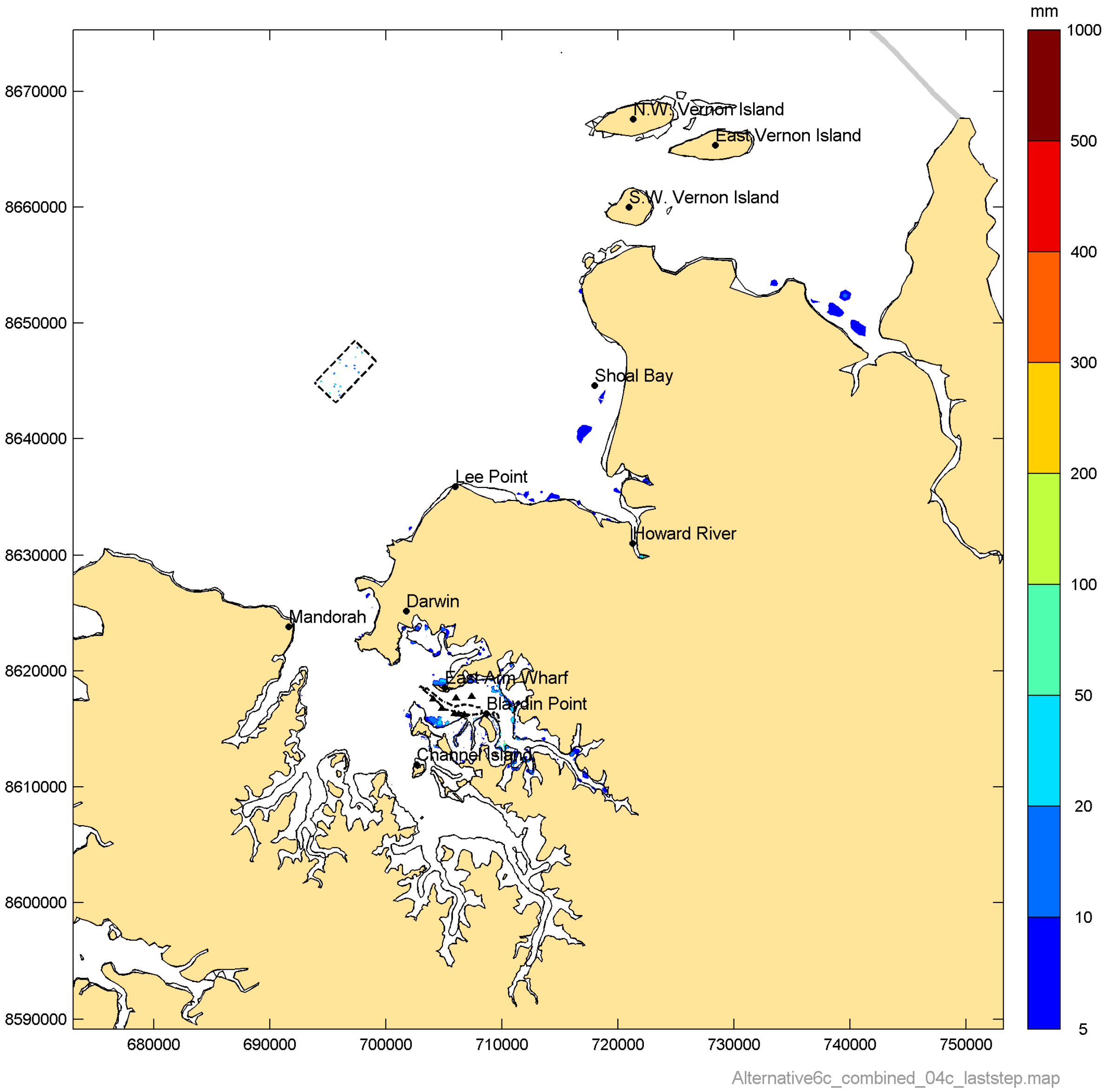


Figure 119 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 4

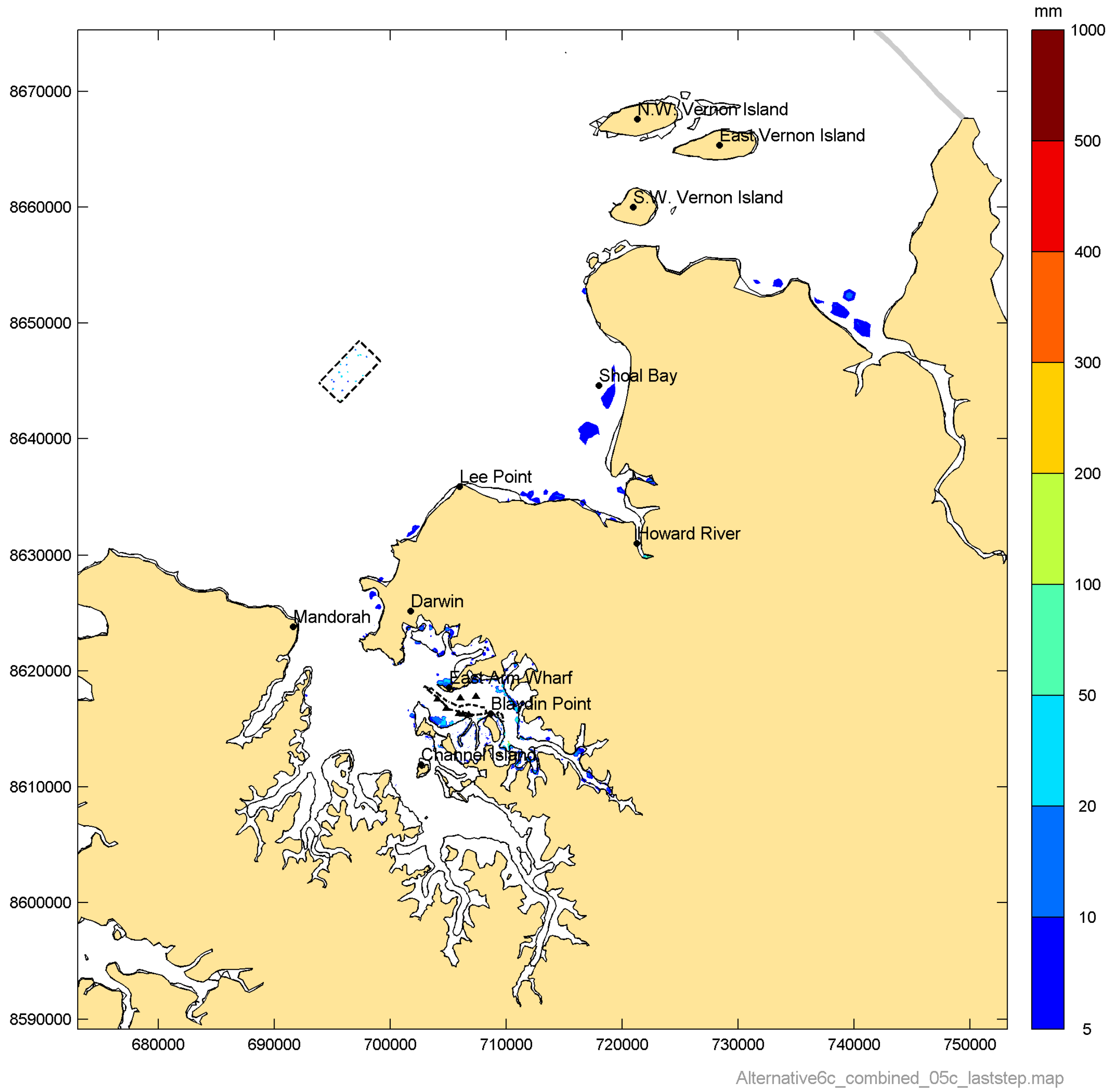


Figure 120 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 5

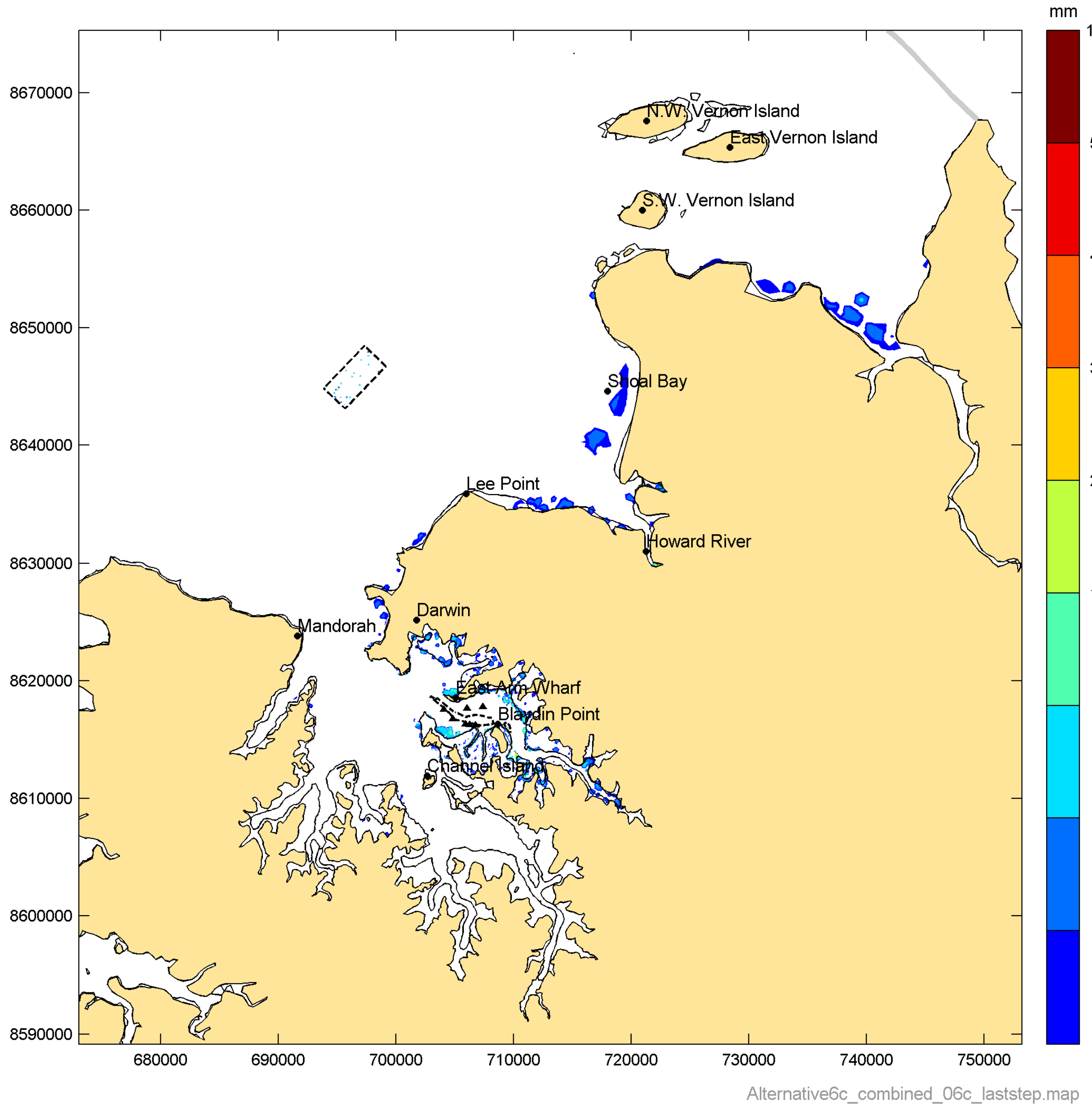


Figure 121 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 6

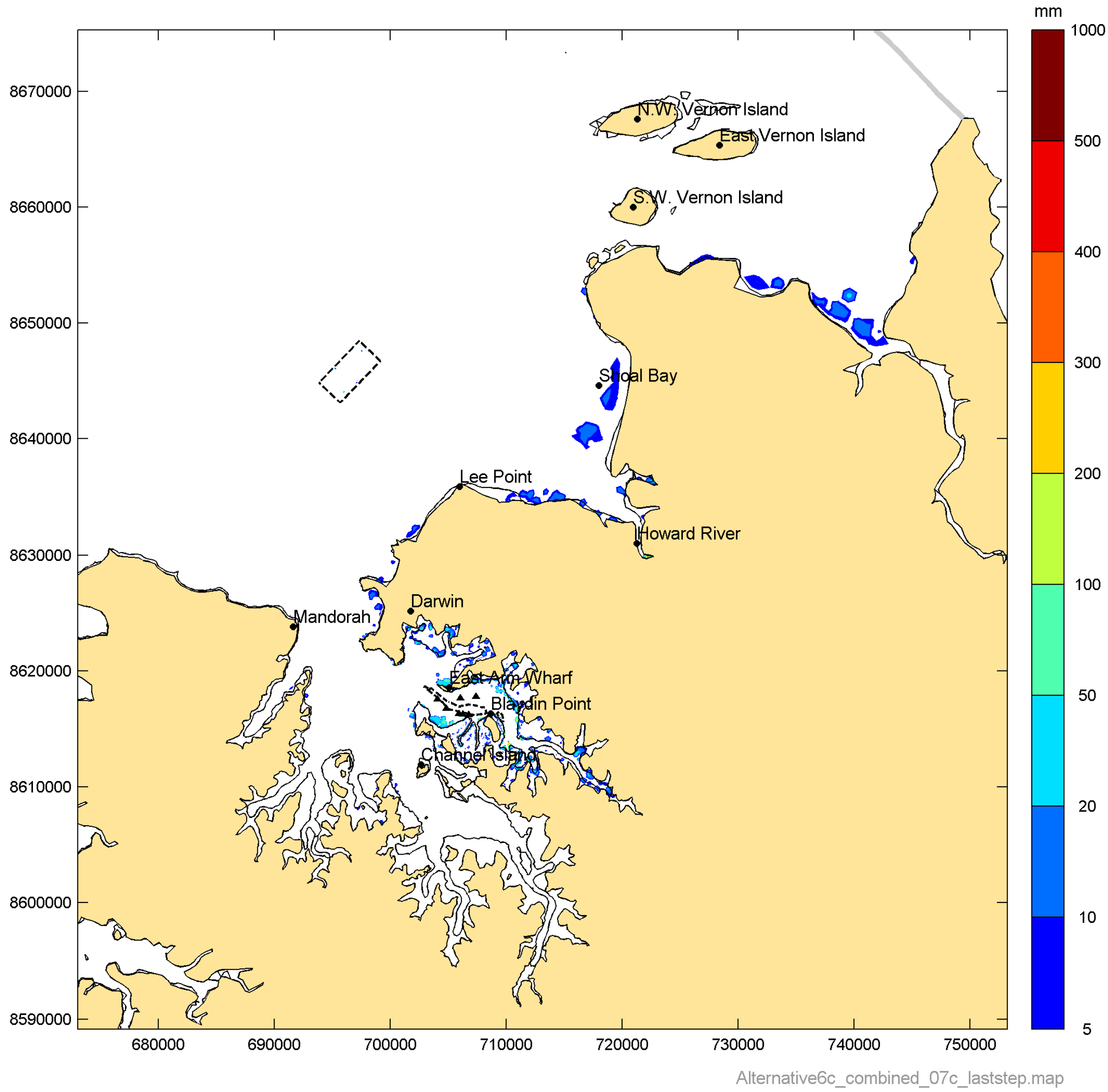


Figure 122 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 7

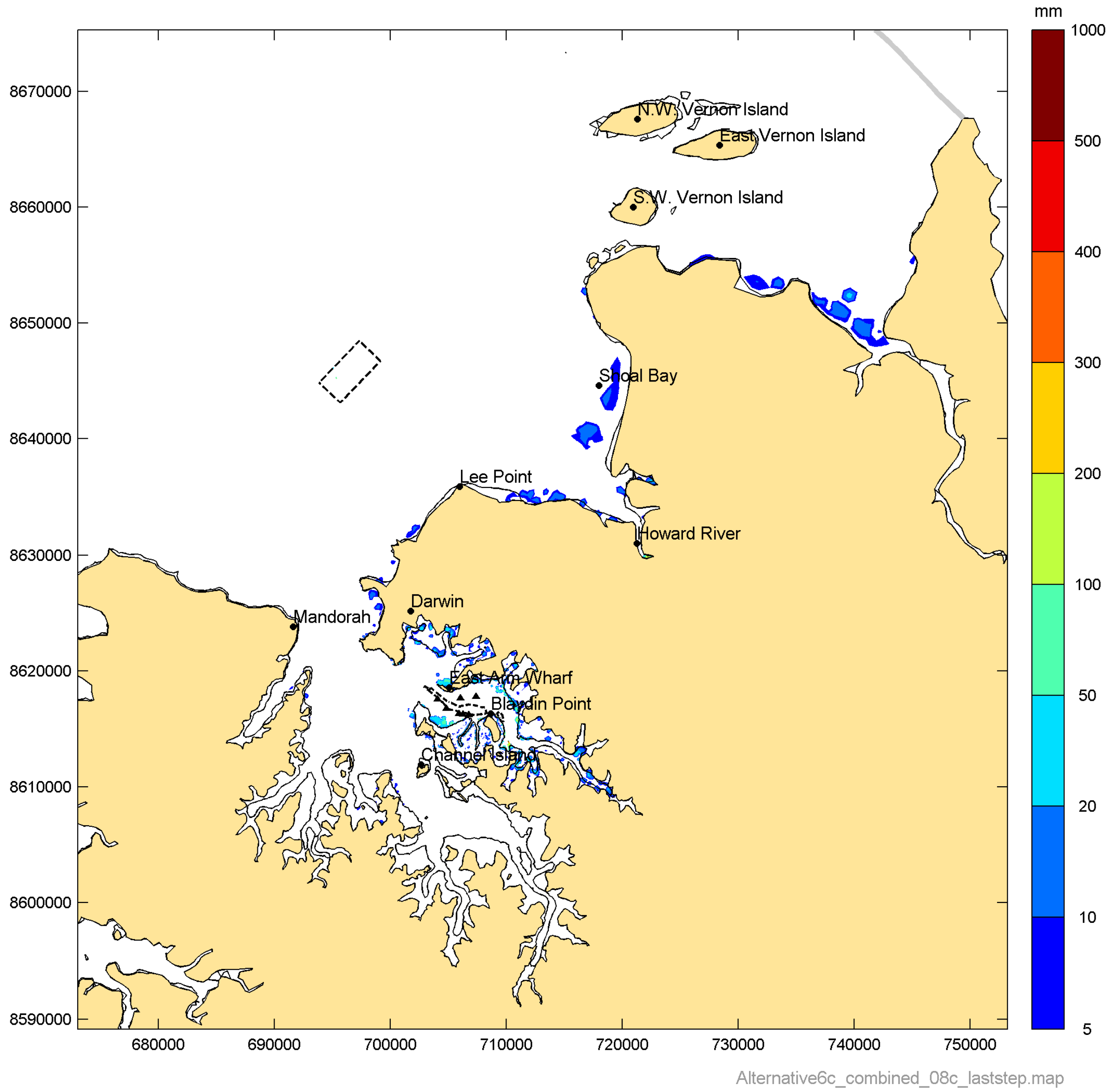


Figure 123 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 8

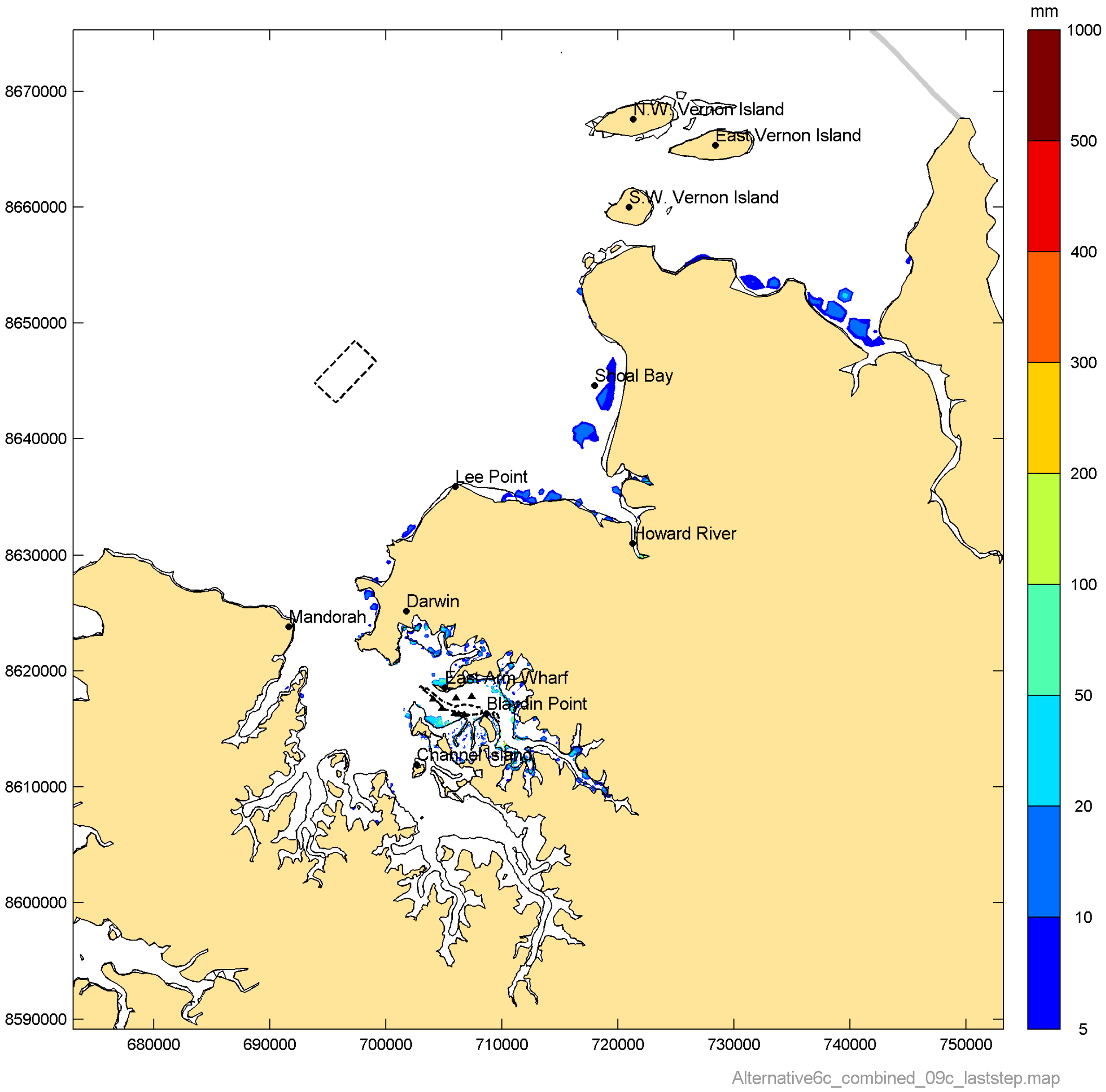


Figure 124 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 9

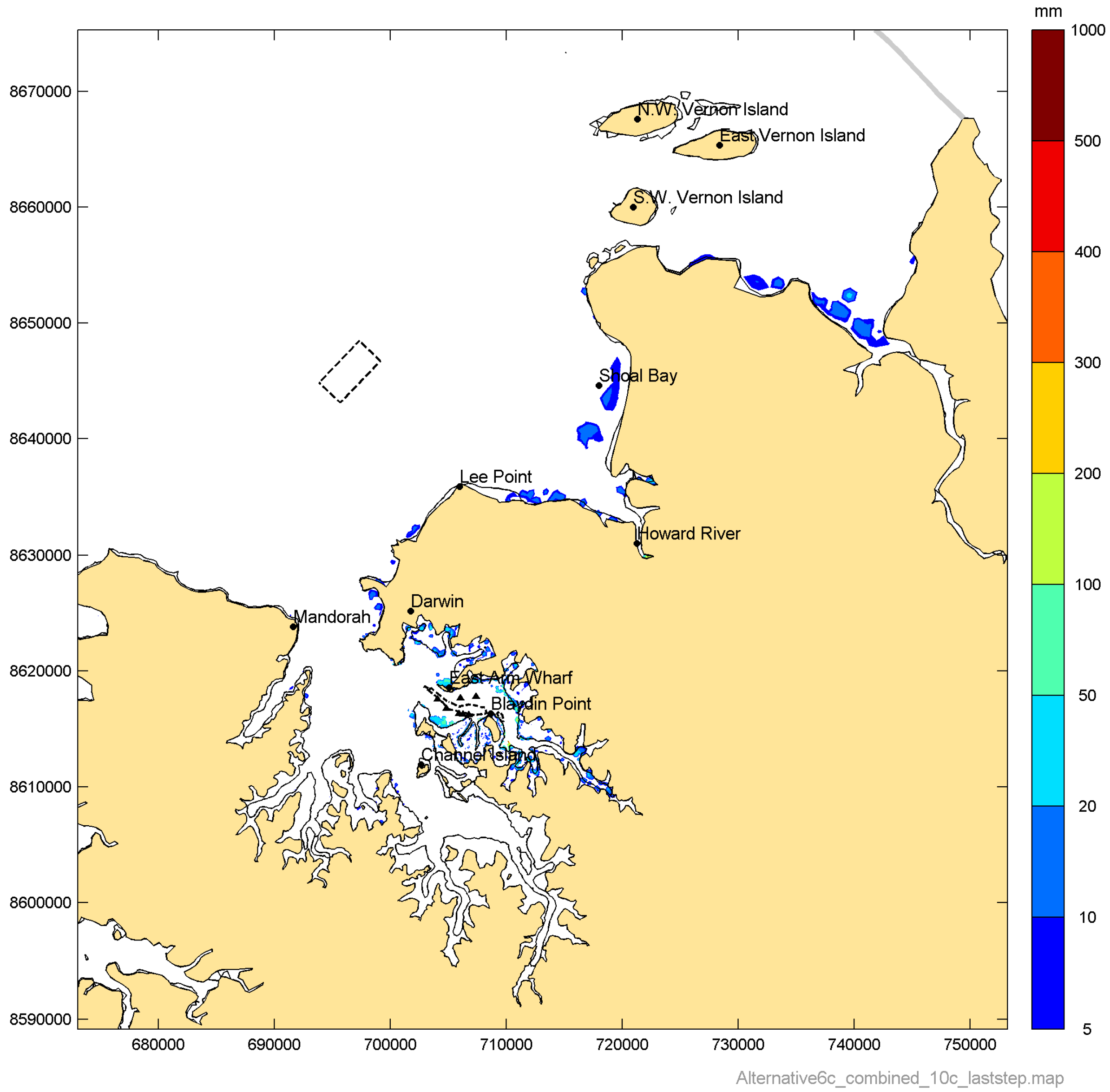


Figure 125 Simulated depth of fine sediment accretion in the vicinity of Darwin Harbour at the end of Phase 10

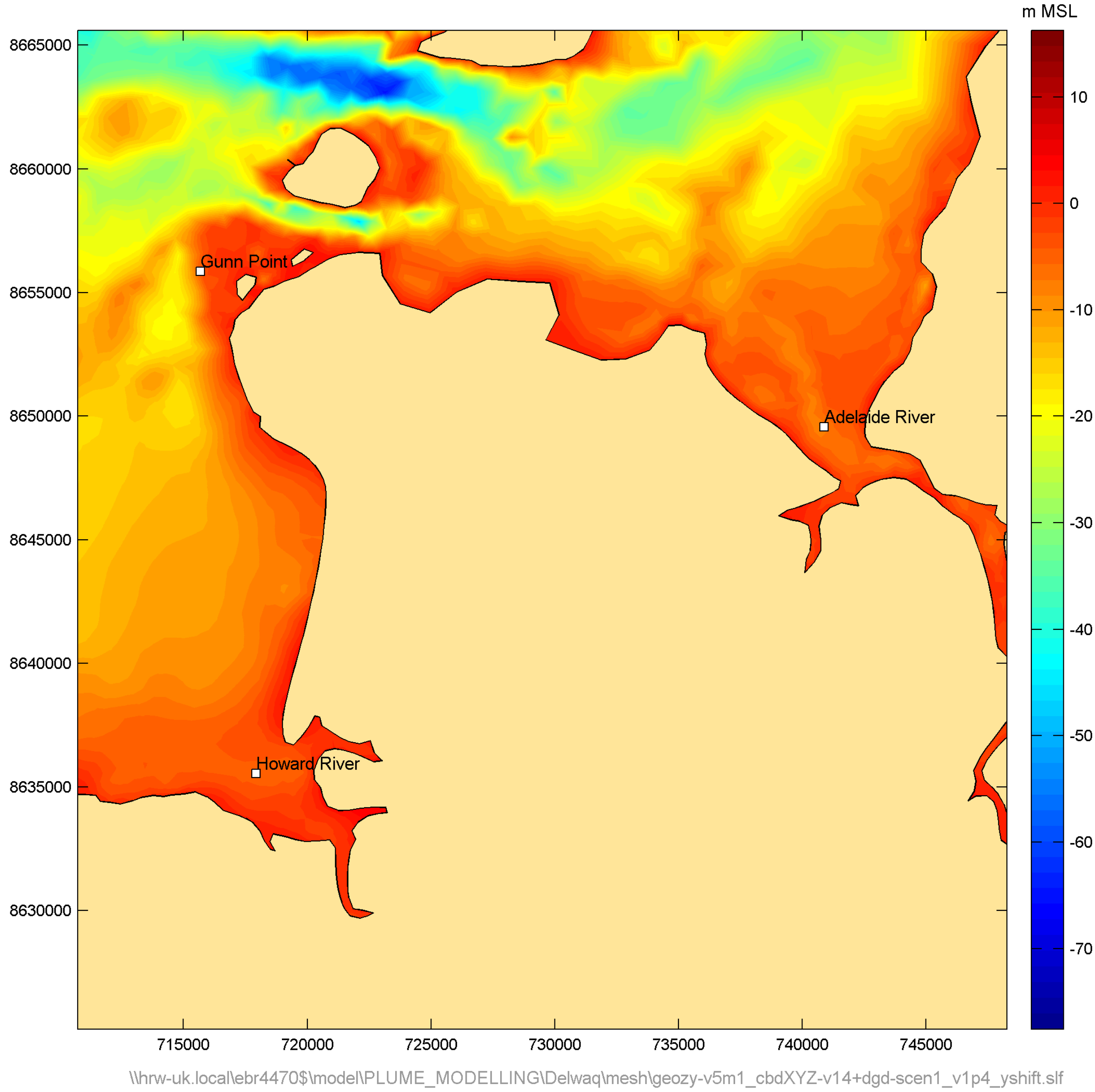


Figure 126 Locations used to extract time-series concentrations shown in Figure 127 to 129

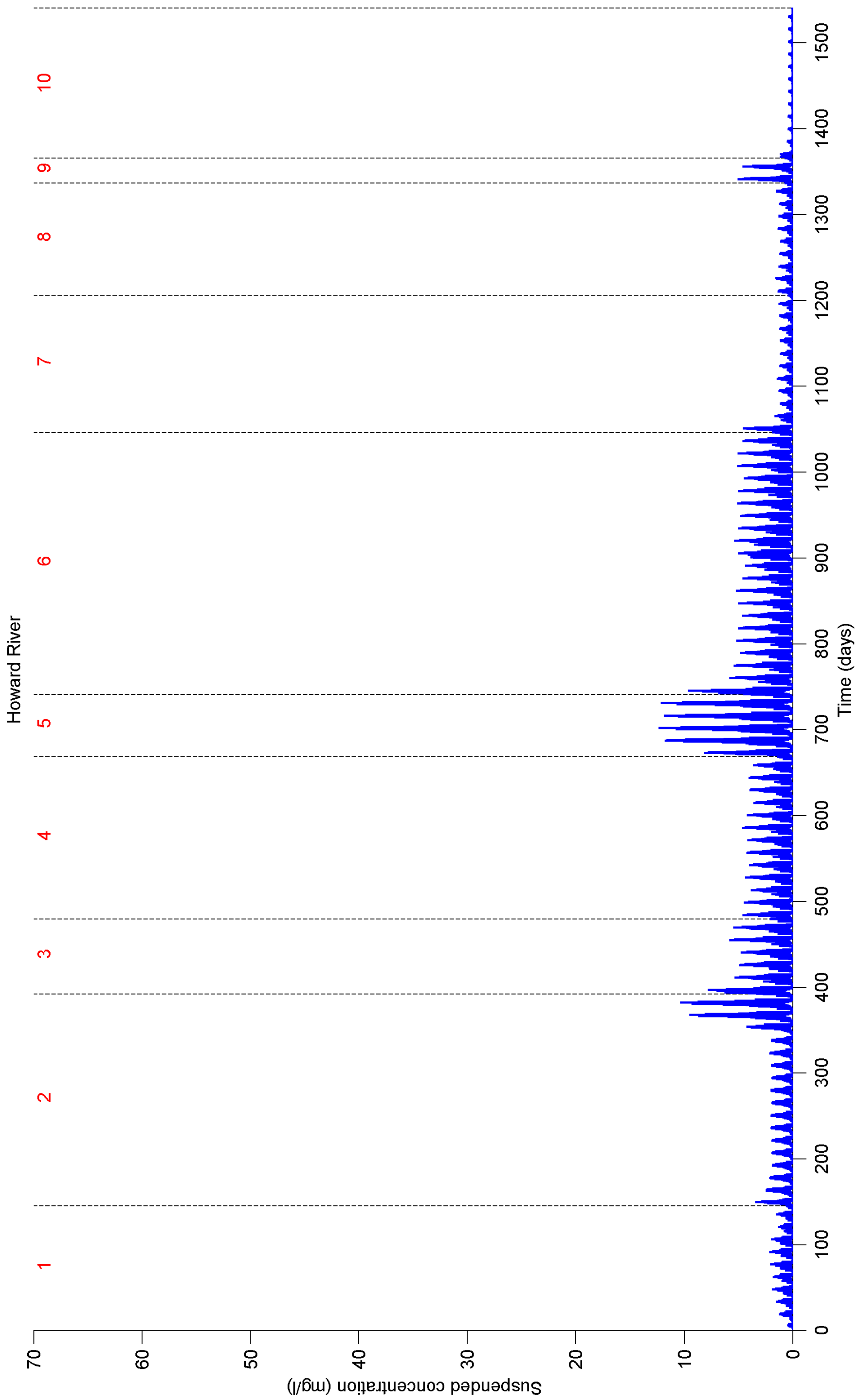


Figure 127 Time-series of simulated suspended sediment concentrations at the Howard River

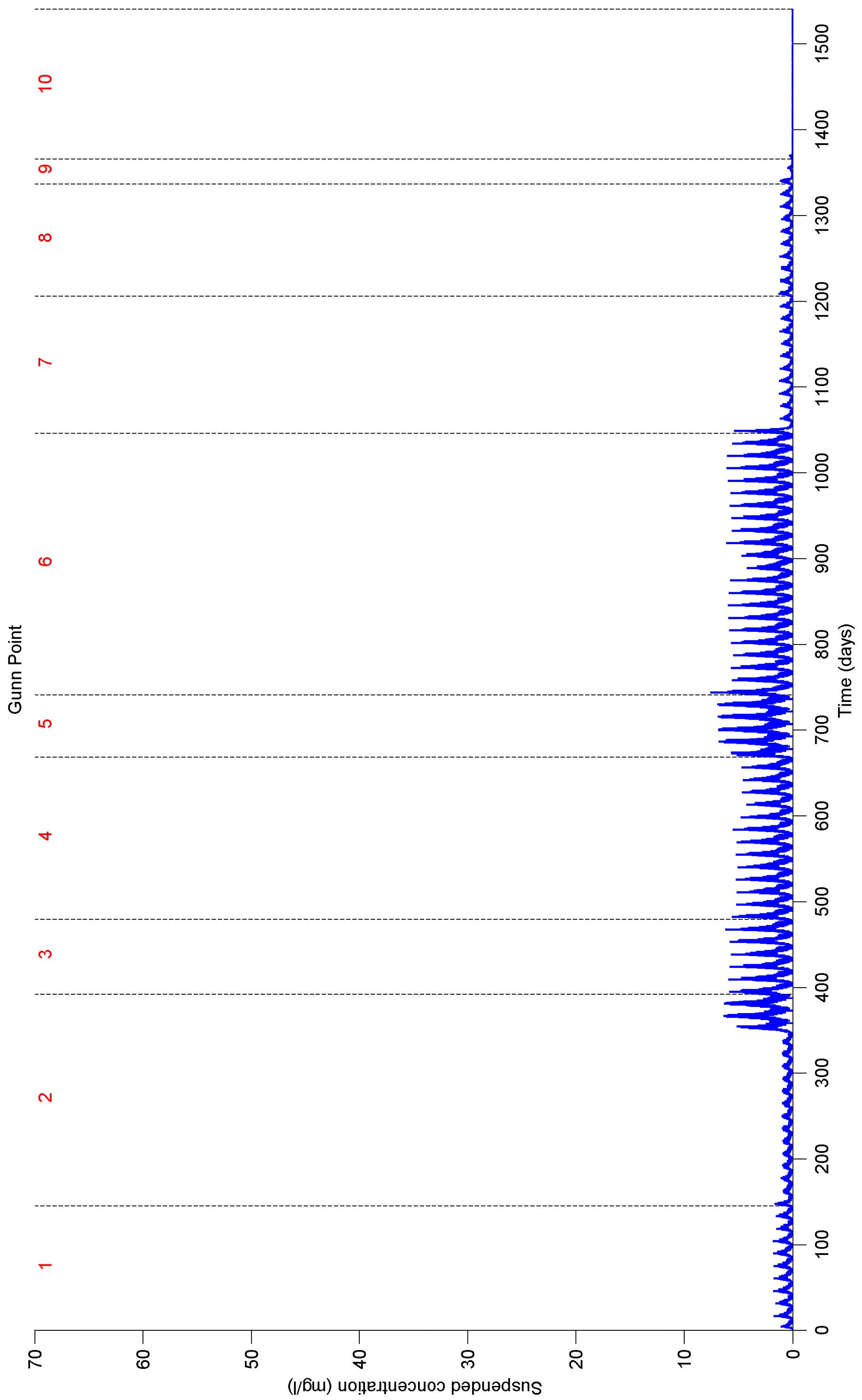


Figure 128 Time-series of simulated suspended sediment concentrations at Gunn Point

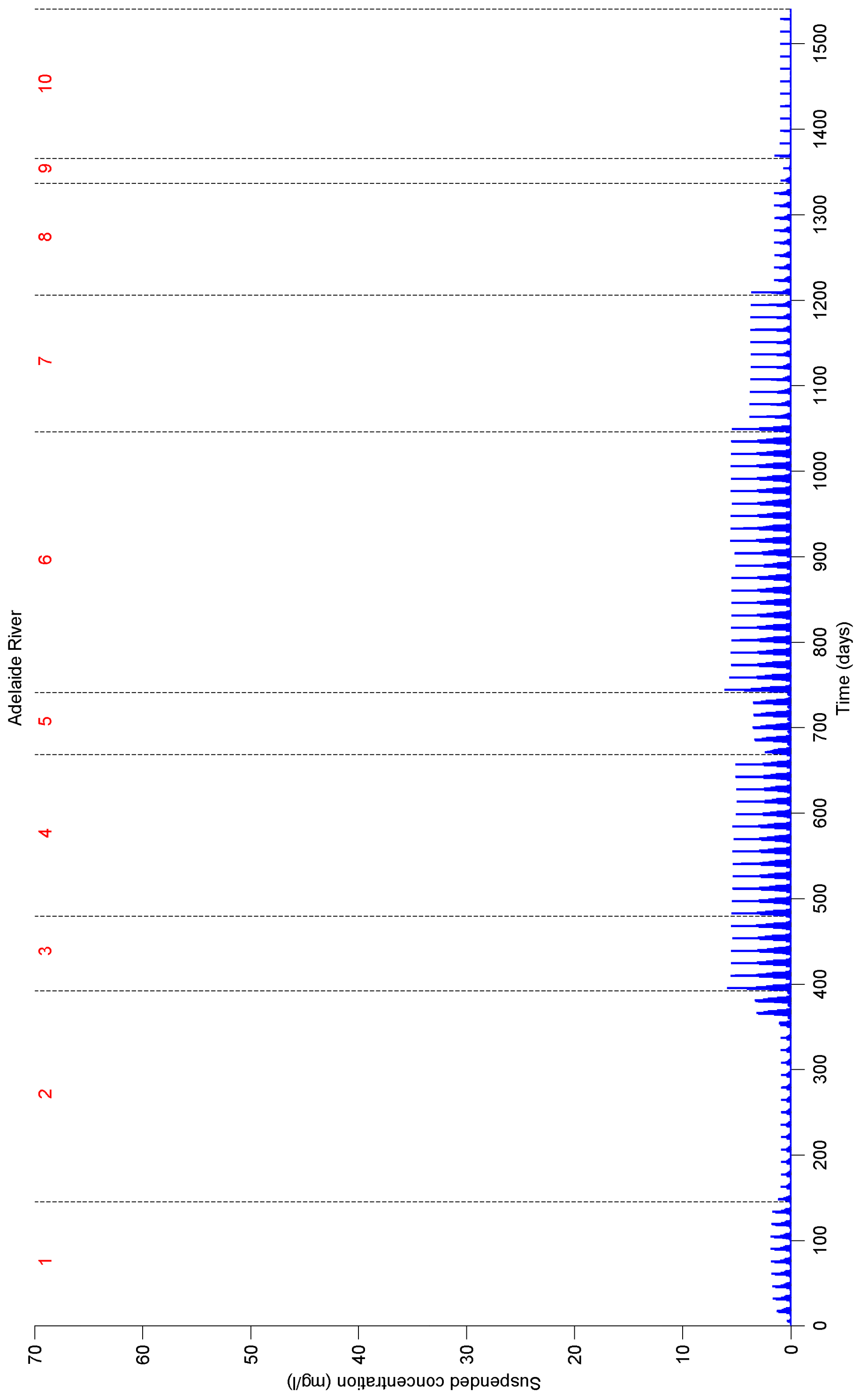


Figure 129 Time-series of simulated suspended sediment concentrations at the Adelaide River

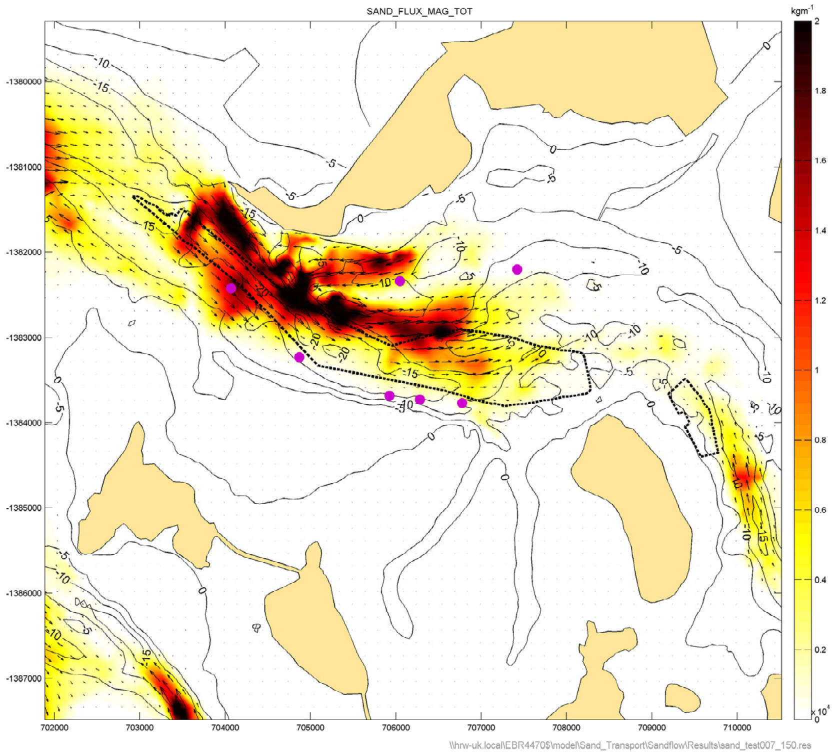


Figure 130 Net sand transport for spring-neap cycle 150 µm sand under tide-only conditions for predredge bathymetry

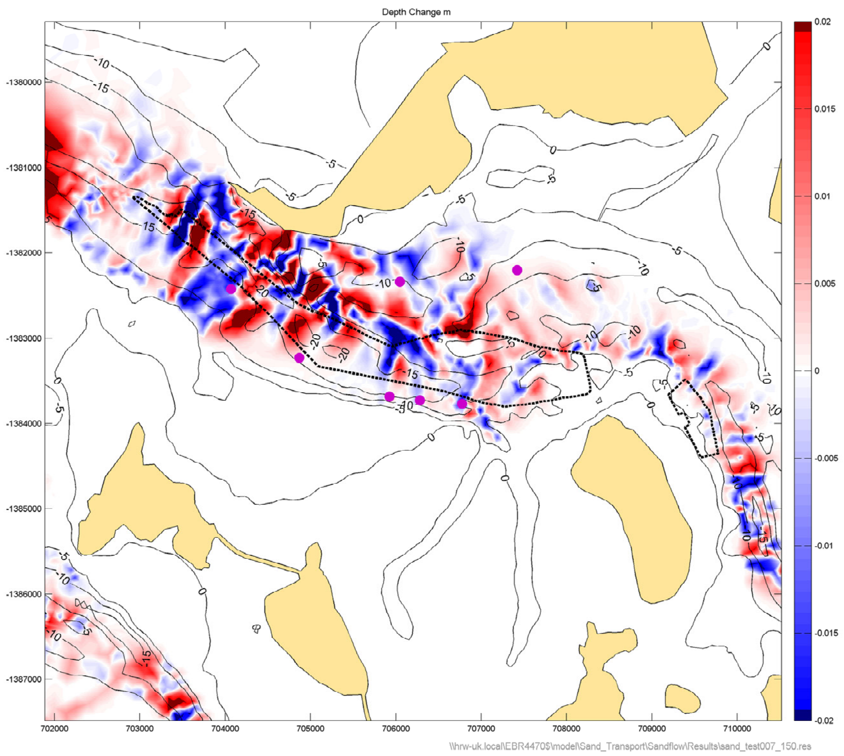


Figure 131 Indicative areas of net erosion and deposition for spring-neap cycle 150 µm sand under tide-only conditions for predredge bathymetry

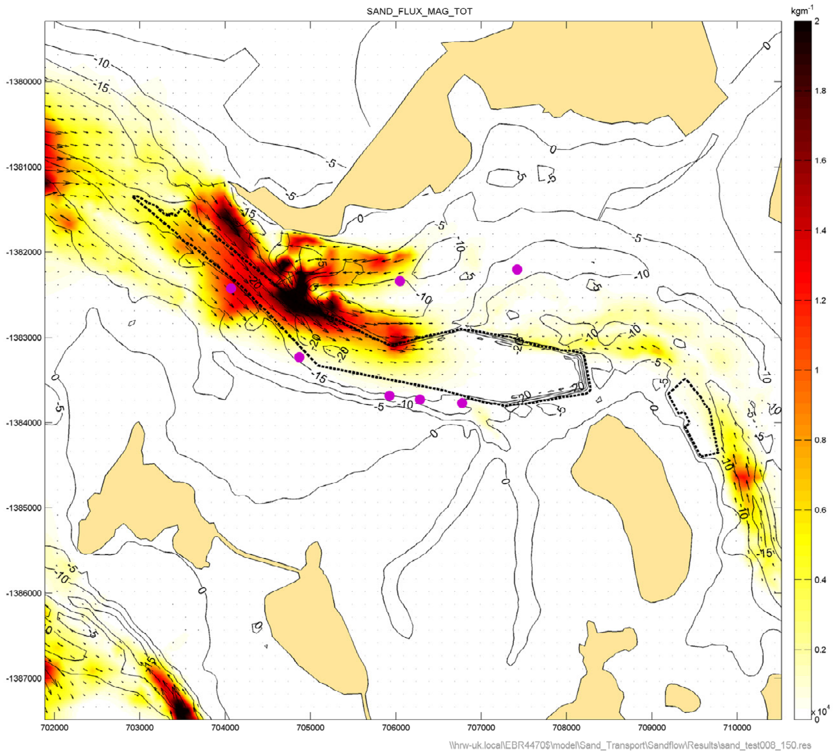


Figure 132 Net sand transport for spring-neap cycle 150 µm sand under tide-only conditions for postdredge bathymetry

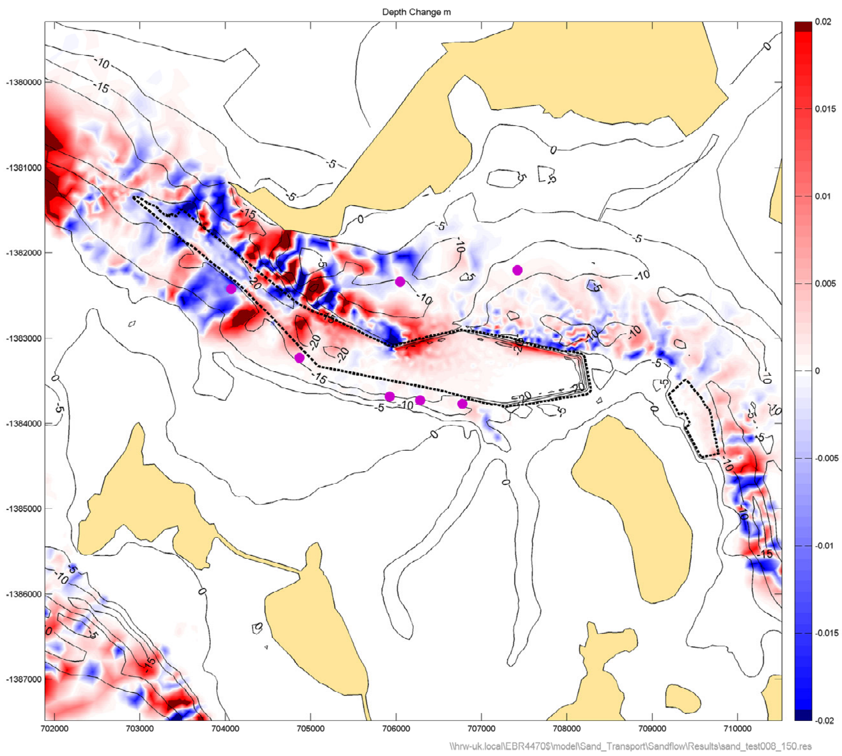


Figure 133 Indicative areas of net erosion and deposition for spring-neap cycle 150 µm sand under tide-only conditions for postdredge bathymetry

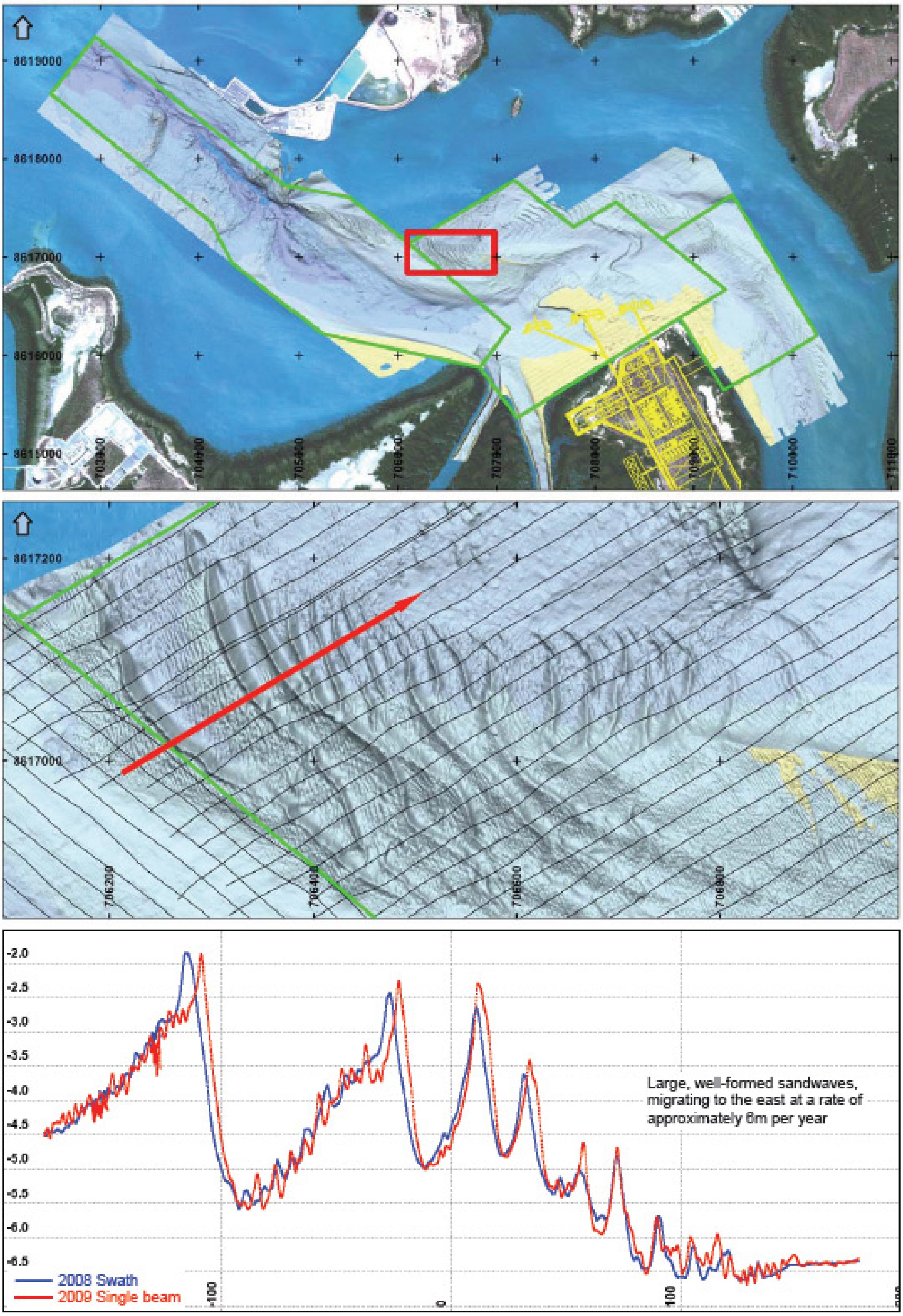


Figure 134 Observed Sandwaves and migration path within East Arm

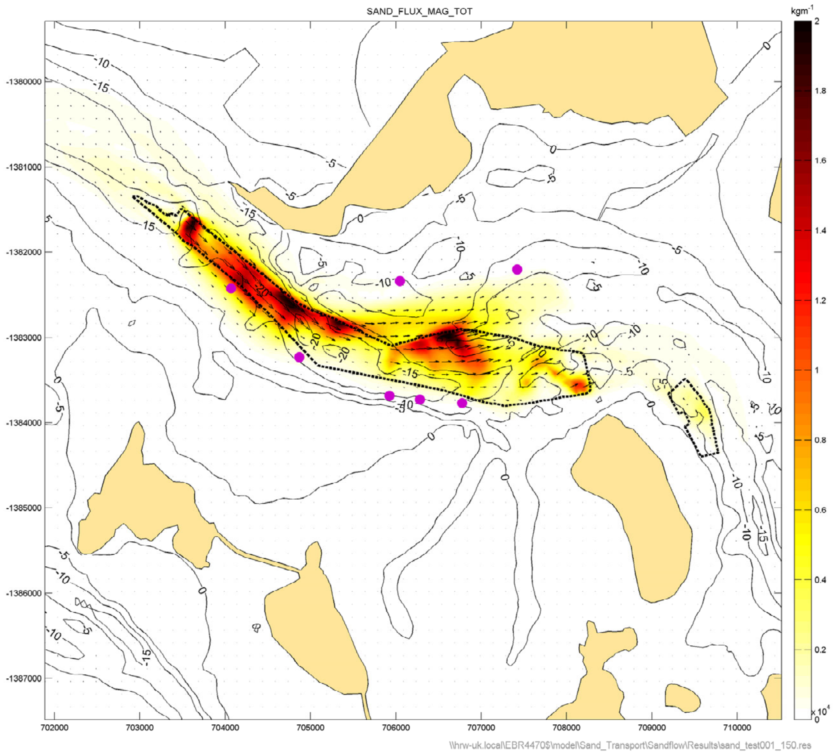


Figure 135 Net sand transport for spring-neap cycle 150 µm sand under tide-only conditions for predredge bathymetry (mobile material only within dredge footprint)

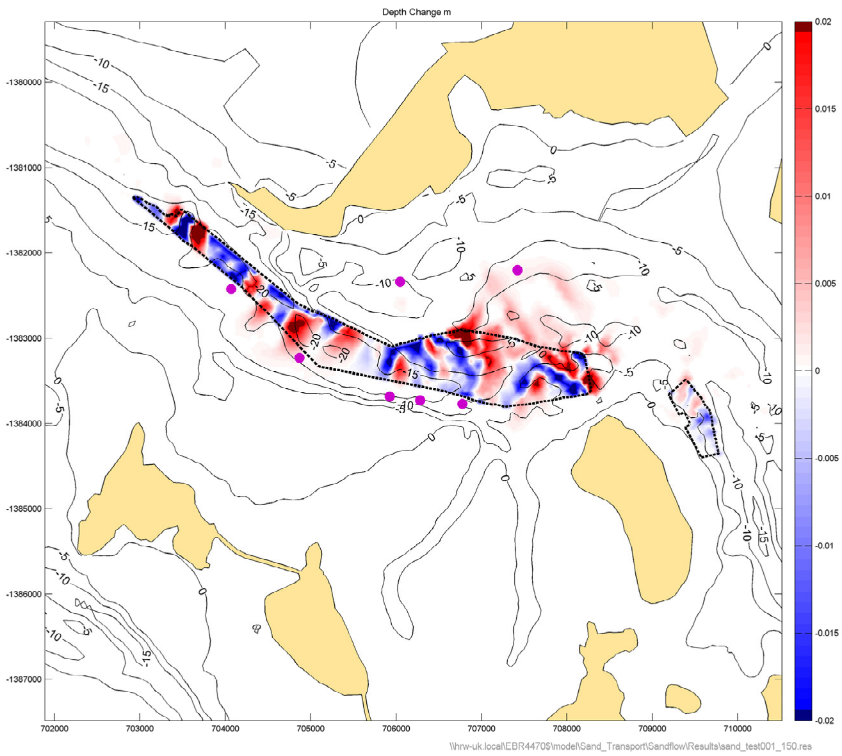


Figure 136 Indicative areas of net erosion and deposition for spring-neap cycle 150 µm sand under tide-only conditions for predredge bathymetry (mobile material only within dredge footprint)

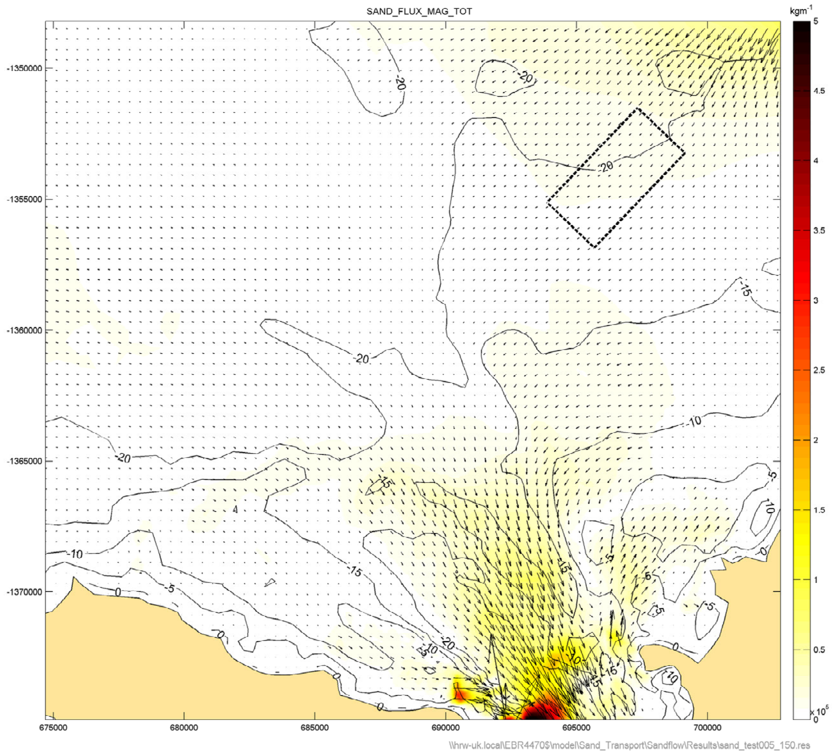


Figure 137 Net sand transport for spring-neap cycle 150 µm sand under tide-only conditions for pre-dredge bathymetry

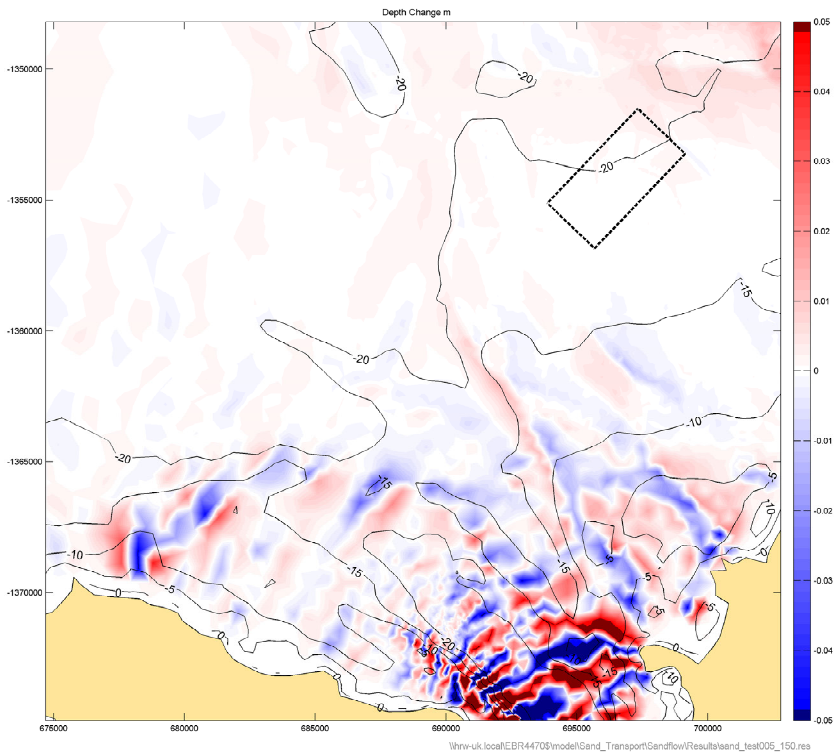


Figure 138 Indicative areas of net erosion and deposition for spring-neap cycle 150 µm sand under tide-only conditions for pre-dredge bathymetry.

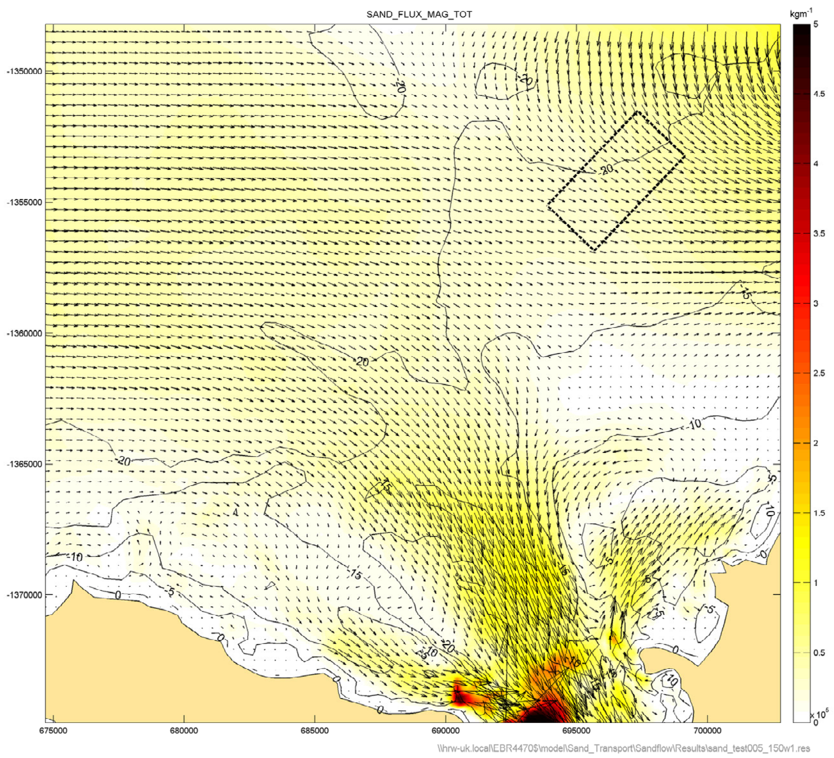


Figure 139 Net sand transport for spring-neap cycle 150 µm sand under tide plus wave conditions for pre-dredge bathymetry

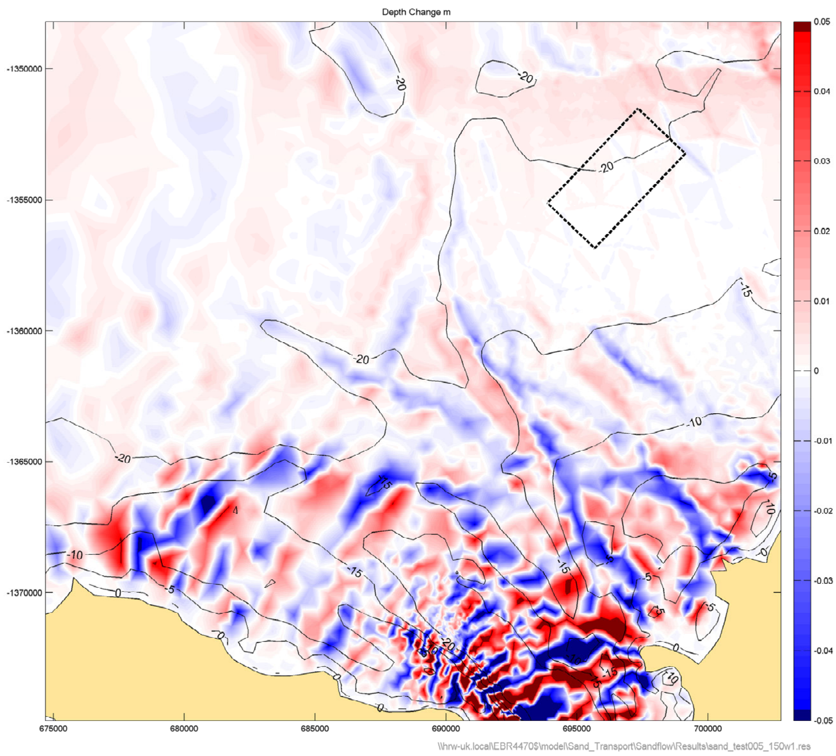


Figure 140 Indicative areas of net erosion and deposition for spring-neap cycle 150 µm sand under tide plus wave conditions for pre-dredge bathymetry

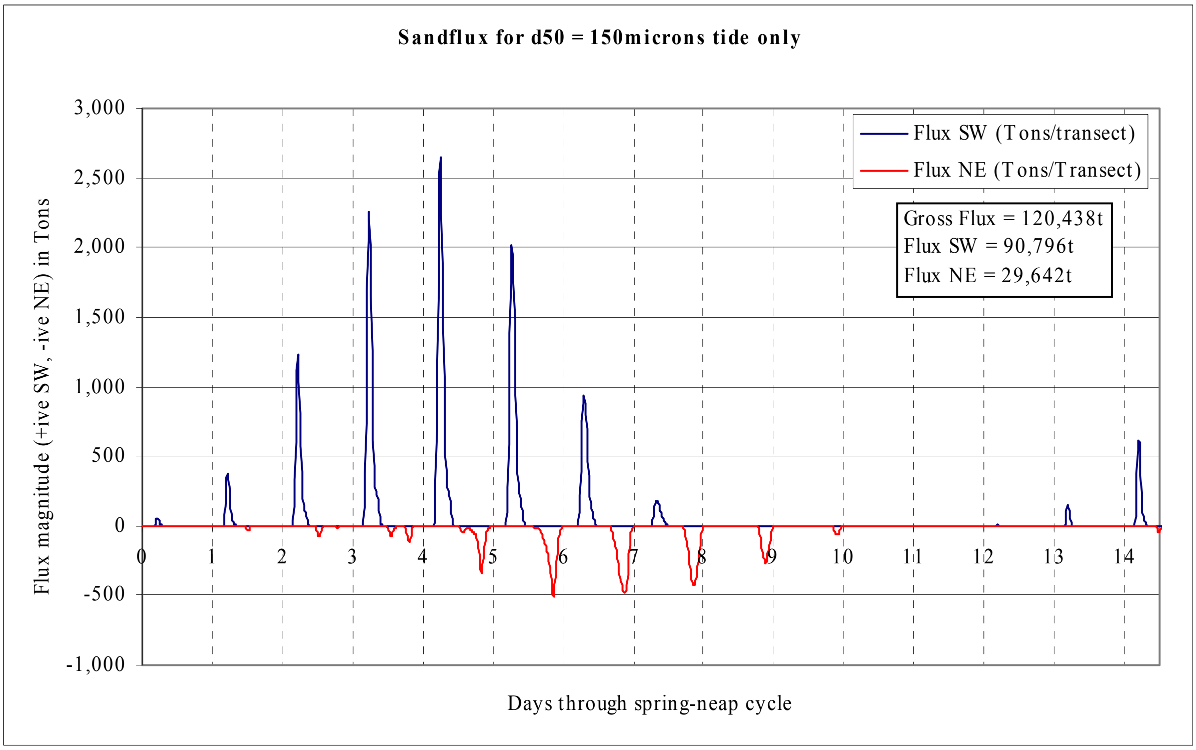


Figure 141 Potential through tide sandflux magnitudes for spring-neap cycle for tide-only conditions and pre-dredge bathymetry at the offshore disposal ground

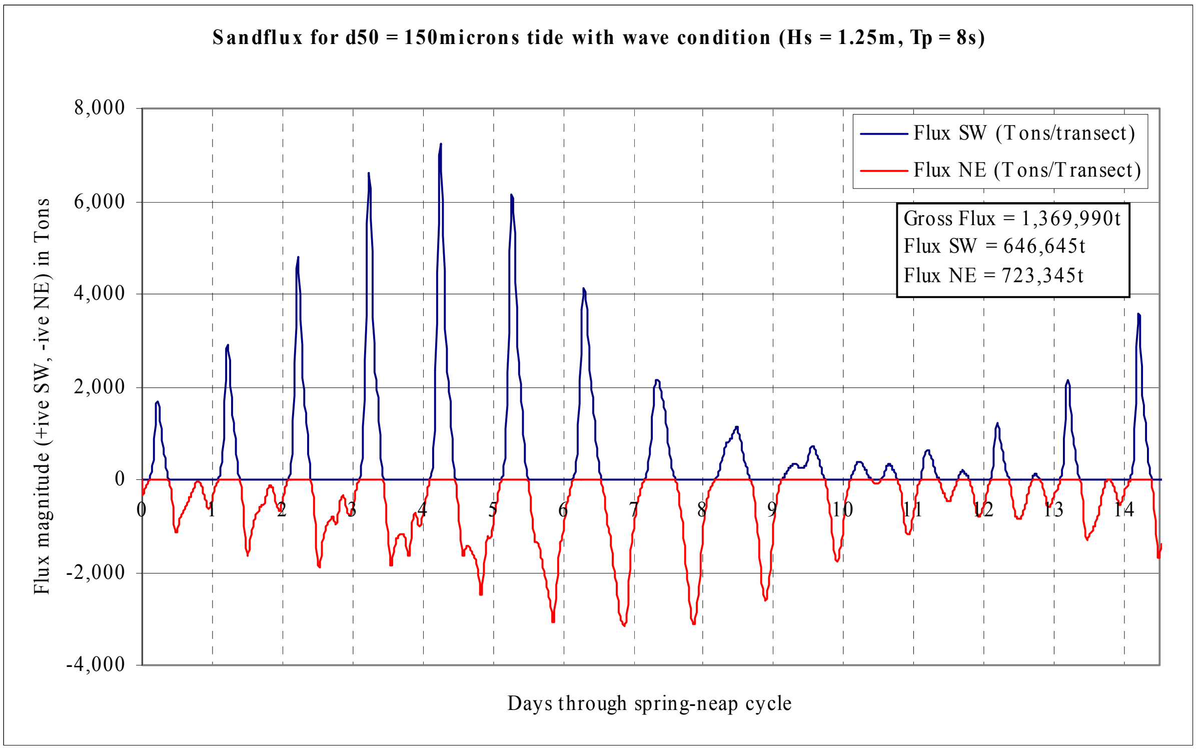


Figure 142 Potential through tide sandflux magnitudes for spring-neap cycle for tide plus wave conditions and pre-dredge bathymetry at the offshore disposal ground

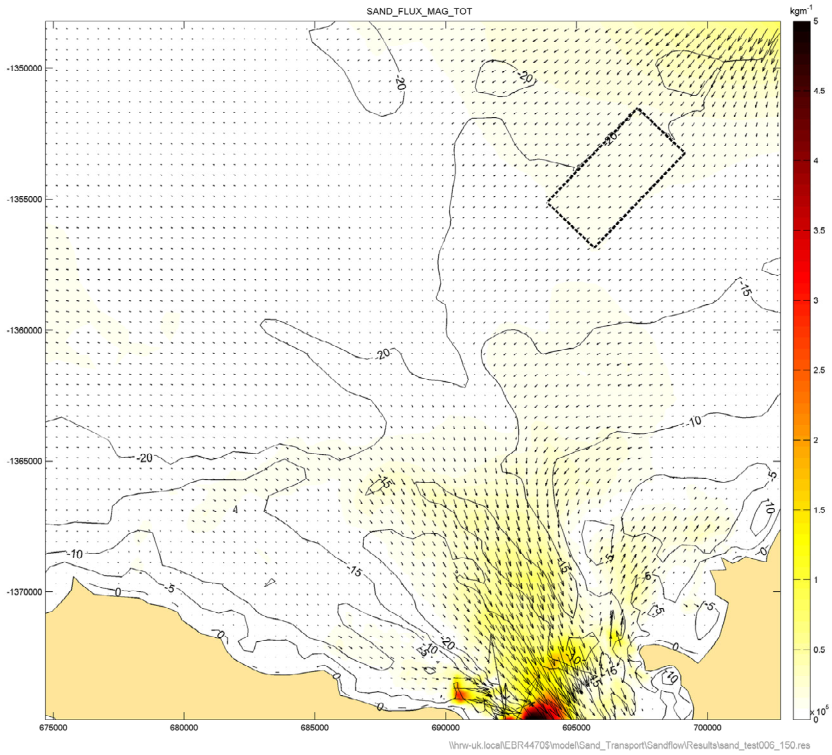


Figure 143 Net sand transport for spring-neap cycle 150 µm sand under tide-only conditions for post-dredge bathymetry (offshore disposal ground +1.0m)

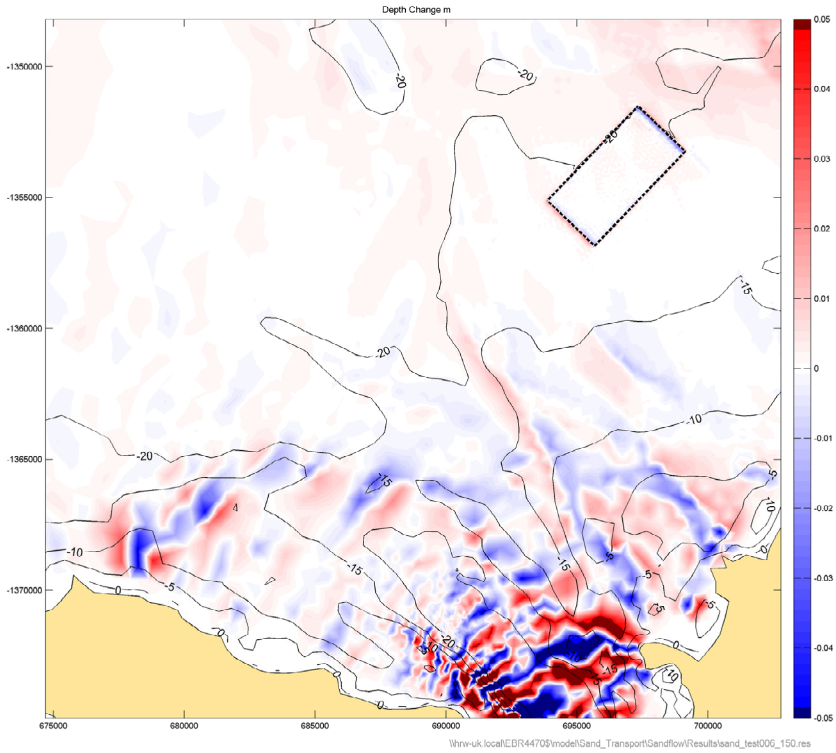


Figure 144 Indicative areas of net erosion and deposition for spring-neap cycle 150 µm sand under tide-only conditions for post-dredge bathymetry (offshore disposal ground +1.0m)

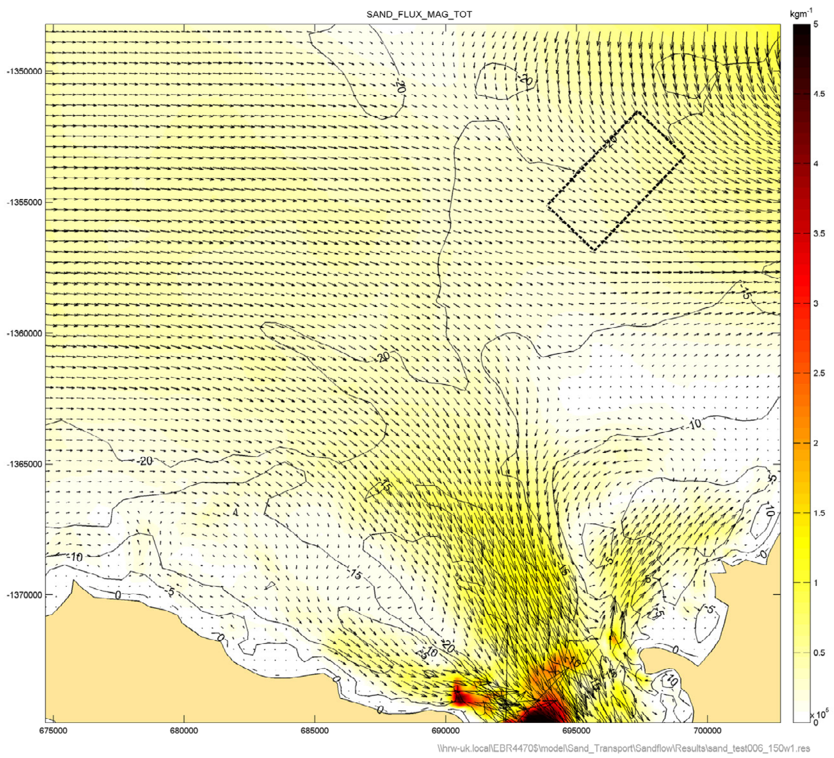


Figure 145 Net sand transport for spring-neap cycle 150 µm sand under tide plus wave conditions for post-dredge bathymetry (offshore disposal ground +1.0m)

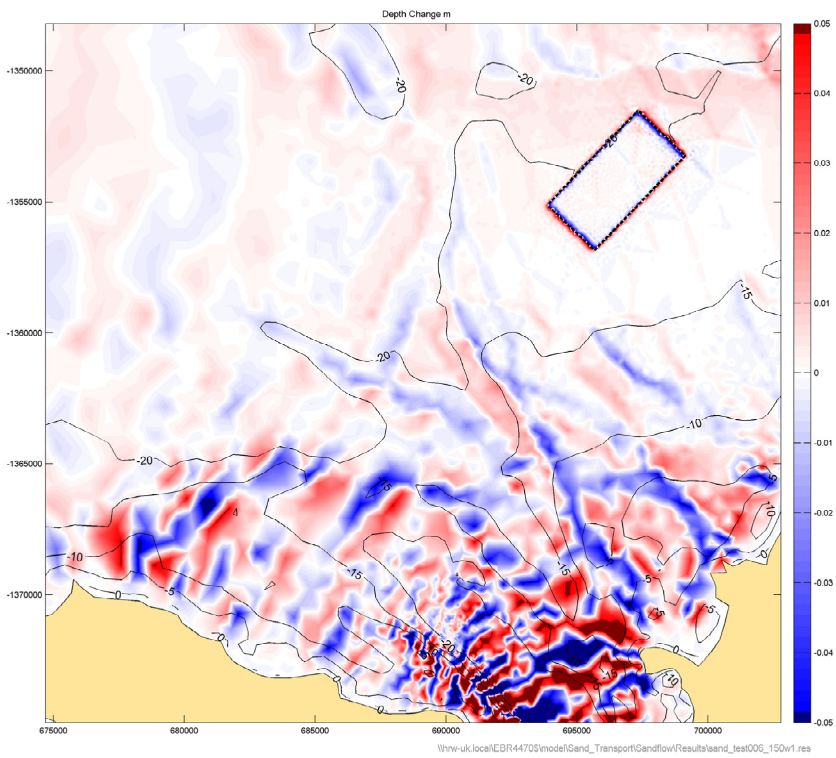


Figure 146 Indicative areas of net erosion and deposition for spring-neap cycle 150 µm sand under tide plus wave conditions for posr-dredge bathymetry (offshore disposal ground +1.0m)

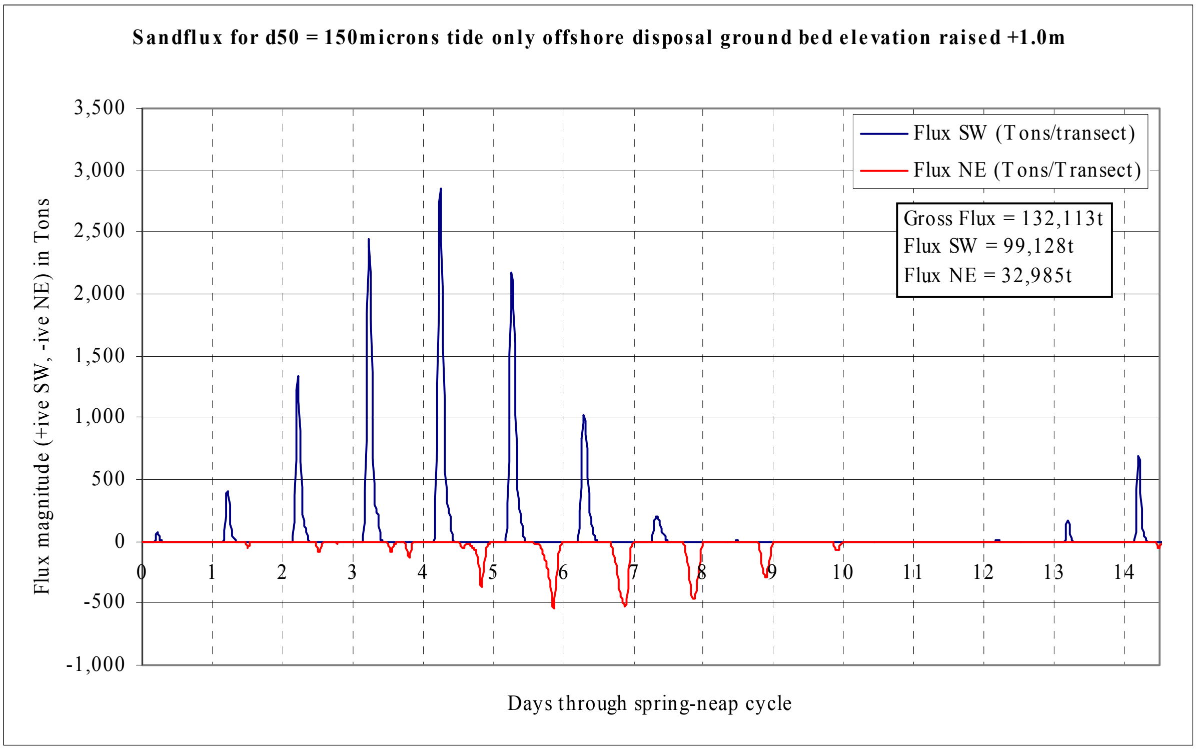


Figure 147 **Potential through tide sandflux magnitudes for spring-neap cycle for tide-only conditions and post-dredge bathymetry at the offshore disposal ground**

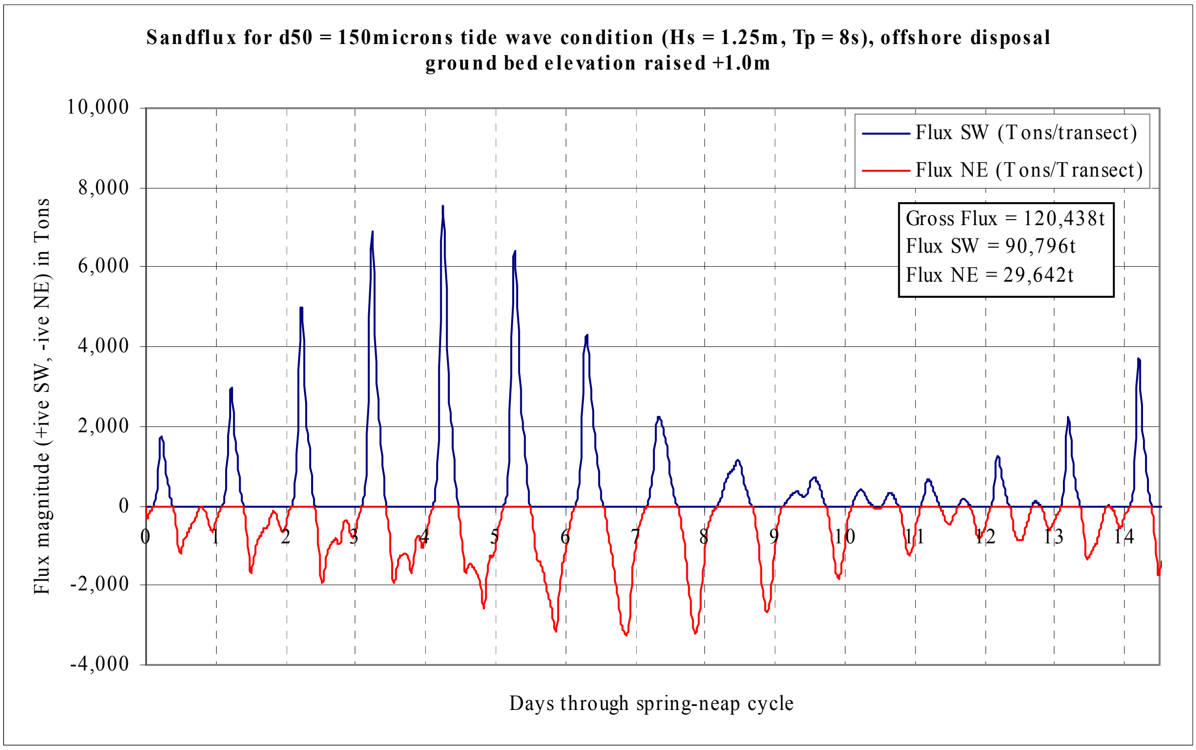


Figure 148 **Potential through tide sandflux magnitudes for spring-neap cycle for tide plus wave conditions and post-dredge bathymetry at the offshore disposal ground**

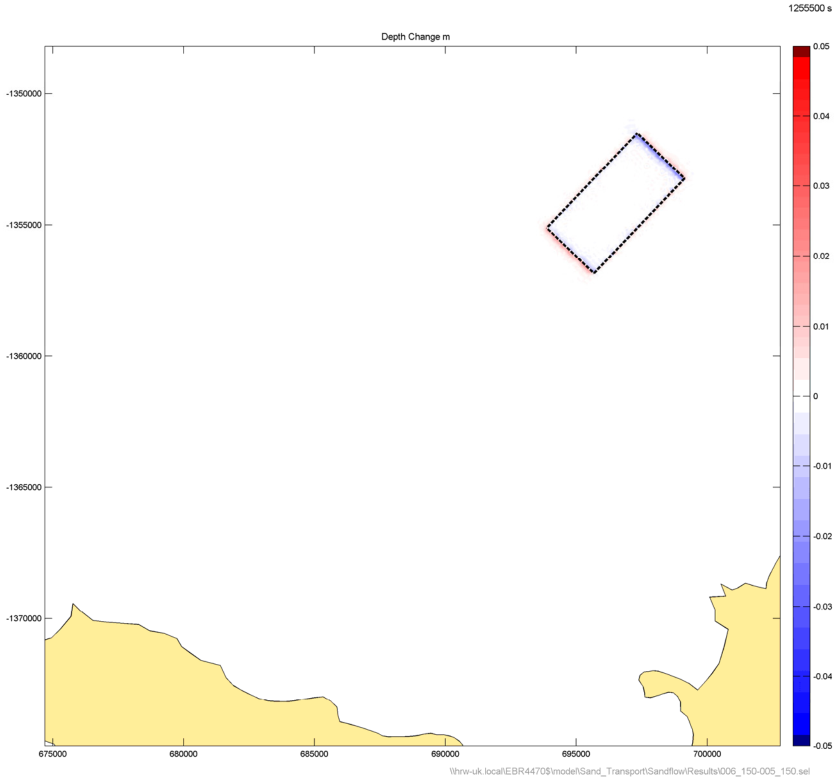


Figure 149 Difference in potential area and magnitude of deposition and erosion at the proposed offshore disposal ground under tide only conditions

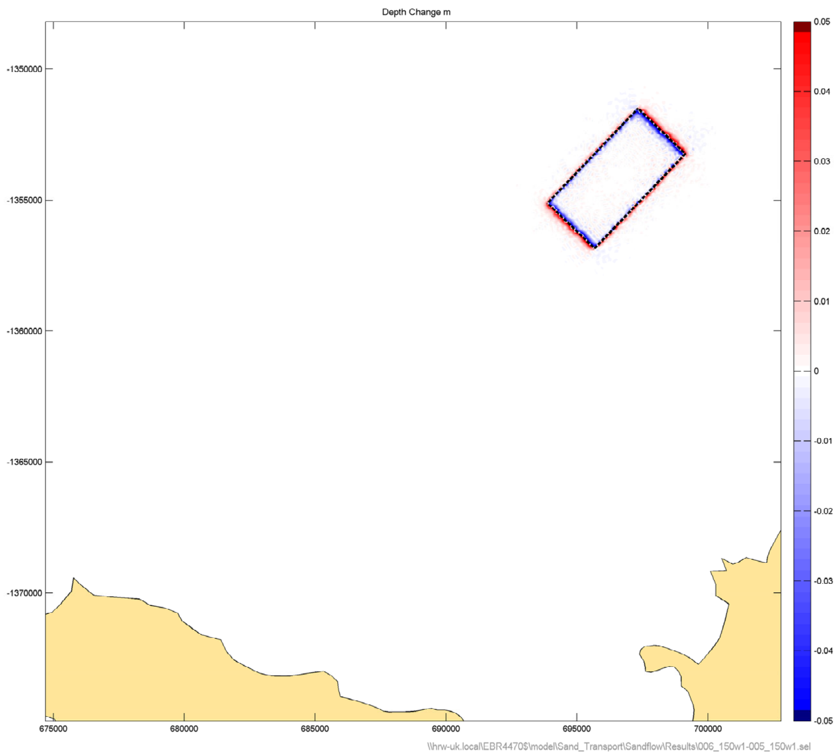


Figure 150 Difference in potential area and magnitude of deposition and erosion at the proposed offshore disposal ground under tide plus wave conditions

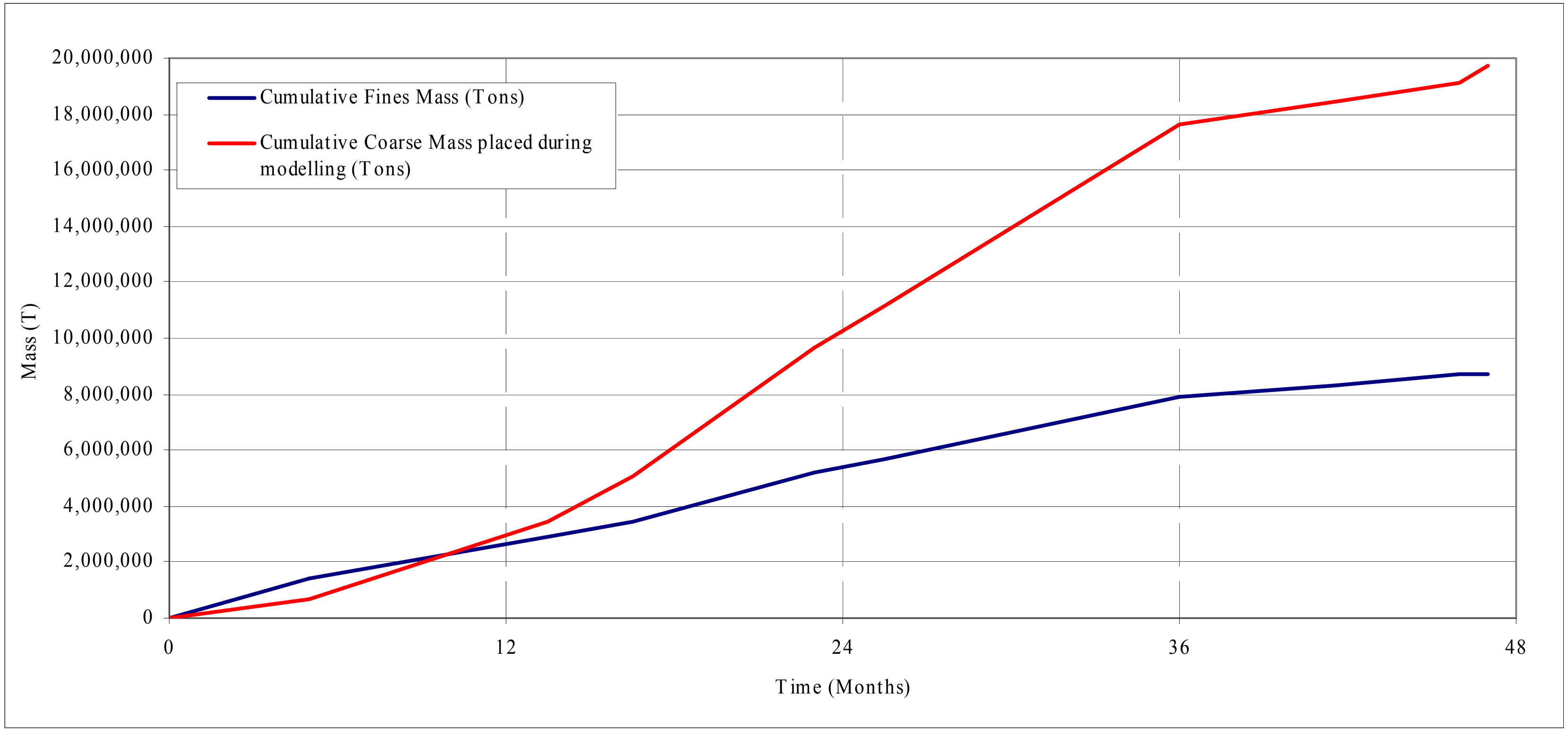


Figure 151 Cumulative mass of fines and coarse material released at offshore disposal ground during the proposed dredge plan