



# Appendix 14

Dredge spoil disposal ground selection study



# Ichthys Gas Field Development Project Dredge spoil disposal ground selection study

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## EXECUTIVE SUMMARY

INPEX Browse, Ltd. is proposing to undertake dredging operations required for the development of gas processing and export facilities within Darwin Harbour. Dredging is proposed to create a navigation channel, ship berth and turning circle within East Arm, trenching for the burial of a gas export pipeline leading into Middle Arm, and construction of a module offloading facility berth on the eastern side of Blaydin Point. Under the indicative plan, disposal of sediments would primarily be to a disposal site outside of Darwin Harbour. INPEX sought to identify the optimal location that would minimise risks to environmental resources.

A modelling study was undertaken to investigate the likely stability of sediments deposited at locations outside Darwin Harbour as well as the likely migration patterns for sediments that are mobilised during the placement operations, or are subsequently mobilised by currents or waves. Spatial and seasonal trends in shear stress, at bed level, were first calculated using the formulation of Soulsby (1997). Estimates were rendered as contour maps for the median and 80<sup>th</sup> percentile over time for the wet and dry season. Median stress estimates for the dry season indicated that fine to medium sands would be subject to mobilisation within the entrance channel and over the bordering shelf, at least 50% of the time. During the wet season, which included the influence of cyclones, including Tropical Cyclone Helen on the current and wave estimates, median stress estimates were indicated to be sufficient to mobilise coarse sand over a wide part of the seabed outside of the Harbour. The 80<sup>th</sup> percentile estimates, which represent more extreme (less frequent) conditions, were estimated to be sufficient to mobilise coarse sand in either season. The results indicated that finer sediments (silts, clays and fine sands) will be readily mobilised by the strong tidal currents, irrespective of the disposal site (within practical sailing distance of the harbour). Deposits of heavier fractions (at least to coarse sand) are likely to be disturbed during less frequent storms (> once per year). Thus, the channel and offshore shelf are interpreted to be dispersive environments, indicating that an optimum site should be selected based on the potential for sediments to migrate onto sensitive locations.

Dispersion patterns were tested by simulating disposal at nine offshore sites. Results indicated that a disposal area located approximately 20 km north of the Harbour entrance (14-15 m water depth) would provide for optimum stability and patterns of sediment migration. Fine sediments dispersed from this area were predicted to migrate alongshore and eastward, year-round, minimising risks of sediments drifting back into the Harbour or onto the coast. Simulations indicated that rocks, gravel, coarse sand and a large proportion of the fine sands would deposit within or immediately surrounding the limits of the disposal ground and will then be relatively stable. In contrast, finer sediments are predicted to drift more widely due to the strong tidal currents operating offshore from the harbour and the slow sinking rates of the finer sediments. Subsequent resuspension of the finer sediments is expected to occur under the prevailing current regime. A notable outcome of the disposal simulations was the repeated settling and resuspension of fine sediment, representing flocs of silt and clay size material, immediately above the seabed. These flocs were represented as being repeatedly mobilised, both on the regular cycling of the tidal currents and more haphazardly due to swell waves. Seabed plumes generated through this process are predicted to migrate back and forth along the tidal axis but disperse in the direction of the net drift current, which is generally towards the northeast from the site identified as optimum.

## 1 INTRODUCTION

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<sup>2</sup> 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.

Asia Pacific ASA (APASA) was commissioned to carry out environmental work associated with INPEX's preparation of the EIS and this technical report, *Dredge spoil disposal ground selection study*, was prepared in part fulfilment of that commission

In addition to the longer-term operations, the development proposal includes dredging in the nearshore development area. This study focussed upon offshore disposal of dredged sediments, with the aim of locating an optimal site that would minimise the return of dredged sediments into the harbour, into coastal habitats surrounding Darwin, or onto offshore resources of special interest, including identified fishing grounds.

Simulations were undertaken to identify the likely migration of sediments disposed from hopper vessels, accounting for the variable sinking rates of different particle sizes and the prevailing tidal patterns. To identify the longer term migration patterns for the finer sediments, it was also necessary to follow the fate of material that was subsequently resuspended from the seabed. Resuspension is the process whereby sediment particles are mobilised into the water column due to hydrodynamic forces under the combined influence of the prevailing currents and waves. Waves tend to cause vertical stirring of material while currents mostly



cause their horizontal transport. Resuspension occurs naturally where the combined shear force exerted by waves and currents exceeds the critical force necessary to break the gravitational, frictional and electrostatic forces holding particles on the seabed. The necessary magnitudes of the shear-force have been shown to vary greatly depending upon the history of deposition and consolidation of the surface sediments (Van Rijn 2005). Recently settled light material tends to have high water content and as a result require weaker resuspension forces. Consequently, recently formed (hours to weeks) deposits of relatively low-weight particles, as generated by sediment disposal, can result in secondary plumes and sedimentation. The SSFATE model applied in this study was configured to account for resuspension due to wave and tidal forcing.

## 2 METHODOLOGY

### 2.1 Study datum

Water depths and levels presented in this report are with respect to Mean Sea Level (MSL; 4.20 m in Chart Datum; 0.24 m AHD) unless otherwise stated and are in units of metres. All models applied to the study used tidally varying depth levels and wetted areas, hence accounted for the large tidal range within Darwin Harbour.

Position units are in latitude/longitude, in decimal degrees, using the WGS 1984 datum, unless otherwise stated.

All units are in standard SI units.

### 2.2 Model details

Simulations of sediment disposal operations were carried out using the SSFATE (Suspended Sediment FATE) model, a computer model originally developed jointly by the U.S. Army Corps of Engineers Engineer Research and Development Center and Applied Science Associates (ASA; Johnson et al. 2000, Swanson et al. 2000, 2004) and further extended by ASA for operations in marine and coastal environments, where wave forcing becomes more important for reworking the distribution of sediments (Swanson et al. 2007). The model estimates suspended sediment concentrations generated in the water column and deposition patterns on the seabed.

SSFATE is formulated to simulate far-field effects (~25 m or larger scale) in which the mean transport and turbulence associated with ambient currents are dominant over the initial turbulence generated at the discharge point. A particle-based model predicts the transport and dispersion of the suspended material. Particle advection is based on the simple relationship that a particle moves linearly with a local velocity, obtained from the hydrodynamic model, for a specified model time step. Particle diffusion is assumed to follow a simple random walk process. The Lagrangian approach of calculating transport through a grid-less space removes limitations of grid resolution and artefacts due to grid boundaries.

The SSFATE model requires specification of circulation and wave parameters in the area of interest, physical characteristics of the discharge, and the loss rate and initial vertical distribution at the release point. Using a random walk procedure, the model tracks representative particle classes as they disperse in the water column and settle to the bottom. Particle diffusion is affected by estimates of the local horizontal and vertical diffusion rates. Sinking rates vary with particle size and with the concentrations of particles in the water column. Sinking rates of clay and fine silt-sized particles are enhanced in the model at increased concentrations of particles of this size range or larger, accounting for the tendency of these size classes to clump together through electrostatic force to form larger particle-sizes with markedly higher sinking rates. The model also calculates a dynamic rate of sedimentation (the process where particles move from the suspended state to accumulate on the seabed) due to local estimates for the combined shear-stress generated by current and wave forcing, following the formulation of Soulsby (1997). This formulation prevents

overestimation of settling where shear stress (due to waves and currents) would inhibit or prevent settling.

SSFATE also calculates sediment re-suspension, if the combined shear-stress subsequently increases above critical thresholds. Different thresholds are applied for resuspension depending upon the duration of sedimentation, based on empirical studies that have demonstrated that newly settled sediments, which have higher water content, and are more easily resuspended by lower shear stresses (Swanson et al. 2007). Resuspension flux (mass per time leaving the seabed) for lighter fractions will be affected by the magnitude of shear stress and the average particle size distribution of the deposits, with resuspension flux reducing to zero at a critical average size. This latter function is to account for armouring of fine particles within the interstitial spaces of larger particles. Thus, the model can indicate whether deposits will stabilise or continue to erode over time given the shear forces that occur at the site.

SSFATE formulations and proof of performance have been documented in a series of USACE Dredging Operations and Environmental Research (DOER) Program technical notes (Johnson et al. 2000; Swanson et al. 2000), and published in the peer-reviewed literature (Anderson et al. 2001, Swanson et al. 2004; Swanson et al. 2007). SSFATE has been applied and validated by APASA against observations of sedimentation and suspended sediments at multiple locations in Australia.

Specification of the unique sediment discharge characteristics related to a particular operation are controlled in SSFATE by specifying rates of sediment flux (sediment mass released per unit time), initial vertical distributions relative to the seabed and a particle-size distribution for the sediment particles at the time of initial discharge. Rather than releasing sediments at a specific height in the water column, disposal operations result in a rapid spread of material in the vertical plain. Finer sediments tend to be entrained by the rapid sinking of gravels and coarse sand and will sink faster than would occur if discharged separately. On striking the seabed, finer sediments will tend to be carried upward and outward by the displaced water, forming a cloud above the seabed. An example of the observed vertical distribution of sediments due to a dredging operation is given in **Error! Reference source not found.**

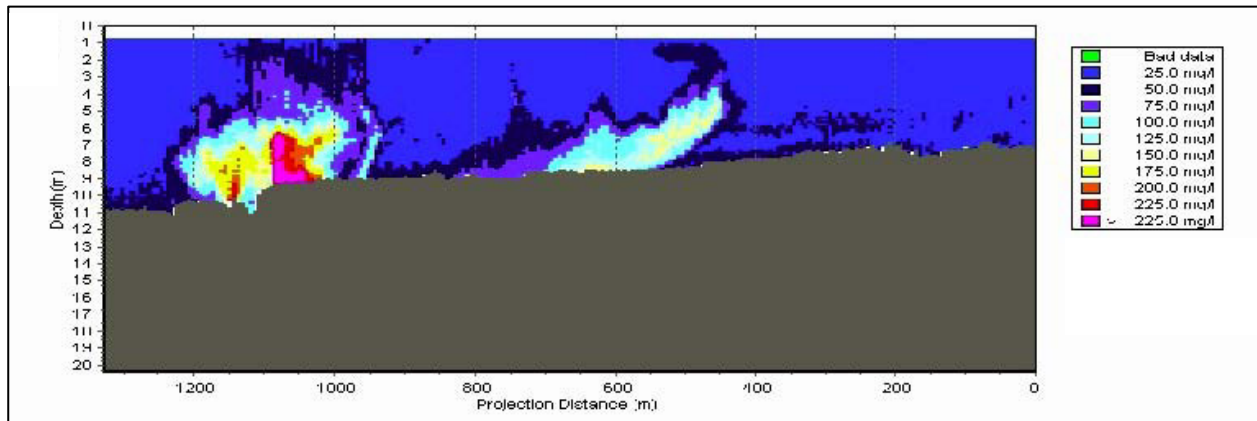


Figure 1: Example cross-section of a sediment plume generated by repeated disposal operations as measured by Acoustic Doppler Current Profiling (reprinted from Swanson et al. 2004).

The initial vertical distribution is specified in SSFATE to account for the variable fall heights through which particles must sink after being initially mobilised by dredging or disposal. This vertical distribution is affected by a number of factors, including the type of operation (in this case, the downward discharge of a sediment mass from a hopper), the depth of the discharge point relative to the seabed and the particle-size distribution of the sediment mixture. In the case of a pulsed release, such as repeated releases from a hopper vessel, the vertical distribution is specified for the time immediately after the plume has struck the seabed to generate a plume above the bed.

In lieu of direct measurements of the vertical distributions set up by disposal operations, empirical data are available from past operations for a range of dredging equipment (DOER 2000, Hays & Wu 2001, Anchor Environmental 2003, Damara 2004, Swanson et al. 2004, US Army Corp of Engineers- unpublished database in SSFATE). Note that the vertical distribution setting is specific only to the location of the discharge at the time of each release. This vertical distribution is dynamically varied thereafter by the model at each time step depending on the variable sinking rate of particles and prevailing hydrodynamic forces. Particles transported into shallower or deeper water will also have decreased and increased distances to fall to the seabed, respectively.

The location of a discharge may be specified for a fixed location, or more generally as a moving source to represent a disposal vessel progressively working forward. This is achieved by specifying a disposal path between start and end points (by latitude and longitude) for each sub-operation (i.e. a single disposal run) and the elapsed time to complete that operation.

Input variables in SSFATE are not fixed in time but may be varied among sub-operations to account for variability in an overall disposal programme, including variations in the discharged volume, particle size distribution and disposal location. Input settings may be varied as frequently as the specifications for the disposal programme dictate.

While SSFATE is a Lagrangian model, and calculates transport processes for sediment particles without the use of a grid, estimates for concentrations of sediments (per volume for suspended sediment concentrations and per area for sedimentation) are calculated for

defined grid sizes and vertical steps. Smaller grid sizes and vertical steps maximise the resolution of variations in these variables at the compromise of model efficiency.

### 2.3 Modelling strategy

Two procedures were followed to identify an optimal disposal site for offshore sediment placement:

1. Predictions for the current and wave fields representing wet and dry seasons spanning 7 years were used to estimate the distribution of shear stress at seabed level for the full model domain, following the formulation of Soulsby (1997). Estimates over time were summarised as the median (50<sup>th</sup> percentile, or most common level) and the 80<sup>th</sup> percentile level (representing more extreme conditions) at each grid cell. These results served to identify locations where sediments of a given grain size would tend to be more stable. Details of the hydrodynamic and wave models used in the study have been reported in APASA (2009).
2. Based on the results of the first analysis and other limitations, including proximity to sensitive fishing grounds and travel distances from the dredging sites (which would affect the duration of the operations), sediment modelling was undertaken at a short-list of candidate disposal sites.

The SSFATE model used current and wind fields that varied over time and space, which enables sediment dispersal patterns to be calculated under a range of forcing conditions, and accounting for the unique characteristics of the discharge associated with different operations. An assessment of the suspended sediment concentrations and sedimentation patterns over time provides a guide to the expected evolution of these parameters.

For comparative purposes, separate simulations to represent a subset of the disposal operation (2 months) were run at nine candidate locations using common samples of current and wind data representing the two main metocean seasons (wet and dry). The sediment mixture was biased towards fine silts and clays to provide a conservative indication of the spread of sediment, due to transport by currents during initial sinking and following any resuspension. Because this modelling was intended as a preliminary culling exercise, to identify likely migration patterns under commonly occurring conditions, the relatively short duration was sufficient. A more detailed analysis for the full disposal programme is reported separately for the site identified as optimum by this study. Relative estimates of sedimentation rates for dredged sediments were derived in terms of relative rates of change in thickness (mm/hr), calculated from estimates for the average mass of sediments per area of seabed within 70 m by 70 m grid cells (4900 m<sup>2</sup>) over the duration of the simulations. This conversion required estimates of the pore water content and sediment-grain density to determine a bulk density for the sediment deposit. To provide a conservative estimate of sediment thickness, the water content was assumed to have reduced to 50%, yielding a bulk density of 1850 kg m<sup>-3</sup>. Because the disposal specifications represented a relatively short portion of the disposal operation, the results should be treated as a comparison among the sites, rather than a final outcome of the full disposal operation that is planned.

The sediment model only considered the fate of the sediments placed at the sites by hopper discharge. Hence, results are presented as concentrations that will be over and above background sedimentation.

### 3 RESULTS

#### 3.1 General hydrodynamic climate offshore Darwin Harbour

Simulations of the current field affecting the entrance to Darwin Harbour and offshore waters, validated by measurements at multiple locations, indicate that there is marked steering of the tidal currents by the shelf bathymetry (Figure 2). Tidal currents offshore from a general line connecting Cox and Shoal Bay Peninsulas, which form the headlands of the offshore channel draining Darwin Harbour, flow approximately east at the peak of the flooding tide and west at the peak of the ebbing tide (Figure 3 and Figure 4). The main drainage channel to the Harbour trends north-west, cutting through a wide and relatively shallow (< 10 m) shelf. The shelf extends up to 12 km beyond the coast and is widest where the channel enters the shelf edge from offshore. Flooding tides diverge towards the coast in response to the funnel shaped bathymetry and are steered and accelerated along the axis of the entrance channel. Ebbing tides display the reverse trend, diverging and slowing with distance offshore along the channel. Thus, there is marked spatial variation in the speed and direction of tidal currents over the study area, which will influence the patterns of transport of sediments suspended by disposal, or subsequently resuspended by currents and waves.

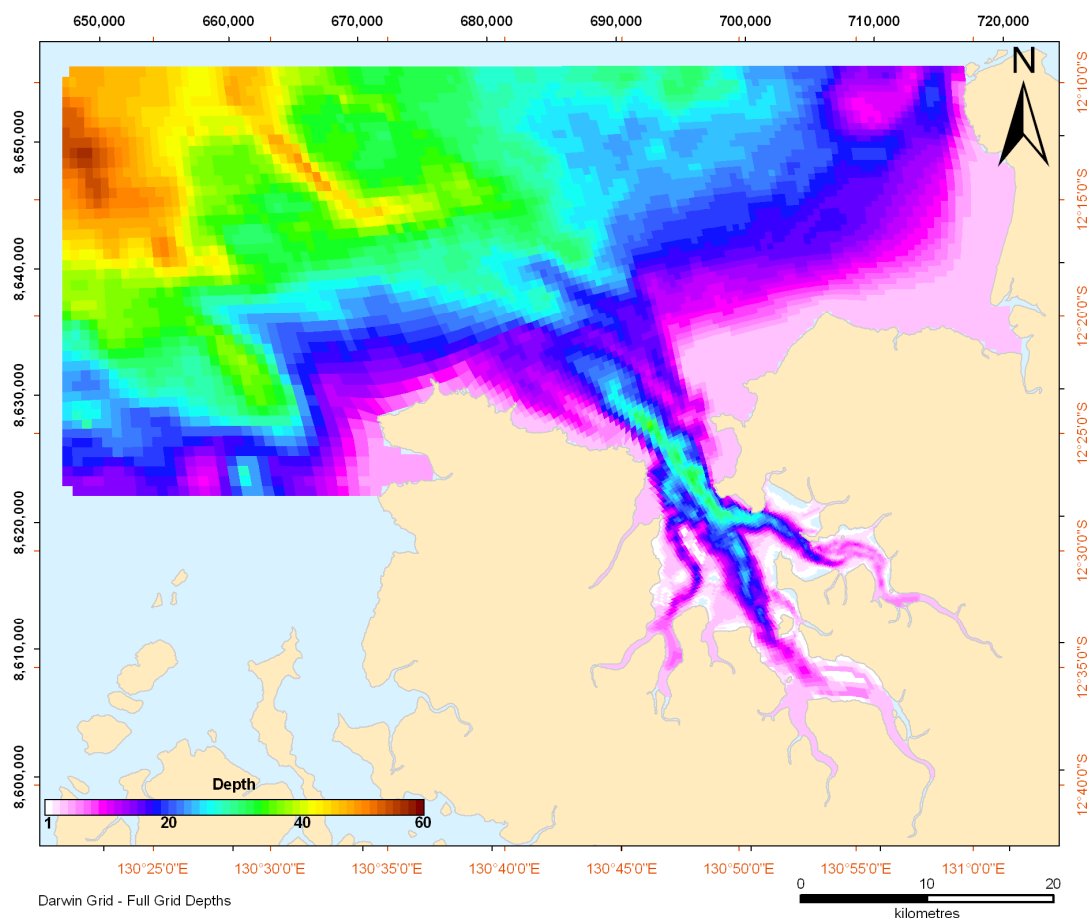


Figure 2: Bathymetry over the model domain.

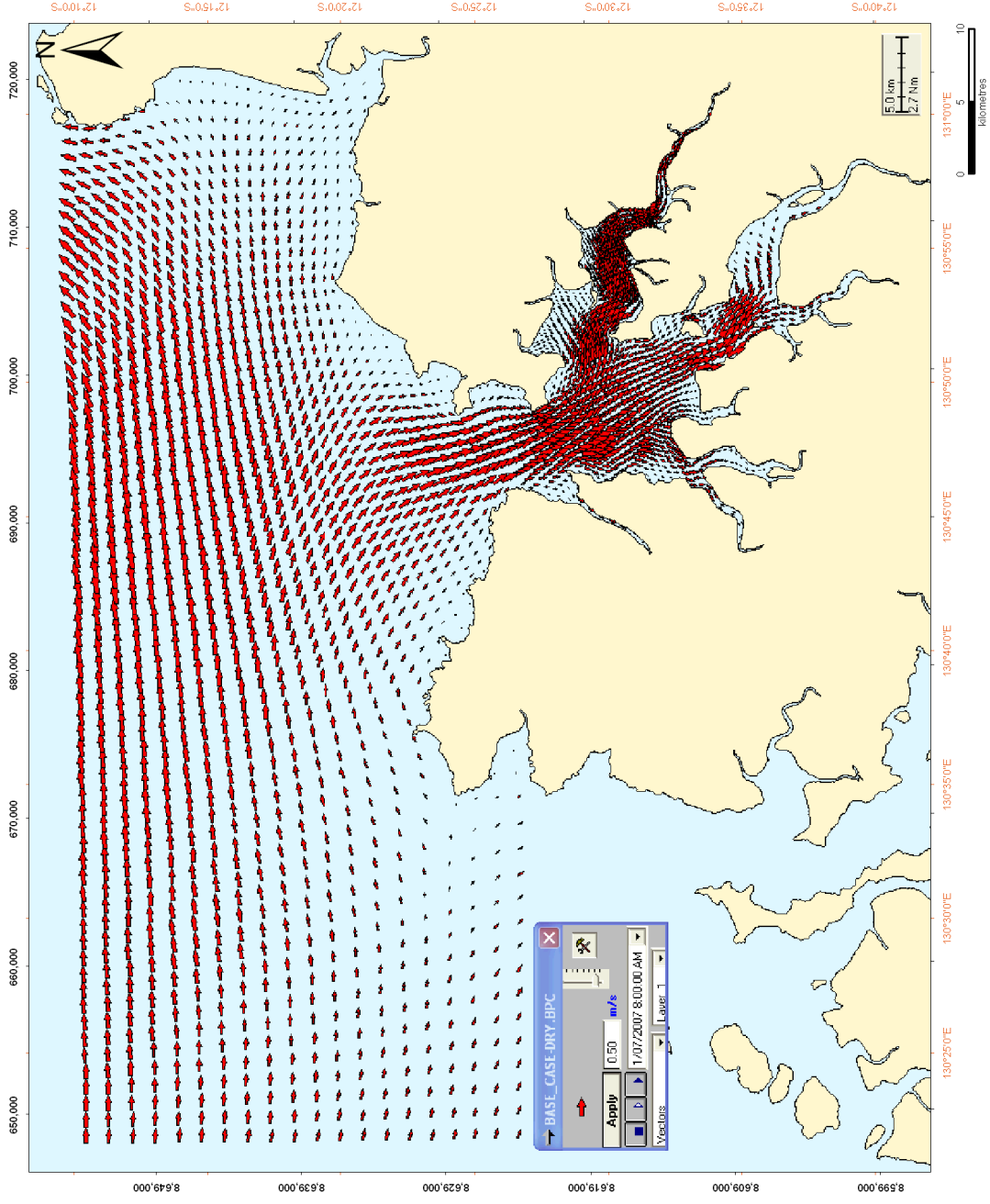


Figure 3: Example of the current flow predicted near the seabed at one point during a flooding tide



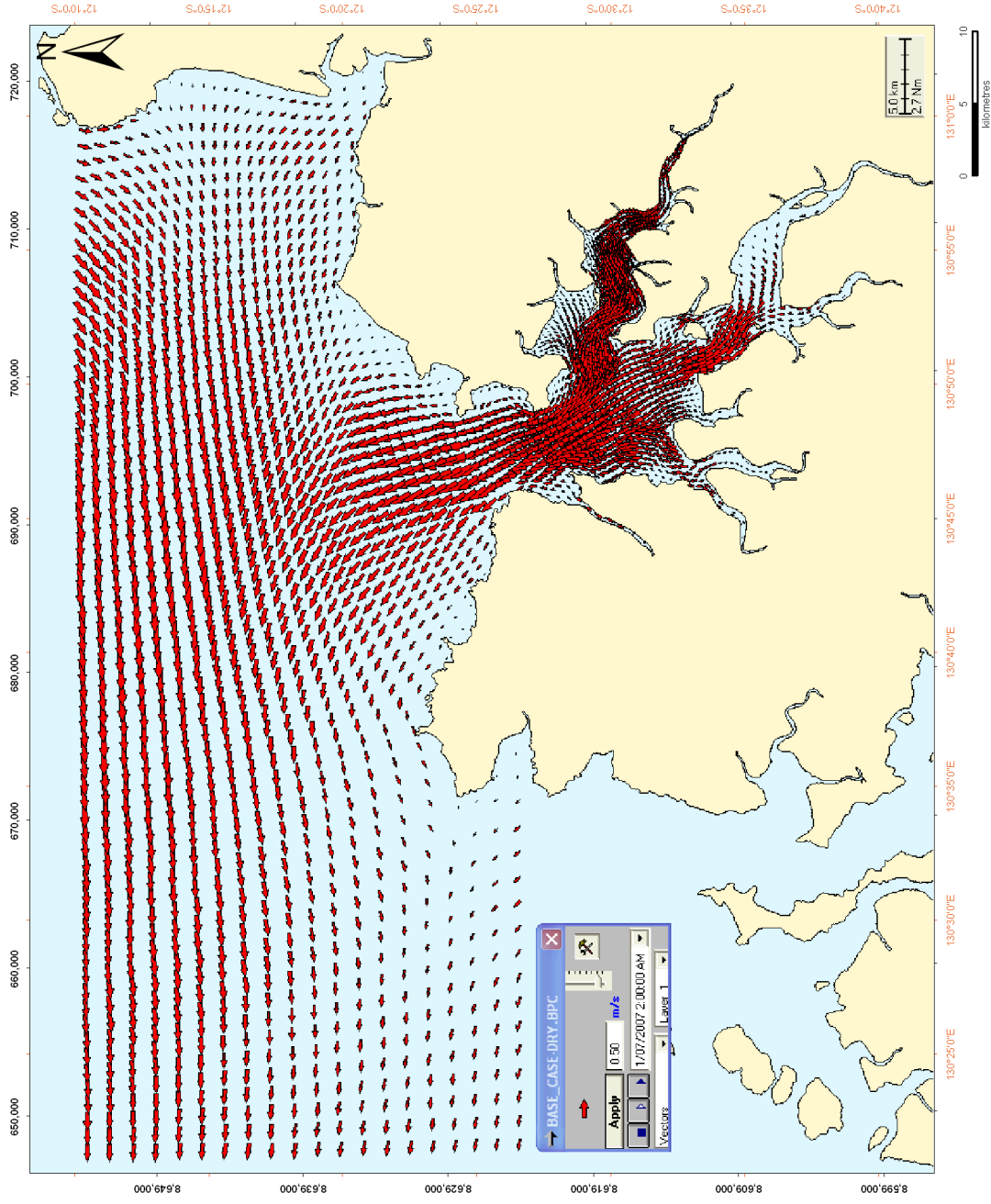


Figure 4: Example of the current flow predicted near the seabed at one point during an ebbing tide

### 3.2 Shear Stress estimates

Estimates for the distribution of shear stress at the seabed, which were calculated for both tidal currents and wave forces, are presented for the wet and dry seasons in Figure 5 and Figure 6. These estimates indicate that there would be marked spatial variations in the forces acting to remobilise sediments that deposit onto the seabed. Irrespective of the season, the 50th percentile (or median) shear stress estimates were generally highest over the shallow shelf to the east and west of the entrance channel and decreased with increasing depth. This pattern indicates the influence of wave action, and more specifically the penetration of swells to the seabed, on the stress estimates.

There were also marked seasonal differences in the estimated stress levels. The median stress estimates for the dry season indicated that fine to medium sands would be subject to mobilisation within the entrance channel and over the bordering shelf, at least 50% of the time. However, the median estimates for the wet season sample, which included the influence of Tropical Cyclone Helen on the current and wave estimates, indicated exponentially higher shear stress over the shelf waters outside of Darwin Harbour, sufficient to mobilise sediments up to the size of coarse sand. Estimates for locations within the Harbour were similar to the dry season samples due to sheltering from cyclone generated waves and the reduced wind fetch inside the Harbour.

Estimates for the more extreme levels of shear stress at the seabed, represented by the 80th percentile value over the three month samples, indicated that particles as large as medium to coarse sand would be mobilised at least 20% of the time during the dry season. Fine sand and larger particles were only expected to be stable for this proportion of time within the deeper holes at long distances from the Harbour, or within sheltered pockets along the coast. The wet season estimates indicated that exponentially larger particles would be mobilised from the inshore shelf at least 20% of the time.

Collectively, these results indicate that Harbour sediment disposed offshore is unlikely to remain as a stable pile. Irrespective of the location of the disposal ground, mobilisation of the clay and silt-sized particles would be expected to occur at relatively high frequency (50% or more of the time). This mobilisation would be moderated by burial of the fines by larger particles. However, mobilisation of sand and larger particles is also expected to occur 20% or more of the time during both the wet and dry seasons, which would result in localised spreading of these materials and further mobilisation of fines.

The rate of remobilisation would be expected to vary among locations and would be markedly reduced in water depths > 12 m LAT due to the reduced penetration of swell waves. Hence, locations in deeper water would be favourable for limiting resuspension.

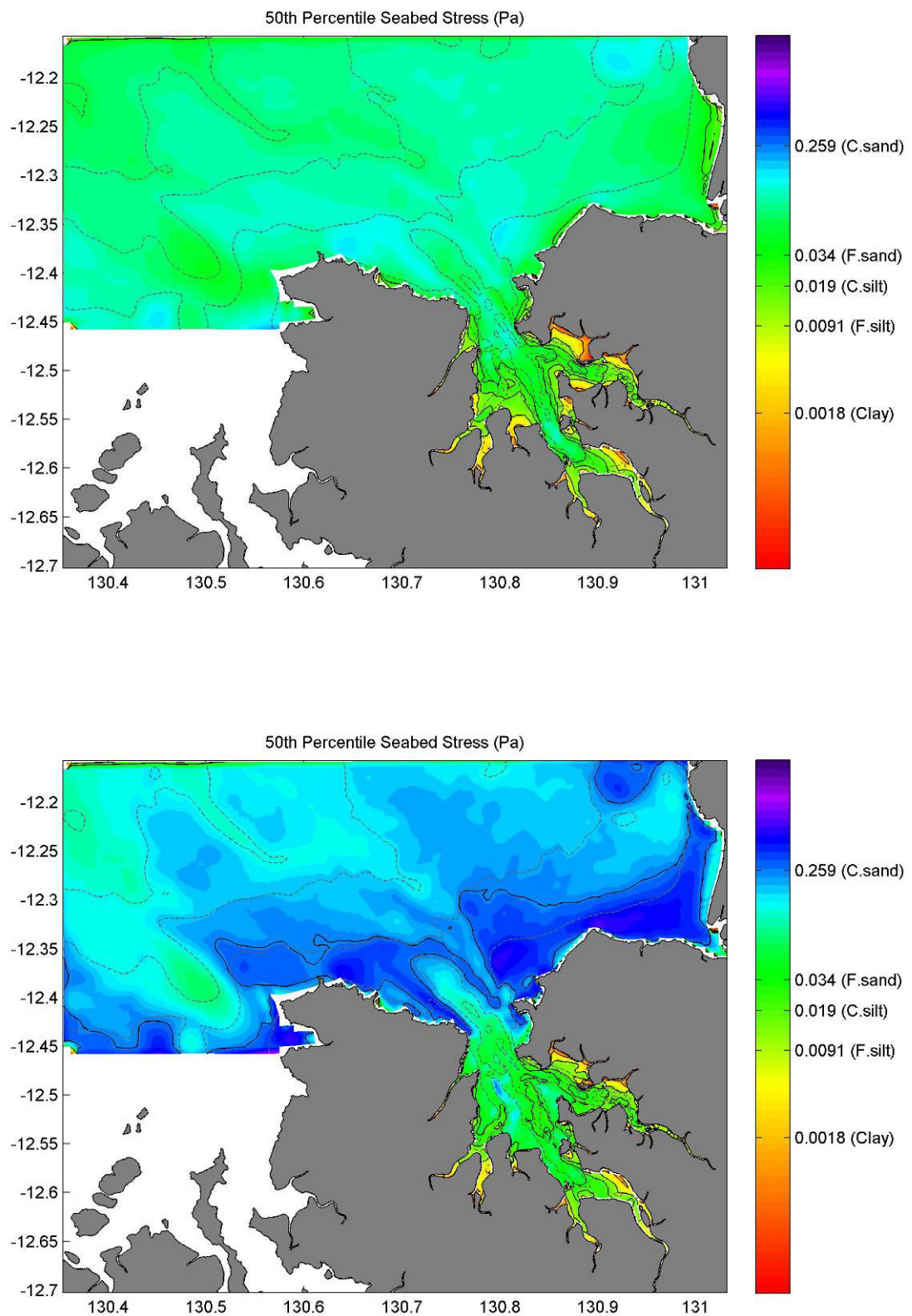


Figure 5: Estimates for the 50th percentile (median) seabed stress over different locations for the dry (top panel) and wet (bottom panel) season samples

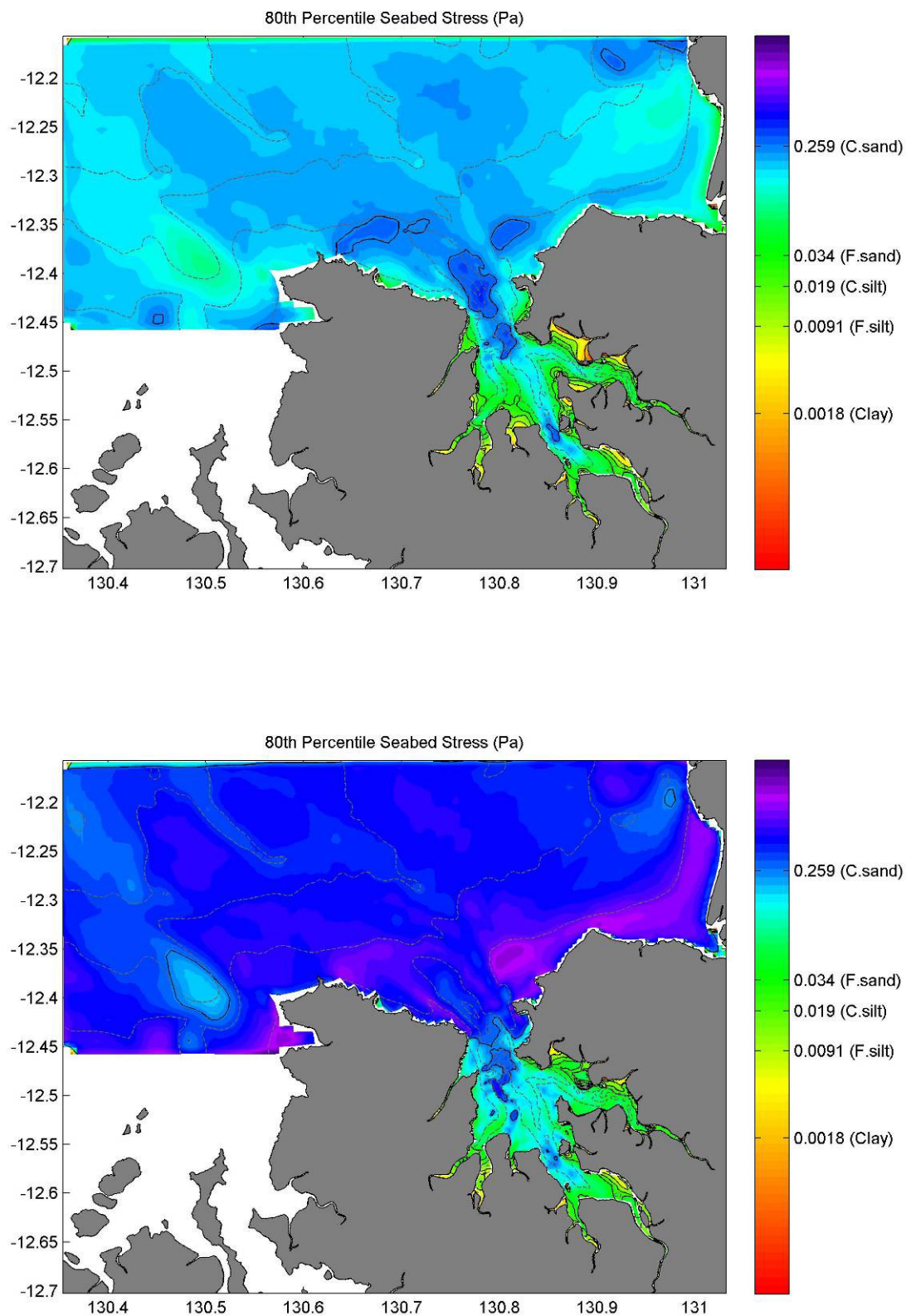


Figure 6: Estimates for the 80th percentile (median) seabed stress over different locations for the dry (top panel) and wet (bottom panel) season samples

### 3.3 Outcomes of disposal simulations

The disposal simulations were useful for defining the likely transport pathways and potential deposition rates for dredged sediments, given variations only in the disposal site. Figure 7 shows the disposal locations that were tested in relation to potentially sensitive reef sites and other geographic features. Results were based on relatively small samples of environmental data (30 days) and so were preliminary in nature. However, the dominance of tidal flows on circulation in the study area indicates the results are suitable for comparative purposes. Simulations were repeated for different sediment mixtures and seasons to test the sensitivity of the sediment distribution patterns to these variables.

Results are presented in terms of the highest deposition rate, as the thickness increase per hour ( $\text{mm h}^{-1}$ ), for material depositing at each location in the model domain. The results are additional to any background increases from natural causes. The outer contour represents the full field of effect over the duration of the simulation and the internal details highlight the worst expected sedimentation rate for each location, independently. The maximum values will occur at different times at each location and sediments will redistribute over time within the field of effect. Hence, the results should not be interpreted as cumulative loads at one point in time and should not be summed across sites.

The simulations indicated that a proportion of the finer sediments (clays and fine silts) would tend to form turbid plumes close to the seabed that will tend to drift with the tide and to undergo settling over the slack tide with subsequent resuspension as tide speeds increase. Consequently, plumes of these components were predicted to migrate back and forth with the tide. Due to the limited duration of each tidal flow (ebb to flow reversal approximately each 6 hours), the distance that particles will travel in either the flood or ebb direction were limited by the tidal migration distance. Hence the distribution patterns for deposited sediments were most strongly influenced by the orientation and speed of the tidal currents around each of the sites. The particle size distribution of the sediments deposition to the seabed was predicted to change exponentially with distance, with the coarse sand and gravels settling close to the source (from tens to hundreds of metres), and with substantially wider excursions for increasingly lighter fractions. This outcome was predicted to result from both the extended time for the lighter particles to originally sink and settle, hence drift initially, and the greater potential for the lighter particles to subsequently resuspend.

After the initial, rapid, settling phase of the sediments, sediment plumes generated by resuspension were predicted to drift close to the seabed, where the currents are less influenced by wind forcing. Hence, seasonal effects were small in the model outputs, and were observed as a small shift in the wider field of effect (deposition rate of  $< 0.1 \text{ mm h}^{-1}$ ) due to a net drift of the finest sediment classes towards the east of the tidal axis during the wet season and the west during the dry season. The particle size distribution of the discharge was predicted to affect the field of effect, with a wider spatial effect with increasing proportions of finer material but an otherwise similar distribution along the tidal axis. Results have been presented below for the finer mixture during the wet season, chosen as the worst case outputs.

Site 1 was positioned over water depth of 12 m LAT within the main tidal channel leading into Darwin Harbour, where the tidal currents speed up and steer parallel with the channel. Plumes generated by disposal of the relatively fine sediment mixture at this site were predicted to drift up to 15 km, depositing at rates of up to  $10 \text{ mm h}^{-1}$  at up to 4 km along the main channel on the flood tide at seabed level, and up to  $0.1 \text{ mm h}^{-1}$  off Emery Point. Suspended sediments transported on the ebbing tide were predicted to diverge westward with distance offshore, hence away from the coast. Deposition rates onto parts of Six Mile Grounds were estimated to peak at  $3\text{-}4 \text{ mm h}^{-1}$  (Figure 8). Relatively low deposition rates ( $< 0.1 \text{ mm h}^{-1}$ ) were also predicted over the intertidal beaches along the Darwin waterfront, spanning from Fort Point to Cullen Bay, as well as shorelines extending further along the eastern side of the Harbour as far as Nightcliff.

Site 2 was positioned in deeper water ( $\sim 17 \text{ m LAT}$ ) approximately 7.5 km to seaward from Site 1, and on the eastern side of the main entrance channel. The predicted distribution of sedimentation indicated that the reduced current speeds around this location would result in shorter migrations along the flood and ebb tidal paths. The maximum distance over which suspended sediment plumes were predicted to exceed  $5 \text{ mg l}^{-1}$  was approximately 9 km on the flood tide and 8 km on the ebb tide. The field of effect for sediment deposition was predicted to follow the tidal axis with clay and silt particles depositing up to 10 km shoreward (Figure 9). Deposition rates were predicted to peak at up to  $0.5 \text{ mm h}^{-1}$  on parts of Six Mile Grounds. The Harbour and coastal beaches were indicated to be outside of the field of effect from this site over the duration of the simulation. However, the migration towards the Harbour in the flooding tide direction indicates a risk of sediment transport into the coast or onto the eastern coastline over longer durations.

Site 3 was located in relatively shallow water ( $\sim 10 \text{ m LAT}$ ) offshore of Charles Point Patches on the western side of the Harbour entrance. Tidal currents flow approximately east–west over this location, then diverge to the south-east to follow the Harbour entrance channel. Because the tidal axis is parallel with the predominant wind directions, the predicted distribution of turbid plumes and sedimentation followed the tidal axis more closely, with little migration across this axis (Figure 10). Clays and silts were predicted to drift up to 9 km towards the Harbour entrance over the 30 day simulation, due to on-going resuspension cycles. However, greater distances might be expected with a more substantial disposal program lasting up to 18 months. Relatively high sedimentation rates ( $> 10 \text{ mm h}^{-1}$ ) were predicted for the location of Charles Point Patches when disposal coincided with ebbing tides.

Site 4 was also placed on the western side of the Harbour but approximately 3 km to the northwest of Charles Point Patches, and in deeper water ( $\sim 15 \text{ m LAT}$ ). The shift in depth was predicted to result in a more compact deposit of heavier sediments below the disposal area and a marginally more compact distribution for the finer components, compared to results for Site 3 (Figure 11). Relatively high deposition rates ( $5\text{-}10 \text{ mm h}^{-1}$ ) of finer sediments were still indicated for Charles Point Patches.

Site 5 was placed on the eastern side of the Harbour entrance channel, about 2.4 km northeast of Site 2, and in similar water depth ( $\sim 16 \text{ m LAT}$ ). The expected distributions of the suspended sediment concentrations and sedimentation were similar to those from Site 2. However, the offshore shift in the position of the ground resulted in a corresponding offshore shift in the inshore extent of plumes. No sedimentation was indicated for locations within 5 km

of the shore (Figure 12), with reduced potential for significant effects upon Darwin Harbour, the inshore habitats or the important reefs used for recreational fishing. However, as for Site 2, the axis of migration is towards the coast, indicating a risk of migrating to the coast over longer durations.

Site 6 was positioned to test the effect of moving the disposal area further east. This placed the site in shallower water (approximately 8 m LAT) and further from the main tidal flow leading into the Harbour compared to Sites 2 and 5. Results indicated that there would be greater rates of initial drift of sediments, and of subsequent resuspension, at this site, resulting in a more diffuse sediment pile (Figure 13). A greater influence of wind drift was also indicated for the finer sediments with a prediction that clays and silts would spread towards the east and drift inshore during wet season conditions to accumulate over the inshore areas toward the east. For the limited release volume and duration, maximum deposition rates over these areas were  $< 0.1 \text{ mm h}^{-1}$ , indicating a low potential for significant modification from background deposition rates.

Site 7 was located 3 km offshore from Site 6 at a depth of 12 m LAT. This shift placed the site beyond the influence of the tides running into Darwin Harbour; hence sediments were predicted to drift along a tidal axis that was approximately east-west (Figure 14). During the wet season, where there was a small net eastward drift, deposition rates  $> 0.1 \text{ mm hr}^{-1}$  were predicted to occur up to 12 km to the east but less than 7 km westward. The dry season simulation indicated the distribution would skew further to the west (up to 15 km) with no indication that sediments will be drawn into the Harbour or onto the coast.

Site 8 was placed 2 km further down slope from Site 7 (~ 13 m LAT) but within the same general current regime. Results of the simulations were very similar to those for Site 7 but the central sediment pile remained more stable over time (Figure 15). The distribution of deposition for the clay and silt sediments around the central pile did not overlap with any known reefs habitats. These outcomes were considered close to ideal.

A final site (Site 9) was selected to maximise the depth of water for a site that remained within the east-west tidal axis at approximately the same travel distance as Site 8. Site 9 was approximately 3.7 km to the north-west of Site 8 and at approximately 15 m LAT. Disposal simulations indicated that the sand and heavier particles would tend to remain near the disposal area while lighter components that drift with the tidal axis, will tend to diverge to the northeast with distance east but track west with distance west (Figure 16). This site was considered optimal for disposal, in terms of reducing the potential for sediments to impinge upon Darwin Harbour, including the shipping channel, or inshore habitats. By placing the site within the offshore tidal currents, finer sediments that are mobilised from the disposal ground over time are expected to disperse alongshore, reducing the likelihood of this material migrating into Darwin Harbour or shallow inshore habitats.

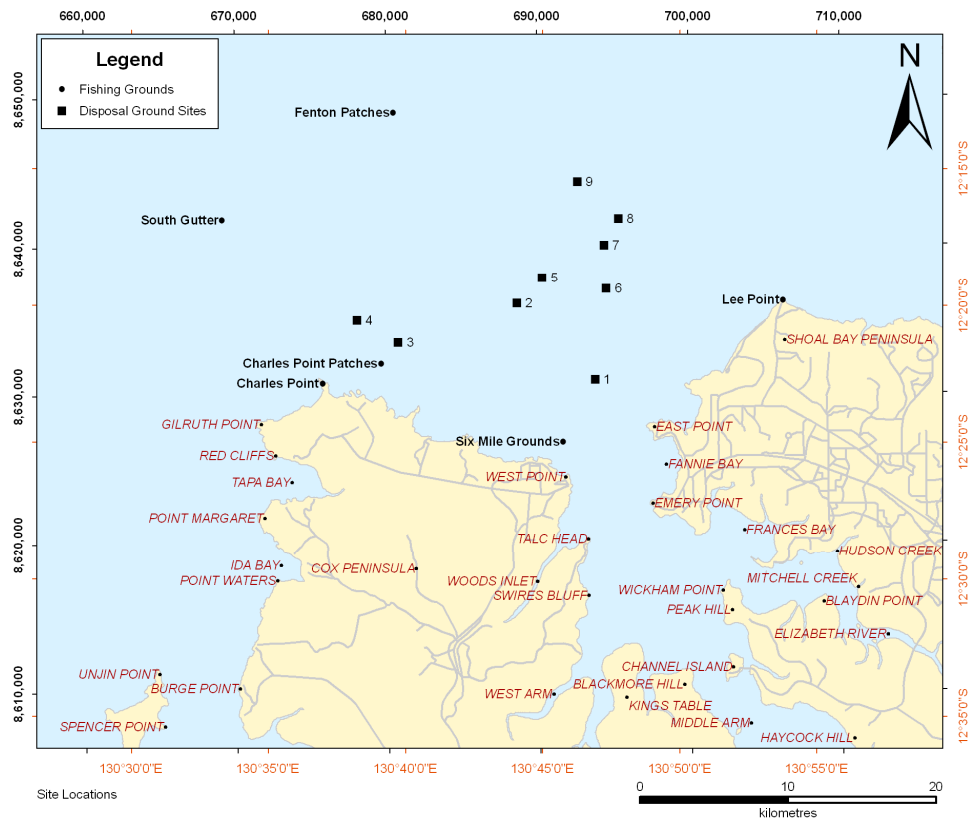


Figure 7: Location of the sites investigated for disposal operations

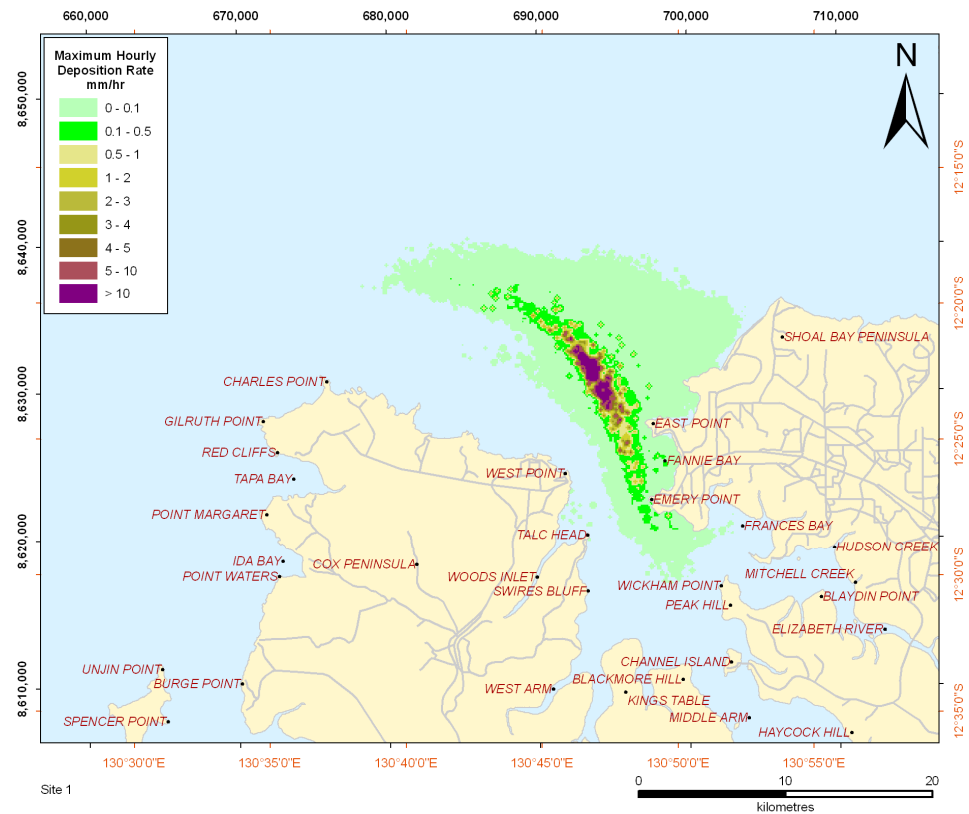


Figure 8: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 1. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.



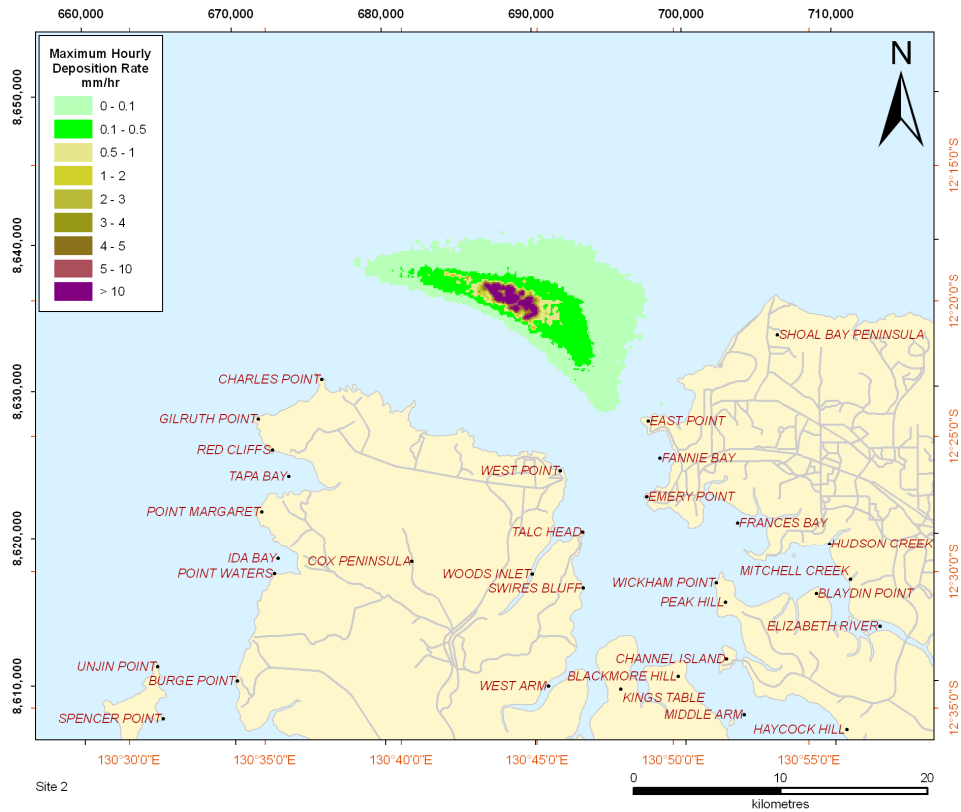


Figure 9: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 2. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

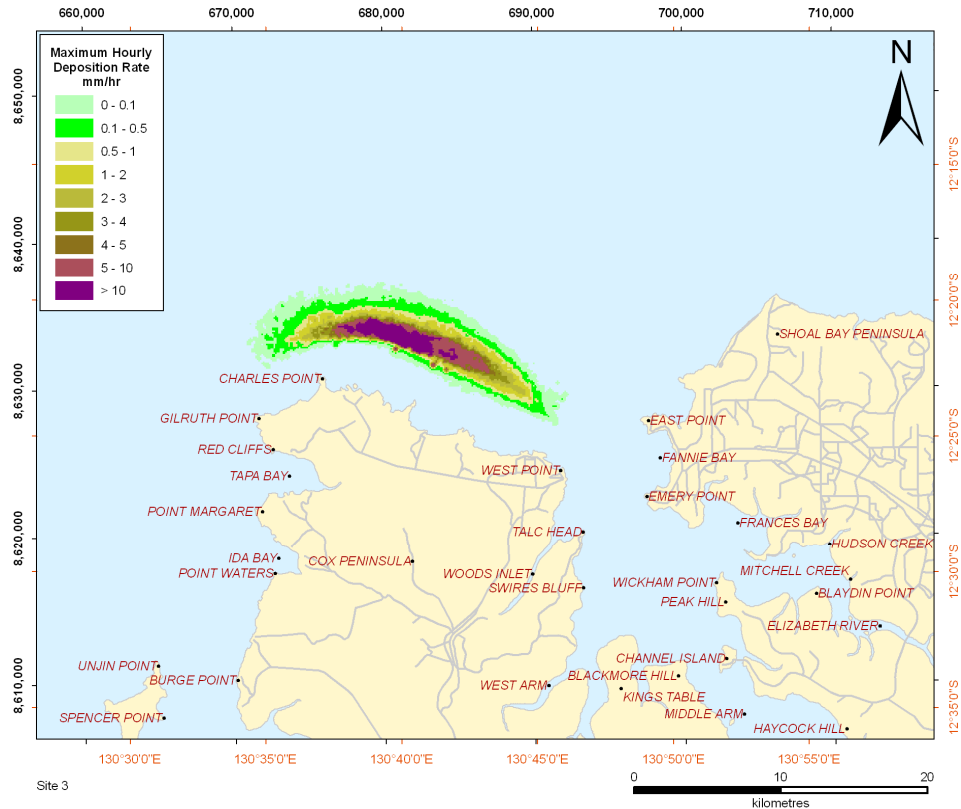


Figure 10: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 3. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

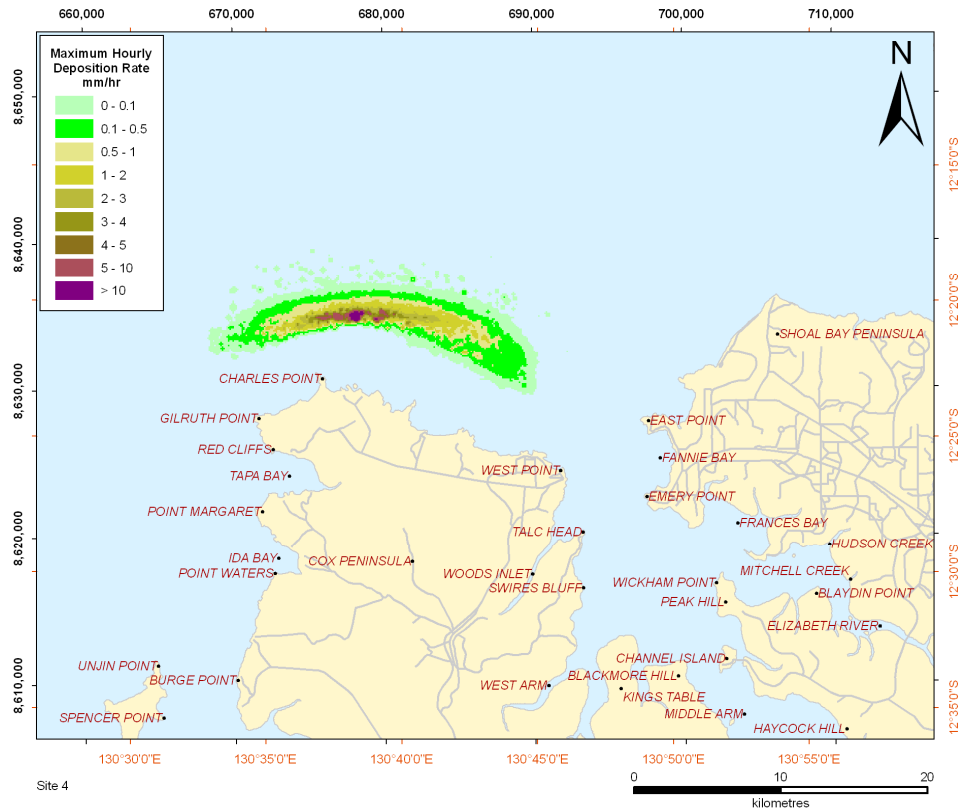


Figure 11: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 4. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

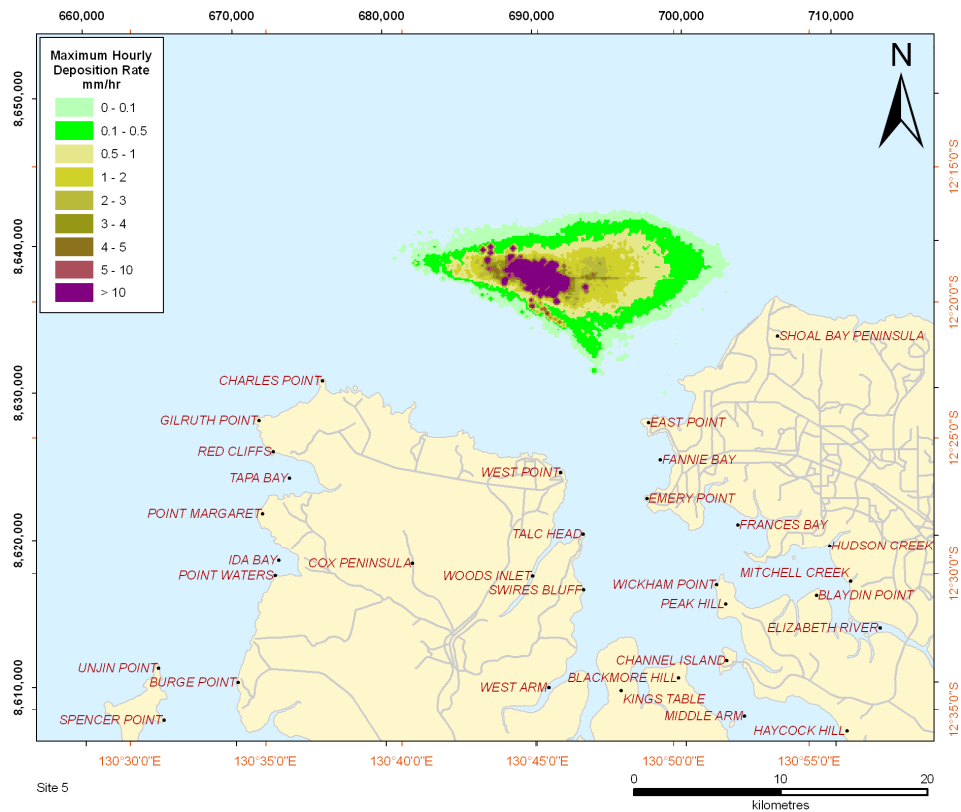


Figure 12: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 5. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

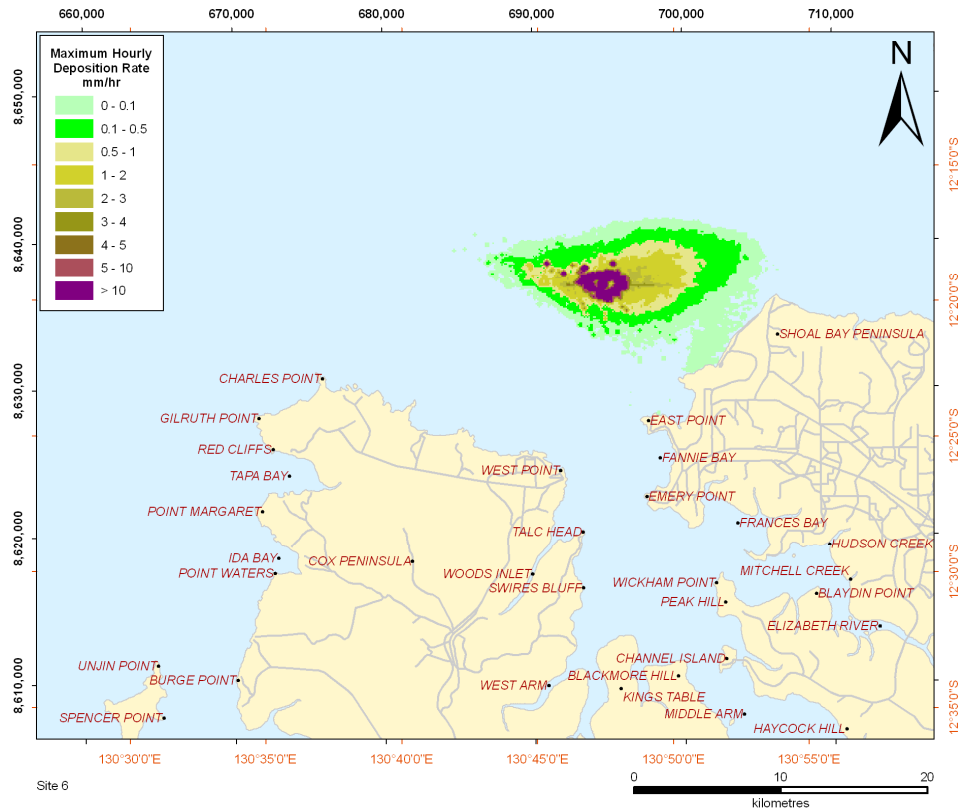


Figure 13: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 6. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

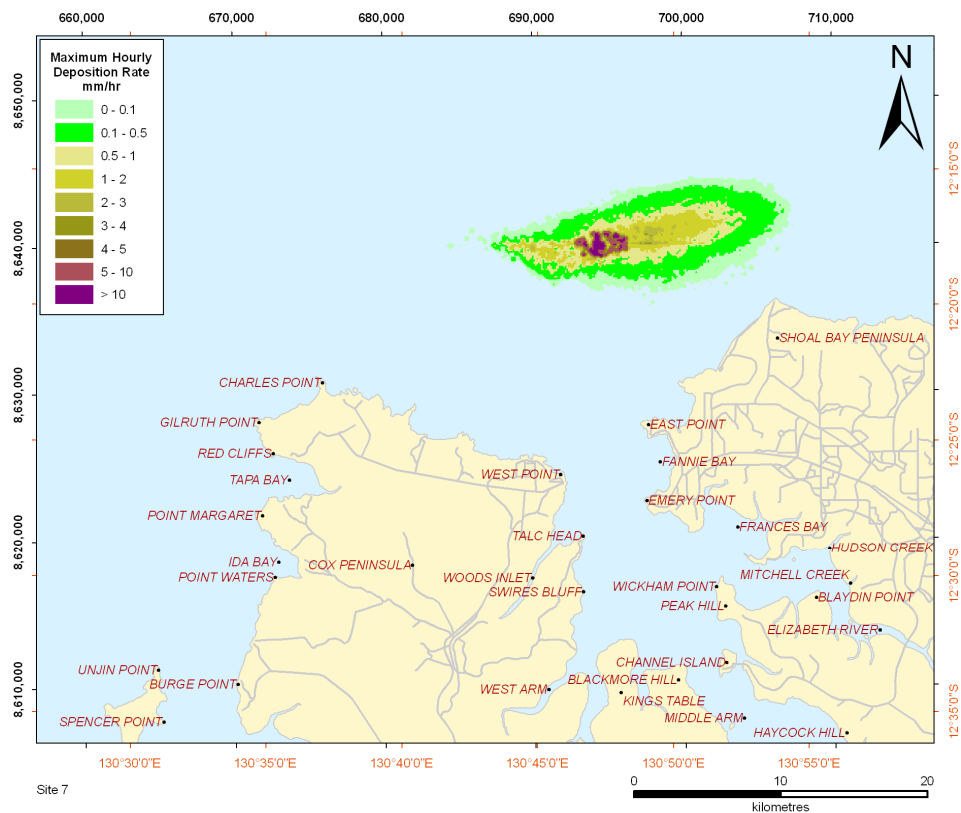


Figure 14: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 7. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

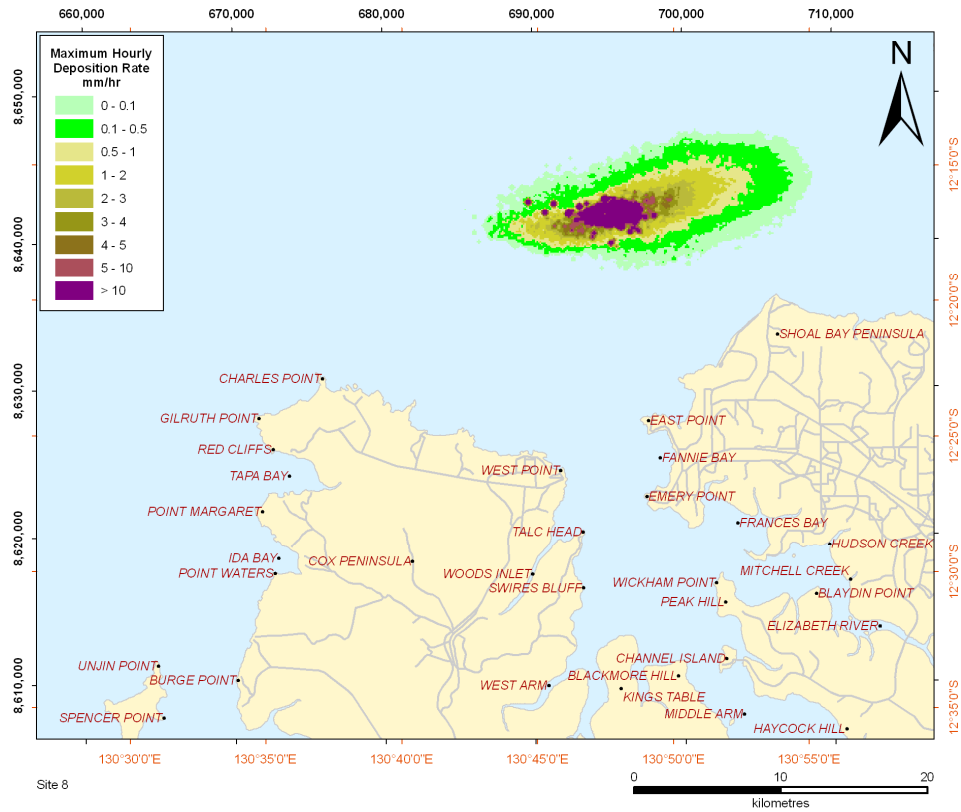


Figure 15: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 8. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

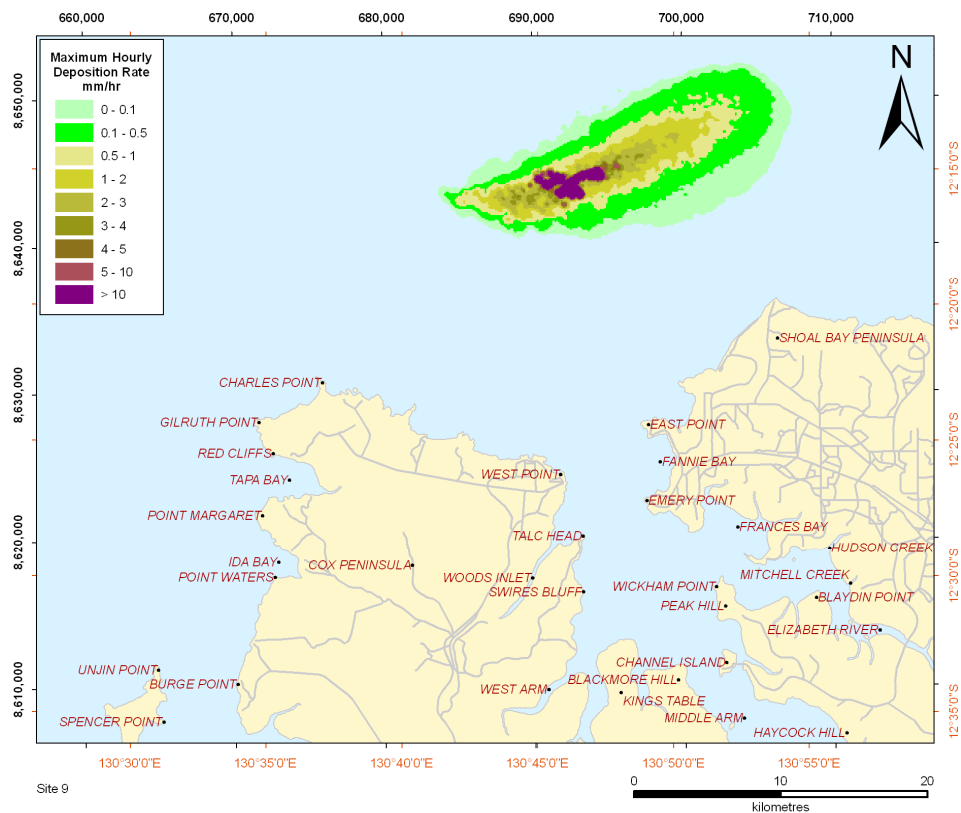


Figure 16: Predictions for the maximum hourly deposition rate at each location over a 30 day simulation, given disposal of a fine sediment mixture at Site 9. Note that maxima occur at different times at each location. Hence the field of effect is shown larger than expected for any one point in time.

## 4 DISCUSSION

A three-dimensional hydrodynamic model and a two-dimensional wave model were developed for Darwin Harbour and approaches and validated against field measurements at multiple locations and times. These checks indicated that the models were suitably precise, stable and accurate in the prediction of the current and wave climate, providing confidence that the hydrodynamic processes affecting the transport of suspended sediments as well as the settlement and resuspension processes affecting sediments were representative for the study area.

The sediment fate modelling component was conducted using a purpose designed dredging model developed by the US Army Corps of Engineers, Dredging Operations and Environmental Research (DOER) Program and Applied Science Associates (Swanson et al. 2000). This model is based on empirical measurements for a wide range of dredging and disposal operations. Importantly, the model includes algorithms that account for both the current and wave climate in the area of study, hence is suited to marine areas exposed to wave action to account for the important processes of settlement of suspended sediments to the seabed and resuspension of settled sediments back into the water column. Settlement and resuspension of sediments are natural processes that have been documented for Darwin Harbour and East Arm (Williams et al. 2006). Relatively high levels of suspended sediments have been observed, with concentrations related to tidal resuspension – hence varying temporally with the state of the tide (spring versus neap tides, flow versus slack) and spatially depending on the local current regime. Further, numerous studies have demonstrated that the resuspension of sediments that have recently settled, after being suspended by dredging, occurs at lower current speeds and wave magnitudes (e.g. Wollanski et al. 1992, van Rijn 2005). Thus, resuspension of dredged sediments has the potential to increase the spatial scale and magnitude of effects of the disposal, in terms of sedimentation and turbidity over the offshore waters surrounding the disposal operations. Hence, it was necessary to consider resuspension to assess the longer term effects of the proposed sediment discharges. These processes are most critical for the finer sediments (clay and silt sizes) that have higher surface area to mass ratios, and therefore are more subject to turbulence and shear stress in the water column and at the seabed (Soulsby 1997, Whitehouse et al. 2000).

Predictions for the rate of settlement and resuspension are sensitive to the mass of fine sediments (clay and silt-sized) specified over units of time in the release specifications. Predictions are also sensitive to estimates for the threshold levels of shear stress required to inhibit settlement to the seabed and induce resuspension from the seabed.

Modelling was applied to optimise the location of the disposal site, in terms of assessing the likely stability of sediment piles and the potential spread of sediments that leave the disposal area. These investigations indicated that dispersal of finer sediments from the disposal pile is expected to occur for all locations that are at a practical travelling distance from the dredging area. This dispersal is expected both from delayed initial settlement of fines winnowed from the descending sediment mass, supplemented by the generation of upward mixing on striking the seabed, and from resuspension of fine sediments after they initially settle. All offshore sites in this region can be considered as dispersive disposal areas under ambient conditions.

Further, the area is subject to periodic cyclones and storms, hence periodic remobilisation would occur for both dredged and ambient sediments.

Differences found between the investigated disposal locations related to the rate at which sediments of a particular size will tend to mobilise, and hence spread from the disposal ground, and the direction that particles are likely to move. Disposal within the channel leading into Darwin Harbour was indicated to result in a high probability of transport into the Harbour, and onto adjacent beaches because the tidal currents diverge through the channel to run inshore. The hydrodynamic study demonstrated that there is a shift in the tidal current axis towards alongshore flow with distance offshore. Placement of spoil further to seaward of the zone where the tidal axis shifts to east-west (seaward of a line connecting Cox and Shoal Bay Peninsulas) was indicated to result in dispersal of fines parallel with the coast. Modelling indicated that a net eastward drift will tend to transport and disperse fines eastward from offshore sites that are placed on the eastern side of the harbour beyond this area of current divergence.

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