Technical Appendix S8

Ichthys Gas Field Development Project: assessment of potential impacts on mud crabs in Darwin Harbour

Ichthys Gas Field Development Project

ASSESSMENT OF POTENTIAL IMPACTS TO MUD CRABS IN DARWIN HARBOUR

- 30 March 2011

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Executive Summary

INPEX Browse, Ltd (INPEX) is seeking approval to undertake the Ichthys Gas Field Development to extract liquefied gas from the Browse Basin. This project will require the development of offshore, nearshore and onshore infrastructure as well as a considerable amount of dredging in Darwin Harbour. The construction and operation of the project facilities may have direct and indirect impacts on marine habitats and communities and potential impacts of the project were investigated in the *Ichthys Gas Field Development Project: Draft Environmental Impact Statement* (Draft EIS). During the submissions period of the Draft EIS concerns were raised from stakeholders over potential impacts to mud crabs in Darwin Harbour and Shoal Bay as a consequence of elevated suspended sediment and sedimentation and this report was produced in response to these concerns.

This report identifies and describes the potential direct and indirect impacts that the Project dredging and spoil disposal activities may have on aspects of key life history stages, identifies and describes mitigating factors for each of these potential impacts to mud crab populations in Darwin Harbour and Shoal Bay and assesses the level of impact associated with each of the identified potential impacts.

A thorough literature review, including key stakeholder consultation, was completed to determine the potential impacts of suspended sediment on mud crabs in Darwin Harbour. Potential impacts to aspects of mud crab biology and ecology including the habitat, migration, feeding, mating, activity, growth and settlement and recruitment patterns at key phases on the life cycle were investigated.

An environmental risk assessment was undertaken to identify all potential impacts to mud crabs and identifies impacts to each life cycle phase of the mud crab. The risk assessment shows that all identified potential impacts to mud crabs were low residual risk with the exception of one impact on migration of adult and juvenile mud crabs which was identified as a medium risk.

1. Introduction

1.1. Background

INPEX Browse, Ltd (INPEX) is seeking approval from the Northern Territory Government and Commonwealth Government, to undertake the Ichthys Gas Field Development Project (the Project) to extract liquefied gas and condensate from the Ichthys Field in the Browse Basin located 820 km west-south-west of Darwin. The majority of the condensate is expected to be exported directly from an offshore central processing facility, while natural gas will be transported via a gas export pipeline from the Ichthys Field to onshore processing facilities located at Blaydin Point in Darwin Harbour.

The Project will require the development of both offshore, nearshore and onshore infrastructure. Major offshore infrastructure will consist of subsea wells and a floating central processing facility. The nearshore development will encompass an area at Blaydin Point for construction of a shipping channel, approach area, turning basin, tanker berthing area and module offloading facility and a corridor for the gas export pipeline from the mouth of Darwin Harbour to an onshore crossing south of Wickham Point on Middle Arm Peninsula, where it will connect to onshore gas processing facilities.

A significant amount of dredging is required in Darwin Harbour to support the Project. Based on preliminary estimates of dredge volumes for each of the key Project components, it is expected that a total of 16.9 million cubic metres (Mm^3) of dredge spoil will be generated over the duration of the dredging program. The dredging required for the installation of the shipping channel, turning basin and berthing area will generate the majority of the dredge spoil (15.1 Mm^3). Dredging activities for the module offloading facility and subsea section of the gas export pipeline are expected to generate smaller volumes of dredge spoil (1.2 Mm^3 and 0.6 Mm^3, respectively). All dredge spoil will be transported to an offshore disposal ground site 20 km north of Darwin Harbour.

The construction and operation of the Project facilities may have direct and indirect impacts on marine habitats and communities. Potential impacts of the Project were investigated in the development of the *Ichthys Gas Field Development Project: Draft Environmental Impact Statement* (Draft EIS) (INPEX 2010). This included an impact assessment that considered the potential impacts of nearshore dredging and dredge spoil disposal on significant nearshore marine habitats and communities in Darwin Harbour (Draft EIS, Chapter 7, INPEX 2010). Potential impacts to mangrove, hard coral, soft-coral and sponge communities, marine mammals, reptiles and fish within and surrounding the Project area in Darwin Harbour were assessed, and the outcomes of the impact assessments are presented in Chapter 7 of the Draft EIS (INPEX 2010).

Recreational fishing for mud crabs is a locally important pastime in Darwin Harbour and Shoal Bay. Potential impacts to mud crabs as a consequence of elevated suspended sediment and sedimentation were not specifically addressed in the Draft EIS. Therefore, in response to the concerns raised in draft EIS submissions from stakeholders, the proponent has commissioned Sinclair Knight Merz to investigate the potential for environmental impacts to mud crabs in Darwin Harbour and Shoal Bay from elevations in suspended sediment and sedimentation as a consequence of dredging and dredge spoil disposal activities associated with the development of nearshore infrastructure.

1.2. Objectives

The key objectives of this desktop study were to:

- identify potential environmental impacts on mud crabs from the dredging and dredge spoil disposal activities associated with the nearshore construction activities of the proposed Ichthys Gas Field Development Project; and
- assess the level of risk of each of the identified impacts.

1.3. Methods

Two species of mud crabs, *Scylla serrata* and *S. olivacea,* are known to occur in Darwin Harbour and Shoal Bay. A review of the existing literature was undertaken to compile relevant information on key aspects of mud crab biology and ecology at various life history stages including habitat, migration, feeding, growth, reproduction, settlement and recruitment. Background information on the existing physical processes in Darwin Harbour and Shoal Bay was also reviewed, with a specific focus on existing water quality and sedimentation regimes.

The information on the biology of the two species and the physical processes was then examined within the context of the Project activities and outcomes of the predictive modelling of sediment dispersal for the proposed dredge program to:

- identify and describe the potential direct and indirect impacts that the Project dredging and spoil disposal activities may have on aspects of key life history stages for each of the two species that occur in Darwin Harbour and Shoal Bay;
- identify and describe mitigating factors for each of the potential impacts to mud crab populations in Darwin Harbour and Shoal Bay; and
- assess the level of risk associated with each of the identified potential impacts.

2. Stakeholder consultation

Table 2-1 in Chapter 2.2.4 of the Draft EIS (INPEX 2010) was used to identify the relevant stakeholders to contact.

Representatives from the Northern Territory Fisheries (NT Fisheries), Darwin Aquaculture Centre, Australian Institute of Marine Science (AIMS), Queensland Department of Employment Economic Development & Innovation (DEEDI) and Bribie Island Research Centre were contacted for additional information on mud crab distribution and the potential impacts of suspended sediments and/or sedimentation on mud crabs.

Anecdotal advice on recreational mud crab fishing activities including information about fishing methods and key fishing grounds was sought from AFANT. Chris Makepeace (the Executive Officer of AFANT) provided information on areas within Darwin Harbour and Shoal Bay that are targeted by recreational fishers, when recreational fishing occurs, and the fishing methods. This information is included in Section 3 of this report. The stakeholders contacted provided information on the general distribution of mud crabs, but detailed information on interannual or seasonal catch variability was not available. NT Fisheries are preparing a report on recreational fisheries, but this information will not be available for public access until next year.

No stakeholders were able to provide any information on the potential impacts of suspended sediments and/or sedimentation on mud crabs.

3. Darwin Harbour mud crab fisheries

Mud crabs sustain valuable commercial and recreational fisheries throughout the Indo-west Pacific, the most economically important species being *S. serrata* (Ward et al. 2007). *Scylla serrata* is the key species targeted by the Northern Territory Mud Crab Fishery, while *S. olivacea* accounts for less than 1% of the overall catch (Handley 2010). The fishery is managed by the Fisheries Division of the Northern Territory Department of Resources (DoR) and consists of four sectors, including commercial, recreational, fishing tour operators and indigenous fishers (Ward et al. 2007).

Commercial mud crab fishing is not permitted in Darwin Harbour or most creeks adjoining Shoal Bay but recreational fishing is a popular pastime for both local fishers and tourists in Darwin Harbour and Shoal Bay. There is no published information available on long-term trends in the recreational fishery catch, effort or catch composition. Surveys of recreational fishers in 1995 and 2000 indicated that most recreational mud crabbing activity in the Northern Territory occurred in the Darwin Harbour and Shoal Bay area and at the McArthur and Roper Rivers (Coleman 1998, 2004). In 2001, recreational fishers harvested over 82 000 mud crabs, 74% of which were caught in the Darwin Harbour and Shoal Bay area (Coleman 2004). Fishing tour operators and indigenous fishers also occasionally target mud crabs in the Darwin Harbour and Shoal Bay area although catches are small compared to that of recreational fishers. In 2009, fishing tour operators harvested only 900 mud crabs (Handley 2010).

Recreational fishers are permitted to fish for crabs in all waters of tidal influence except for those within the boundaries of Kakadu National Park (Handley 2010). Within Darwin Harbour, crabbing activity generally takes place in the intertidal mangrove areas and smaller channels of the numerous creeks (pers. comm., C. Makepeace, Executive Officer AFANT) which flow into the West, Middle and East Arms of the Harbour and that of Shoal Bay. Most recreational mud crab fishers use baited crab pots and a restriction of five pots per person and maximum of ten pots per vessel applies. Crabs may also be harvested by other methods including hand spear, hooks, hooks and lines or nets (Handley 2010).

Recreational mud crab fishing occurs year-round, predominantly during the day on rising tides. Fishing activity usually decreases following heavy rainfall during the wet season, when fishers assume that crab activity is low (pers. comm., C. Makepeace, Executive Officer AFANT).

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4. Darwin Harbour water quality and sedimentation

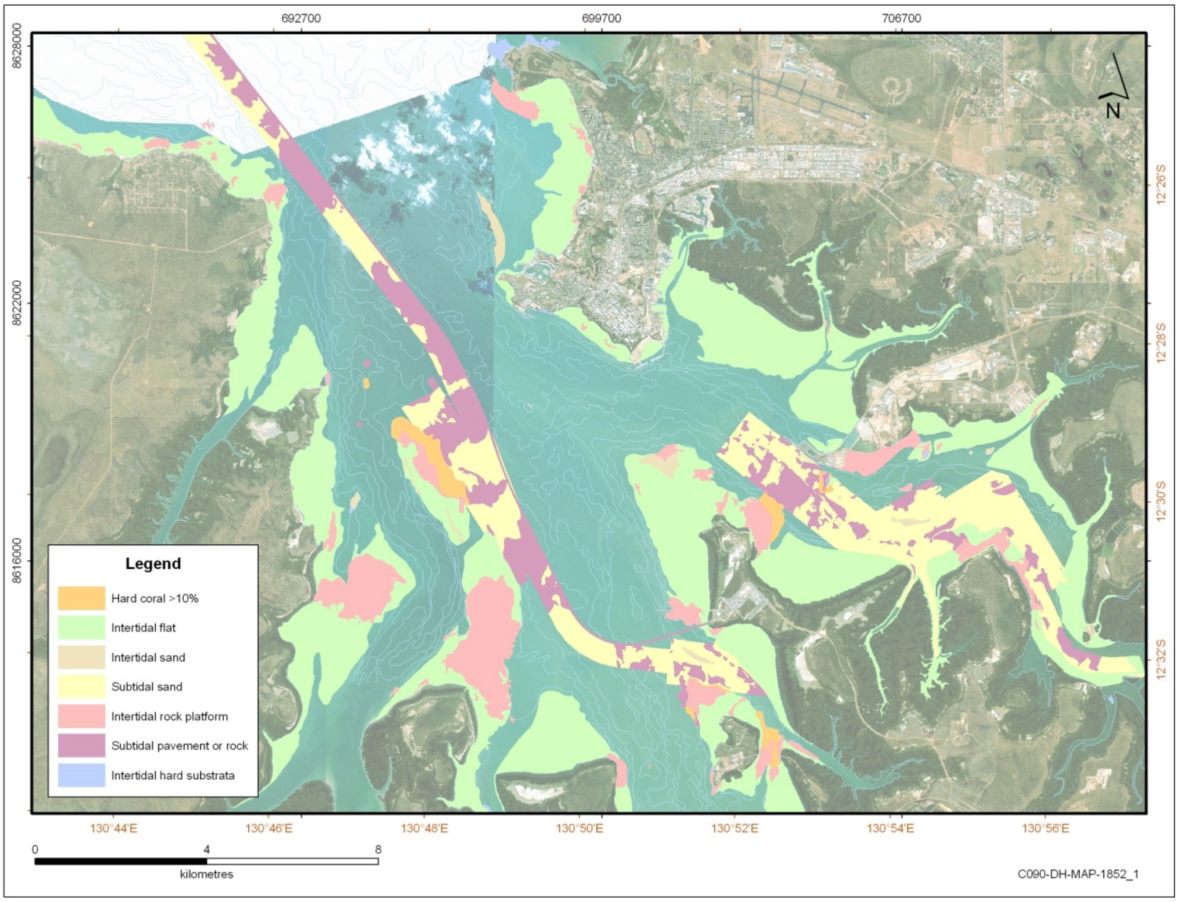
4.1. Background

Darwin Harbour is a large ria system, including the estuarine areas and tributaries of Woods Inlet, West Arm, Middle Arm and East Arm (DHAC 2003). The macrotidal tropical estuary supports an extensive system of intertidal and subtidal mud flats and creeks, fringed by mangroves (**Figure 4-1**) (Semeniuk 1985, Hanley 1988). The mangrove communities cover an area of more than 26 000 hectares and support an abundance of marine and estuarine fauna, including mud crabs (Semeniuk 1985, DHAC 2003). Intertidal and subtidal mudflats cover more than 55 000 and 66 000 hectares respectively (McKinnon et al. 2006). Coral, algal and seagrass habitats in the Harbour are restricted to deeper areas (>5 m depth) characterised by strong currents (e.g. Gunn Point and Channel Island) as frequent high turbidity and smothering by sedimentation inhibit survival in other areas of the Harbour (DHAC 2003, Smit 2003).

The habitats of Shoal Bay, which lies to the east of the main Darwin Harbour port, are similar to those of the Harbour, consisting of shallow intertidal mud flats, sand flats and fringing mangrove communities which are predominantly found on the estuary of the Howard River (DHAC 2003).

Water quality and sedimentation characteristics within Darwin Harbour vary seasonally and in response to local tidal processes. The main driver is the tidal cycle and the Harbour is subject to strong tidal currents and tidal ranges of up to 8 m (McKinnon et al. 2006). Another important influence is the tropical monsoon climate with marked seasonality and average rainfall of approximately 1 700 mm that is mostly confined to the months of January to March during the wet season (December to April). Rainfall runoff discharges into Darwin Harbour via the small catchment of the Blackmore and Elizabeth Rivers, while Howard River drains into Shoal Bay (DHAC 2003). Rainfall is typically negligible during the dry season months of May to November (DHAC 2003, Burford et al. 2008).

The natural background water quality and sedimentation characteristics of Darwin Harbour and Shoal Bay are detailed in Chapter 3 of the Draft EIS (INPEX 2010). A brief overview of typical water quality and sedimentation regimes is provide here with an emphasis on the key parameters which are predicted to be altered during dredging and dredge spoil disposal activities.



- **Figure 4-1 Marine Habitats in Darwin Harbour**

4.2. Existing water quality and sedimentation regimes

4.2.1. Water quality

The water quality in Darwin Harbour varies considerably as a result of the interaction of seasonal and tidal processes. Tidal action is considered to be the most dominant influence on water quality in the Harbour. The estimated daily tidal inflow and outflow is 216 Mm^3 of water during a spring tide and up to 71 Mm^3 during a neap tide (Padovan 1997). Thus there is an estimated tidal exchange of 69% on spring tidal cycles and 29% on neap tides. The large net tidal exchange of water and strong tidal currents that move up to 2 m s^{-1} during spring tides regularly re-suspend and transport sediment within the Harbour (Burford et al. 2008).

The suspension of sediments and other materials causes turbidity, limiting the amount of light that can penetrate the water column. Water within the Harbour is naturally turbid and turbidity is generally highest during spring tides when tidal exchange also peaks. Within the main body of the

Harbour, natural turbidity levels vary between 5 to 35 Nephelometric Turbidity Units (NTU) during a spring tide (Padovan 1997), though higher turbidity levels have been recorded in other areas of the Harbour. In Middle Arm, turbidity levels of up to 70 NTU have been recorded during a spring tide (Padovan 2003). Similarly, levels of 73.6 NTU have been recorded in the proposed nearshore development area (URS 2009). Further, preliminary results from measures of the baseline water quality within and surrounding the nearshore Project area have found turbidity levels to fluctuate from between approximately 60 NTU to less than 10 NTU in the wet season, and approximately 30 NTU to less than 10 NTU in the dry season in the Middle Arm area. Turbidity levels of over 50 NTU and 20 NTU were recorded near the proposed nearshore development during the wet season and dry season, respectively (INPEX unpublished data). This demonstrates that turbidity is naturally quite high within the Harbour and may be highly variable according to tidal cycle, location and season.

The most commonly used measure of suspended sediments, total suspended solids (TSS) is a direct and quantitative measure of the amount of material suspended in the water column. Elevated TSS levels in the Harbour generally coincide with spring tides and the wet season (McKinnon et al. 2006). In a survey by URS at Blaydin Point adjacent to the nearshore development area, TSS ranged between 1.5 and 83 mg L^{-1} with an average of 15 mg L^{-1} (URS 2009). Natural TSS concentrations within the main body of the Harbour are known to range from less than 50 mg L^{-1} up to 250 mg L^{-1} (Williams et al. 2006) and are generally higher in the upper reaches of tidal creeks (McKinnon et al. 2006).

Information on the concentrations of contaminants in the water column of Darwin Harbour is limited (Padovan 2003). The few studies that have been carried out indicate that overall the total concentrations of particulate and dissolved heavy metal contaminants are low (DHAC 2009, Parry 2010). The presence of organic contaminants in the water column is also considered to be low (Padovan 2003).

4.2.2. Sediment characteristics

Like other macrotidal mangrove estuaries, sediment transport, deposition and composition in Darwin Harbour are influenced largely by the interaction of tidal movements and the extent and composition of the mangrove fringe (Semeniuk 1985, Alongi 2009). Mangrove communities promote accretion of soft fine sediments in the intertidal zone by reducing tidal flows and increasing flocculation and trapping of suspended sediments during low tide (Williams et al. 2006, Alongi 2009).

Soft sediments constitute the majority (approximately 80%) of the Darwin Harbour seafloor (DHAC 2003, McKinnon et al. 2006). This includes the mud and fine sands that have accumulated under the influence of the mangrove communities to form extensive intertidal mudflats including the areas supporting mangroves. Coarser sediments of sand and gravel typically occur in the deeper main channels and towards the mouth of the Harbour in the spits, shoals and beaches (McKinnon et al. 2006).

Concentrations of metal contaminants in the sediments of Darwin Harbour are generally low with the exception of arsenic which is present in higher concentrations (Padovan 2003). These high levels of arsenic in the sediment are thought to be a result of local geological processes as opposed to anthropogenic causes (Padovan 2003).

Evidence of elevated concentrations has been found at some sites within Darwin Harbour. At the Iron Ore wharf, high levels of cadmium, copper lead and zinc (10–100 times higher than natural background levels) have been recorded, which was attributed to wharf loading activities. Elevated concentrations of copper, lead and zinc have also been found in nearshore Harbour sediments adjacent to urban and industrial land-use areas. This suggests that run-off from these areas has resulted in the accumulation of these metals (Padovan 2003, Parry 2010).

The analysis by URS of metal concentrations in surficial sediments within East Arm, Middle Arm and Darwin Harbour has been discussed in Chapter 3.3.5 of the Draft EIS (INPEX 2010). The findings of this study were consistent with previous studies in the Darwin Harbour: namely, the concentration of metals in surficial sediments of Darwin Harbour are naturally low except for that of arsenic which occurs naturally at high concentrations in the sediment (URS 2009). Further tests indicated that arsenic is not likely to be biologically available and therefore not toxic in the marine environment of the Harbour and Shoal Bay (URS 2009).

Similarly, concentrations of organic contaminants including hydrocarbons (polyaromatic and petroleum hydrocarbons), butyltins (including tributyltin [TBT] which is a compound derived from antifoulants) and pesticides have been found to be generally low in Darwin Harbour sediments. Some isolated areas of contaminants have been found around existing infrastructure (e.g. the Fisherman’s Wharf area) (Padovan 2003). In a study of sediments within the nearshore development area, hydrocarbons were below laboratory detection and no TBTs were detected at any of the sampling sites (URS 2009, INPEX 2010).

4.3. Predicted impacts to water quality and sedimentation during dredging

The proposed dredging and dredge spoil disposal methods and outcomes of predictive modelling for the Project’s preliminary dredge program are presented in Chapter 4 and Chapter 7 of the Draft EIS, respectively (INPEX 2010). Dredge vessels are expected to operate 24 hours per day 7 days per week during specified periods over a period of four years in order to construct a shipping channel, approach area, turning basin, berthing area, module offloading facility, gas export pipeline and pipeline shore crossing in the nearshore development area. Dredging activity is expected to

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increase steadily and peak when several vessels work simultaneously (approximately 2.5 years into the dredging program) in the berthing area and turning basin, then decrease considerably in later phases of dredging (INPEX 2010).

The nearshore dredging program is expected to generate a total of 16.9 Mm^3 of dredge spoil. The material to be dredged is composed largely (14.2 Mm^3) of clays, silts sands and gravels and a smaller component of stronger material (2.7 Mm^3) including soft (phyllite) and hard rock. Disturbance of this material will cause sediment transport and deposition and associated increases in turbidity and suspended sediment to areas of Darwin Harbour. The hard rock materials to be dredged are considered stable and expected to generate limited amounts (<0.1%) of fines (<75 µm), with the exception of soft phyllite rock, which may potentially generate some fines. The soft unconsolidated sediments, on the other hand, are comprised of large amounts of fines (an average of 39.2%) and therefore have a higher potential to become suspended in the water column (INPEX 2010).

Sediment fate modelling was used to predict the extent and intensity of the impacts that the release of this additional sediment to the water column will have on the nearshore environments of the Harbour. The outcomes of the modelling study are summarised in Chapter 7 of the Draft EIS (INPEX 2010).

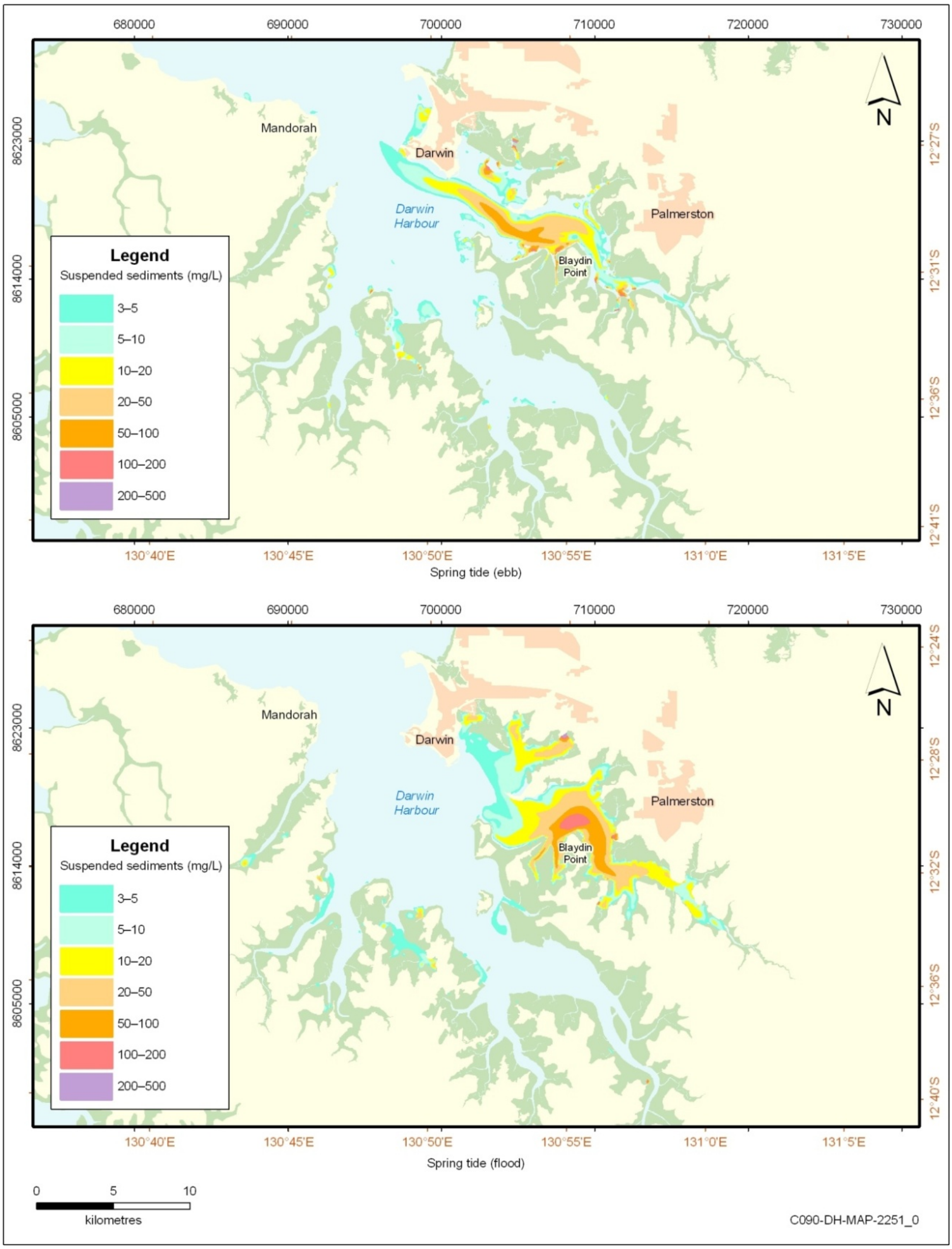
4.3.1. Sediment suspension

During dredging a proportion of fine sediments (<75 µm) will immediately go into suspension and, under the influence of prevailing hydrodynamics, will be dispersed to surrounding areas where the material will potentially settle and be available for re-suspension. A proportion of coarser materials (>75 µm sand and gravel) will also become suspended in the water column. However, these coarser sediments will drop out of suspension close to the sites of dredging and dredge spoil disposal which limits the transport potential of the coarse sediments (Appendix 13, Draft EIS, INPEX 2010).

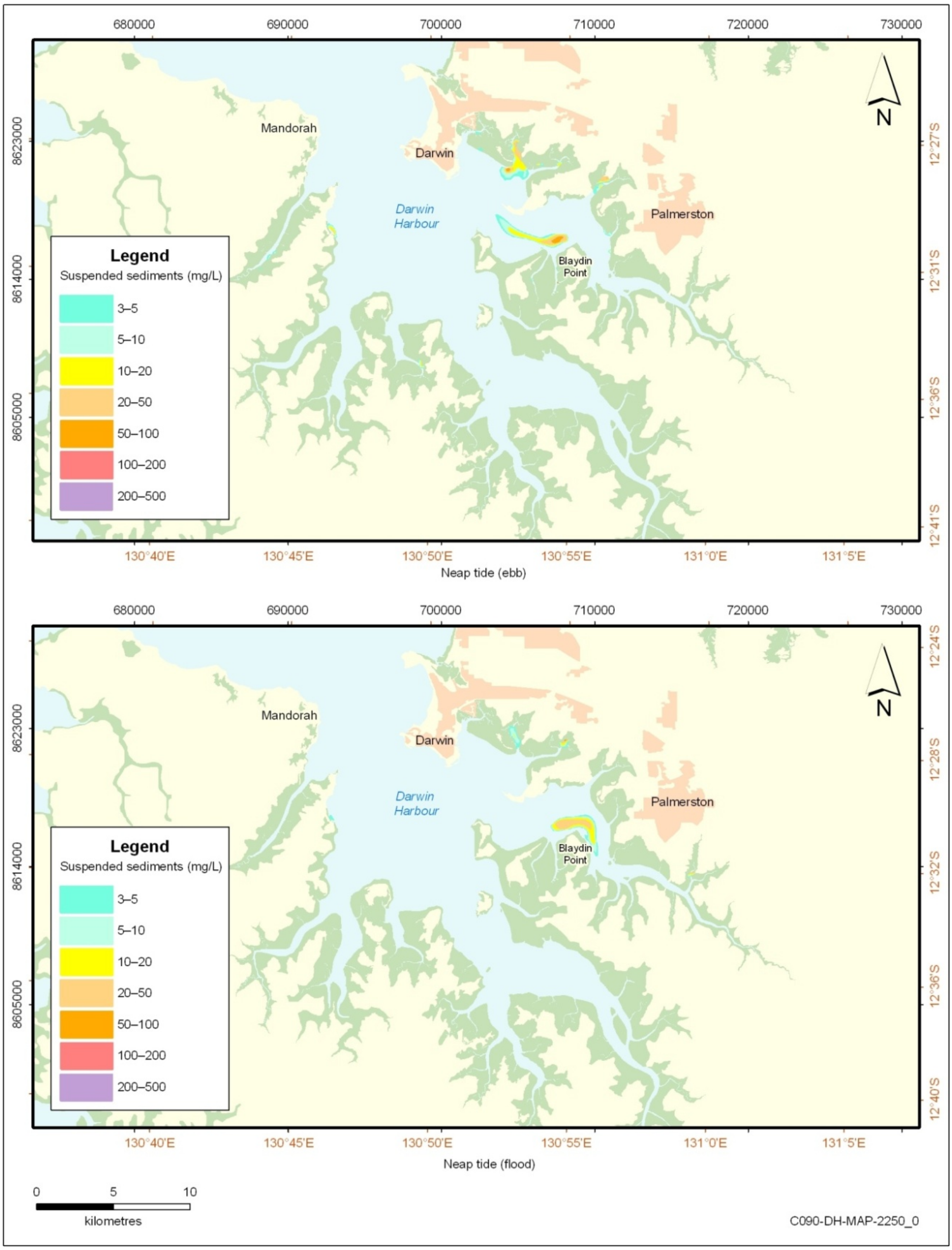
Dredging activities will generate low concentrations of suspended sediments that will generally remain confined to the upper estuary waters of the East Arm but under spring tide conditions, plumes may extend further (**Figure 4-2**). During peak dredging activities (Phase 6, 2.5 years into the dredging program) under the influence of spring tides, concentrations of suspended sediments are anticipated to vary between 3 mg L^{-1} and 200 mg L^{-1} above ambient. The highest concentrations above ambient are expected within closest proximity to the dredge footprint, while the upper reaches and creeks of the East Arm may experience elevated concentrations of suspended sediments between 3 mg L^{-1} and 20 mg L^{-1} and some isolated patches of up to 200 mg L^{-1} above ambient (**Figure 4-2**). During neap tide conditions suspended sediment generated by dredge operations are predicted to remain in the vicinity of the immediate dredge zone, while some isolated areas of elevated suspended sediment are predicted to occur in some intertidal creeks in

East Arm (**Figure 4-3**). Some short-term dredging (approximately 5 weeks) will also be required for the pipeline shore crossing in intertidal and subtidal mud flats near Wickham Point. Predicted suspended sediment concentrations above ambient for this area are relatively low (<20 mg L^{-1}).

Sediment suspension surrounding the dredge spoil disposal ground is predicted to be isolated to a small offshore area and in low concentrations 3 to 5 mg L^{-1} above background for the majority of the duration of the dredging program (Appendix 13, Draft EIS, INPEX 2010). Under worst-case conditions, suspended sediments may be transported into Shoal Bay and into the mouth and tidal creeks of the Howard River. Concentrations are anticipated to range between 3 and 10 mg L^{-1}, with some isolated patches of suspended sediments up to 20 mg L^{-1} and 200 mg L^{-1} (**Figure 4-4**). However it should be noted that **Figure 4-4** represents the 95^{th} percentile of suspended sediment concentrations during Phase 5 of the dredging program. Therefore, although the areas affected are large, the elevations in suspended sediments are generally low intensity (<10 mg L^{-1}), will occur only during spring tides (when background concentrations are naturally high) and the total time wherein suspended sediment concentrations meet or exceed these values is also low (approximately 19 hours) in comparison to the duration of Phase 5 (approximately 4 months) (Section 4.7 of Appendix 13, Draft EIS, INPEX 2010).



- **Figure 4-2 Predicted instantaneous suspended-sediment concentrations during a spring tidal cycle at peak dredging in Phases 6**



- **Figure 4-3 Predicted instantaneous suspended-sediment concentrations during a neap tidal cycle at peak dredging in Phase 6**

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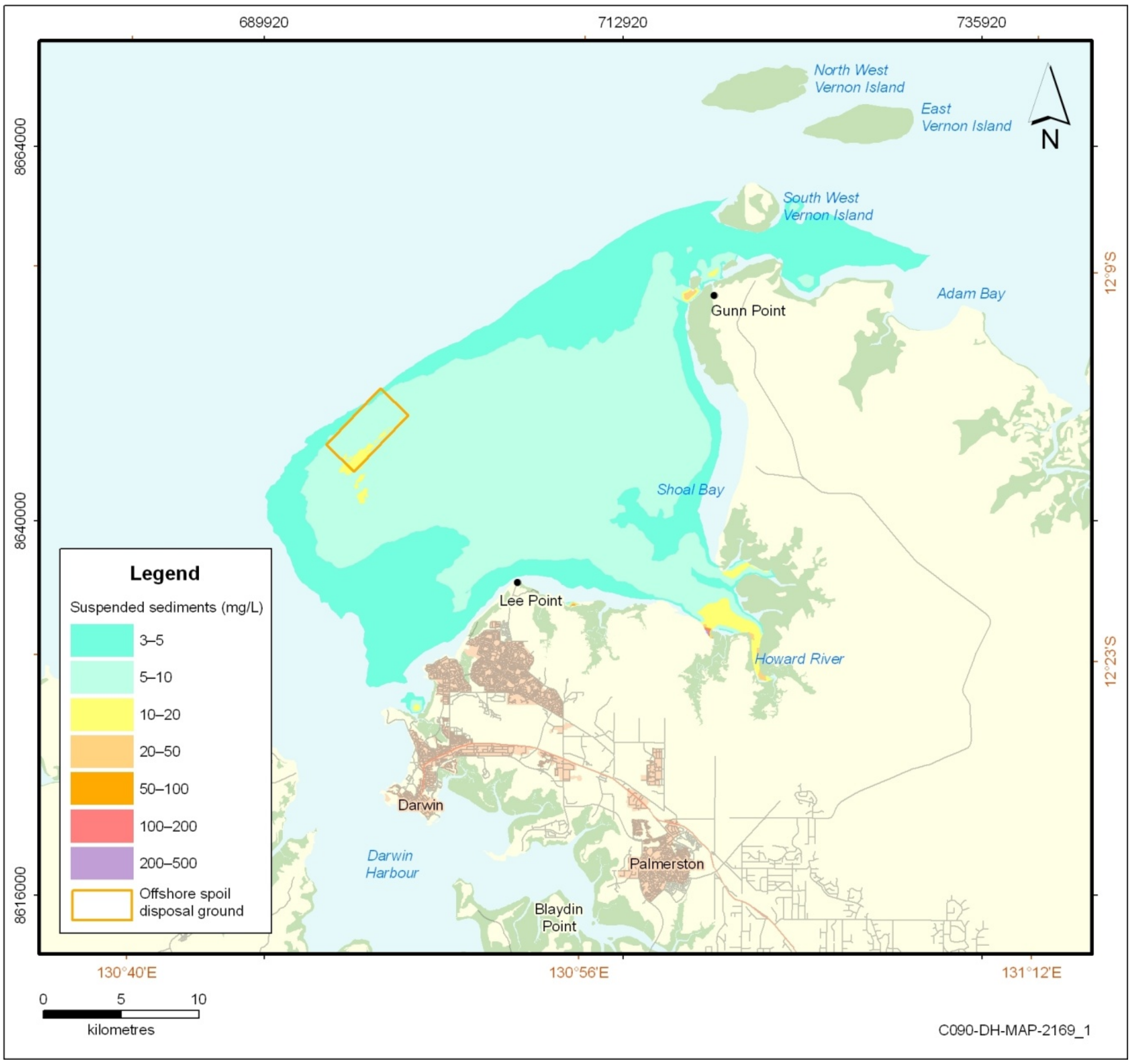

- **Figure 4-4 Predicted 95th percentile suspended-sediment concentrations during Phase 5 of the dredging program**

4.3.2. Sedimentation

Ongoing resuspension of fine sediments disturbed by the dredging and dredge spoil disposal activities is anticipated. These sediments are predicted to eventually accumulate in patches of intertidal areas throughout East Arm (**Figure 4-5**), where mangrove communities act as natural sediment sinks for fine sediments (Alongi 2009). Net sedimentation is predicted to occur gradually in some areas over the duration of the dredging program. An area of 30 ha (of a total of approximately 26 000 ha) of mangroves in Darwin Harbour will accumulate more than 50 mm of sediment within the first three years of the dredging program. Of this area, 2 ha may receive more than 100 mm over the duration of the four-year dredging program; which is approximately 35 mm per year (**Figure 4-5**) (Appendix 13, Draft EIS, INPEX 2010). The area affected will be quite small, less than 1% of the total area of mangroves in Darwin Harbour. Some limited sediment accretion, predicted to range between 5 mm and more than 100 mm, will also occur along the intertidal areas of Shoal Bay and within natural deposition areas of the lower reaches of the Howard River as a result of material escaping the dredge spoil disposal ground over the duration of the dredging program (**Figure 4-6**) (Appendix 13, Draft EIS, INPEX 2010). Increased loadings of sediment to the water column may lead to net increases in sedimentation in some small areas of mangrove in East Arm and Shoal Bay, however in the longer term some of this sediment may be further redistributed. The particle size distributions of the sediments permanently accreted to these areas are expected to be similar to those of the sediments already present at these sites (Chapter 3, Draft EIS, INPEX 2010) as a result of the influence of natural sediment transport and sedimentation dynamics (Alongi 2009).

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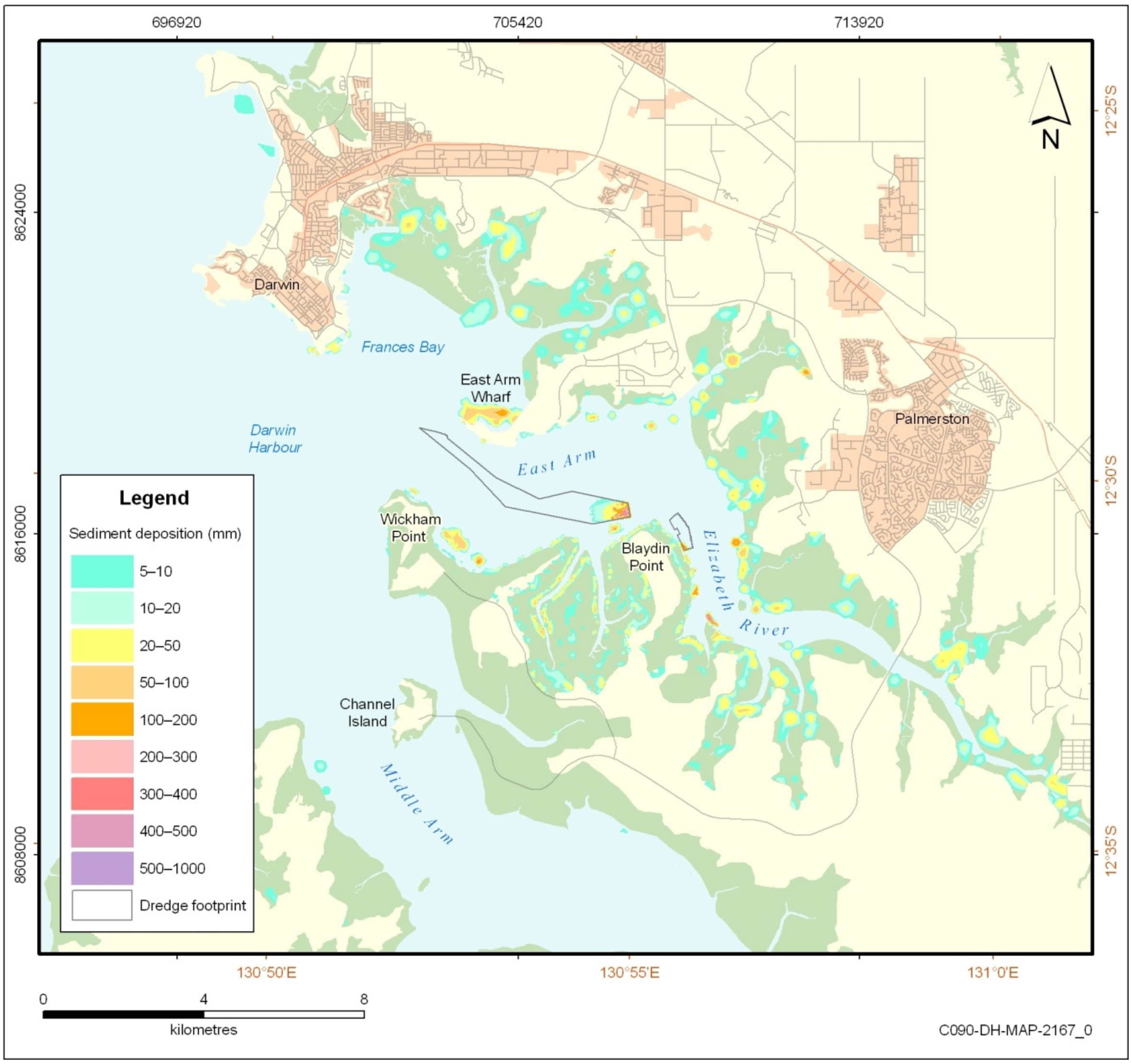
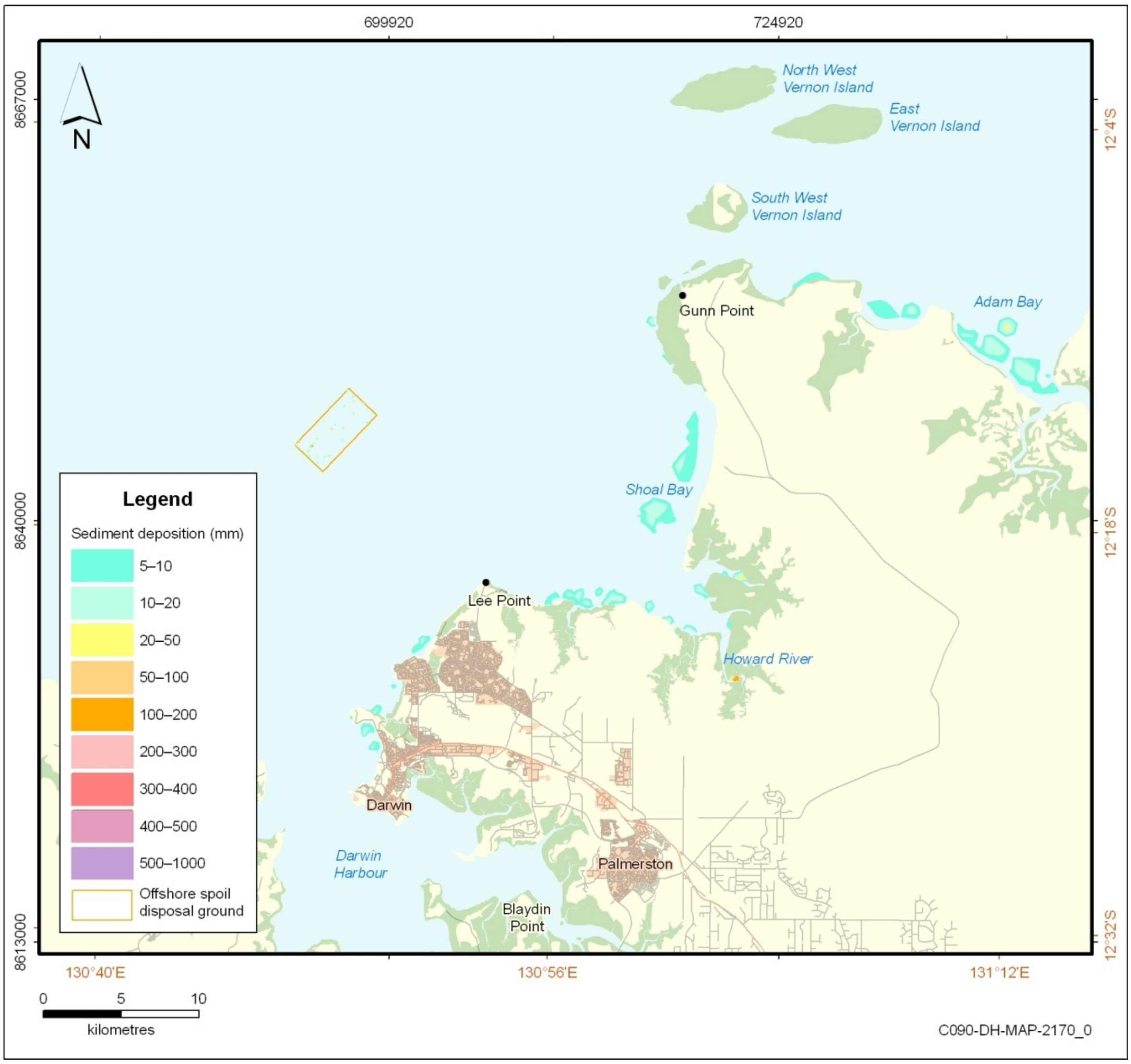


- **Figure 4-5 Predicted shoreline sediment accumulation at the end of peak dredging in Phase 6**



- **Figure 4-6 Predicted coastal sediment accumulation at the end of Phase 6 of the dredging program**

4.3.3. Release of contaminants

The sediment to be dredged is considered to be uncontaminated (Chapter 3 and Appendix 9, Draft EIS, INPEX 2010). Therefore, upon disturbance there is limited potential for significant levels of contaminants to become available in the water column or to accrete in other areas. However, the potential risk for sediments to oxidise upon exposure of dredged sediments to air and form acid sulphate soils was identified at a number of sites within the nearshore development area, including East Arm, the pipeline route and at the pipeline shore crossing (Chapter 3 and Appendix 9, Draft

EIS, INPEX 2010).This may reduce the water quality in adjacent areas by lowering the pH and/or mobilising metals in disturbed sediments. However, as discussed in Chapter 7 of the Draft EIS (INPEX 2010), any leachates are expected to be neutralised rapidly by mixing with sea water and sediments deposited in the intertidal mangrove areas in Darwin Harbour or Shoal Bay are not expected to represent an additional PASS or heavy-metal contamination risk, as the composition of the sediments derived from dredging activities will be similar in composition to the sediments that normally settle in those areas.

5. Mud crab biology

An understanding of mud crab biology is important for identifying and assessing potential impacts to mud crabs in Darwin Harbour as a result of proposed dredging and dredge spoil disposal activities. The following section provides a general overview of mud crab biology with an emphasis on the biology of mud crab populations in Australia and, more specifically, those of Darwin Harbour.

5.1. Distribution

Mud crabs are large recreationally and economically important portunid crabs found throughout the Indo-West Pacific Region. Until recently only one species, *Scylla serrata,* was recognised across the Indo-west Pacific. However, following a recent revision by Keenan et al. (1998) of the *Scylla* genus, four distinct species are now recognised; *S. serrata, S. olivacea, S. paramamosain* and *S. tranquebarica.* Two of these species, *S. serrata* and *S. olivacea,* occur in tropical and subtropical mangrove and estuarine habitats across Northern Australia, including Darwin Harbour in the Northern Territory (Keenan et al. 1998, Ward et al. 2007).

Photographs: David Mann, Agri-Science Queensland

- **Figure 5-1 Adult *S. serrata* (left) and *S. olivacea* (right)**

5.2. Habitat

Mud crabs are cryptic animals, typically associated with muddy mangrove estuaries (Vay 2001, Moser et al. 2002) such as the Darwin Harbour estuary. However *S. serrata* has also been found to occur in mangroves and tidal flats along sheltered island shorelines and reef areas (Hyland et al. 1984).

Tropical and subtropical estuaries are highly turbid environments, characterised by extensive mangrove and mud flat habitats (Burford et al. 2008, Alongi 2009). Within this environment, habitat selection by *Scylla* spp. may be partly defined by developmental stage. For example, adult and juvenile *S. serrata* generally occur in temporary burrows in both intertidal and subtidal mudflats and mangrove habitats (Hyland et al.1984, Demopoulos 2008) while adult and juvenile *S. olivacea* predominantly occupy the intertidal zones of mangrove habitats (Moser et al. 2005). The habitat of larval (zoea and megalopae) and early post-larval mud crabs is less well known compared to that of the adult and juvenile life stages. Despite this, it is generally accepted that megalopae colonise mangrove estuaries (Vay 2001).

In Darwin Harbour, there is an extensive amount of suitable mangrove habitat (>26 000 ha) and intertidal (55 000 ha) and subtidal (66 0000 ha) mud flat habitat available for mud crabs (Semeniuk 1985, DHAC 2003, McKinnon et al. 2006). Similarly, Shoal Bay has a large amount of habitat suitable for mud crabs.

5.3. Migration

The daily migration patterns of *S. serrata* and *S. olivacea* are characterised by relatively small-scale movements around permanent and semi-permanent burrows in intertidal and subtidal mangrove habitats, possibly linked to tidal regimes (Hyland et al. 1984, Demopoulos 2008, Moser et al. 2005). Mud crabs may also migrate larger distances within their available habitats as a result of seasonal regimes, interspecific and intraspecific habitat competition, foraging, mating and spawning activities (Hyland et al. 1984, Koolkalya 2006, Moser et al. 2005). During the wet season, for example, mud crabs may move to the lower reaches of creeks in response to reductions in salinity caused by freshwater runoff. Females are also known to move large distances for spawning which is also believed to be linked to changes in salinity during the wet season (Hill 1994, Moser et al. 2005).

5.4. Reproduction

Mating typically occurs after a mature female or female approaching maturity has moulted and the shell is soft (Fielder and Heasman 1978). Females that are ready to moult release distinct pheromones; males use their chemoreceptors to detect the pheromones in the water column and locate their potential mate (Phelan and Grubert 2007). The male protects the female during the moulting process. When the moult is complete, the male mud crab turns the female upside down to mate which may take up to 18 hours (Phelan and Grubert 2007). Like moulting, reproductive behaviour is thought to take place in the protection of burrows (Heasman and Fielder, Ewel et al. 2009). The transfer of sperm and fertilisation process is internal and females can mate more than once per season (Fielder and Heasman 1978, Ong 1966). Females are capable of storing sperm for several months before undertaking large scale offshore spawning migrations away from naturally turbid waters of their intertidal habitats to deeper offshore waters to facilitate spawning and brooding of eggs and subsequent release of larvae (Fielder and Heasman 1978, Hyland et al. 1984, Hill 1994, Vay 2001). Peak reproductive behaviour for *S. serrata* in northern Australian waters is thought to occur during the dry season (Heasman et al., 1985). However, given the capacity for females to store sperm for extended periods before spawning (Fielder and Heasman 1978), mud crab populations within Darwin Harbour and Shoal Bay may have the ability to mate year-round.

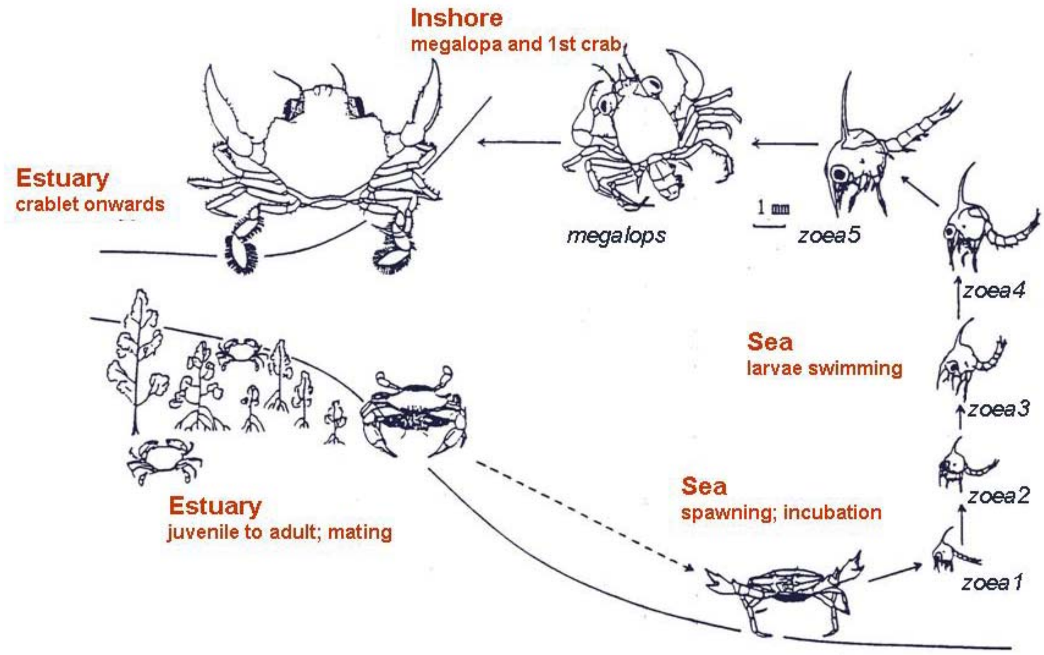
The drivers of this offshore migration pattern are believed to be linked not only to dispersal but for providing a more stable environment for the growth and development of the larval phases than that found in mangrove estuaries, particularly in the wet season, when freshwater runoff can cause rapid changes in temperature and salinity in mangrove estuaries (Alongi 2009, Heasman et al. 1985, Hill 1994).

Offshore spawning is evident in various populations in the Indo-Pacific including northern Australia (Hill 1975, 1994). In a study by Hill (1994) in Northern Australia, female *S. serrata* were found up to 95 km offshore. Mature female *S. olivacea* exhibit similar migratory behaviour to that of *S. serrata* and have been found up to 50 km offshore (Koolkalya et al. 2006). The rapid decline of female mud crabs in commercial catches in the Northern Territory during the wet season corresponds with this offshore migration pattern (Hay et al. 2005). In contrast, during the dry season female crabs contribute to 60–80% of commercial catches (Hay et al. 2005). Anecdotal information from commercial fishers also indicates an offshore migration pattern of female mud crabs in Northern Territory (Mounsey 1989).

Spawning activity varies between populations but in northern Australia and other areas of the Indo-Pacific, peak spawning activity of *S. serrata* usually coincides with the wet season when rainfall and water temperatures also peak (Heasman et al. 1985, Vay 2001). Peak spawning of *S. olivacea* has also been found to occur during the wet season (Koolkalya et al. 2006).

Mud crabs are highly fecund and can produce over 2 million eggs (**Figure 5-2**) (Fielder and Heasman 1978, Koolkalya et al. 2006). The females protect and brood the eggs during development, which may take between two to four weeks, before the eggs hatch into the pelagic larval stage (zoea) (**Figure 5-3**) (Hamasaki 2003).

- **Figure 5-2 Berried female mud crab**



Source: David Mann, Agri-Science Queensland

- **Figure 5-3 Life cycle of the mud crab**

5.5. Growth

All mud crab species grow rapidly by moulting often, but of the four *Scylla* species, *S. serrata* is considered to be the fastest-growing (Fortes 1999a, 1999b, Moser et al. 2002, Sukumaran and Neelakantan 1997, Vay 2001). The moulting process is critical for mud crab growth and involves the shedding of the exoskeleton to allow the expansion of body and limbs within the new soft shell (Fielder and Heasman 1978). During moulting phases, mud crabs are more vulnerable to predation from other animals and cannibalism by other mud crabs. To avoid this, mud crabs that are ready to moult build burrows up to 0.8 m below the sediment surface for protection, where they may remain for the duration of the moulting period (Fielder and Heasman 1978). Burrowing behaviour has been observed in other portunid species during their moulting phases (Caine 1974, McLay and Osborne 1985). Mud crabs also exhibit burrowing behaviour as a mechanism for predator avoidance and they are capable of rapidly burying themselves in soft sediment to hide (Ewel et al. 2009, Fielder and Heasman 1978, Hill 1978).

Growth is rapid in zoea and megalopae stages (**Figure 5-3**), the duration of which ranges between approximately 14–18 days and 6–7 days, respectively (Hamasaki 2003, Suprayudi et al. 2002, Webley 2008). Following settlement, mud crabs continue to moult and reach sexual maturity at a carapace width of approximately 120–150 mm (Knuckey 1999, Vay et al. 2001). In a study by Heasman et al. (1985) in northern Australia, female and male *S. serrata* attained maturity at carapace widths of 128 mm and 165 mm, respectively.

The growth rates and development of larval stages and the size and age at maturity of adult mud crabs, has been found to vary according to fluctuations in temperature, salinity and diet (Baylon et al. 2001, Hamasaki 2003, Jantarotai et al. 2002, Mann et al. 2001, Vay et al. 2001). Under cultured conditions, optimum survival of zoea require stable temperatures within the range of 29–32°C and salinity conditions of 32–35 ppt, which is similar to that observed in the open ocean in tropical regions during summer (Baylon et al. 2001, Hamasaki 2003).

5.6. Feeding

Adult and juvenile mud crabs are highly opportunistic omnivores (Hill 1975, 1979, Phelan and Grubert 2007, Thimdee et al. 2001). They feed on a wide range of bivalve and gastropod molluscs, crustaceans, plant material (detritus) and occasionally other mud crabs (1975, 1979, Webley 2008). Mud crabs also exhibit scavenging and cannibalistic feeding behaviour (Webley 2008). In Darwin Harbour there is an abundance of food items available for mud crabs in their intertidal and subtidal habitats, including a diverse range epifauna and infauna such as marine worms, crabs, and molluscs, and large amounts of plant material derived from the mangrove forests (Smit 2003).

Larval mud crabs are also opportunistic feeders, consuming a range of zooplankton in the water column (Genodepa et al. 2004, Holme et al. 2009). Zoea are capable of pursuing prey from first hatching, while during the megalopae stage feeding is more efficient as they are equipped with large pincers (**Figure 5-3**, Genodepa et al. 2004). Both zoea and megalopae have the ability to capture and ingest prey of a broad size range (Holme et al. 2009). Copepods are likely to contribute to a large proportion of megalopae and zoea diet as these are the dominant zooplankton found in both Darwin Harbour and offshore waters of northern Australia (McKinnon et al. 2006, Rothlisberg and Jackson 1982). Nauplii of a variety of other crustaceans and macrozooplankton such as mysids and decapod larvae, which are also abundant in mangrove ecosystems (Alongi 2009), may also contribute to the megalopae diet in the Harbour.

5.7. Settlement

Mud crab megalopae have little capacity for horizontal movement against tidal flows and consequently are dependent on favourable currents such as flood tides for successful recruitment into estuary areas (Macintosh et al. 1999, Webley 2008). The use of tidal currents to colonise estuaries has been observed in other portunid species, where megalopae rise in the water column during flooding tides to be transported upstream and descend near the substrate during ebb tide and continuing this process until suitable habitat is encountered (Tankersley et al. 2002).

In the Northern Territory, there is no information on the distribution of mud crab megalopae in estuaries, or their behaviour and movement into or out of estuaries. However numerous small crabs have been observed in commercial pots in the upper reaches of other tidal creeks in the Northern Territory (Mounsey 1990, Ward et al. 2007) indicating that megalopae settle here.

6. Potential impacts to mud crabs in Darwin Harbour

The elevated concentrations of suspended sediments and sediment accretion associated with the Project dredging and dredge spoil disposal activities may impact on the mud crab populations (*S. serrata* and *S.olivacea*) within Darwin Harbour and Shoal Bay. The likelihood and scale of potential impacts to the mud crab populations will depend on the interaction of numerous variables including: the influence of local hydrodynamic processes; local water quality and sediment regimes; the physical and chemical properties and concentration of suspended sediments; volumes, rates and distribution of suspended sediments and sedimentation; and mud crab species' exposure time and resilience to the effects of elevated concentrations of suspended sediments and sedimentation.

The significance of any impact also needs to be defined. For the purposes of this impact assessment, any potential impact which may affect more than 25% of the available habitat for mud crabs in Darwin Harbour and Shoal Bay and/or affect more than 25% of the local mud crab populations is considered significant. Currently there is no background information available on the distributions or abundances of the two mud crab species that occur in Darwin Harbour and Shoal Bay. Therefore, for the purposes of this impact assessment, the assumption made was that adult and juvenile mud crabs are evenly distributed within the available suitable habitats of Darwin Harbour and Shoal Bay. Information on current and past recreational mud crab fishery catches in Darwin Harbour and Shoal Bay is also limited and there is no evidence available to suggest current fishing effort is sustainable; consequently any difference between previous and current recreational catches may be the result of habitat loss and/or overfishing. Further, large inter-annual fluctuations (up to 150 tonnes) in catches in the Northern Territory Commercial Mud Crab Fishery (Ward et al. 2007) suggest that the mud crab population in Darwin Harbour and Shoal Bay is highly likely to fluctuate considerably from year to year in response to a variety of different environmental and biological variables, including the recruitment of pelagic larvae. Therefore a significance level of 25%, while high, has been selected to represent a change that would likely be noticeable in terms of potential catches in the fishery over time. The assessment of potential impacts for each phase of the life cycle of these species is also necessary as the different phases of the life cycle have different habitat requirements, and potentially different tolerances and resilience.

The following section investigates potential impacts to aspects of mud crab biology and ecology including the habitat, migration, feeding, mating, activity, growth and settlement and recruitment patterns at key phases of the life cycle. Natural mitigating factors, including the environmental variability of mud crab habitats and specific behavioural and physiological adaptations of mud crab species, are also discussed in relation to the potential for identified impacts to affect the populations of mud crabs in Darwin Harbour and Shoal Bay. As there is limited information available on the mud crabs in Darwin Harbour and Shoal Bay, inferences about the biology and ecology and thus likely mitigating factors (i.e. tolerance ranges) or vulnerabilities of mud crabs, were derived from information on other mud crab populations within tropical estuaries of northern Australia and throughout the Indo-Pacific.

6.1. Potential impacts to adult and juvenile mud crabs

6.1.1. Habitat

To date, the potential effects of elevated concentrations of suspended sediments on mud crabs have not been studied so there is no information available on their likely tolerance to suspended sediments. Mud crab tolerances can, however, be inferred from levels of suspended sediments which occur naturally in their preferred intertidal and subtidal mangrove habitats. Tropical mangrove estuaries like that of Darwin Harbour are naturally highly turbid environments (Burford et al. 2008). Concentrations of sediments in the water column of Darwin Harbour can fluctuate markedly under the influence of the spring-neap tidal cycle (**Section 4.2.1**). Natural suspended sediments concentrations within the main body of the Harbour near Wickham Point have been found to range from <50 mg L^{-1} up to 250 mg L^{-1} (Williams et al. 2006). In the intertidal and subtidal mud flats of the upper estuary where mud crabs occur, natural suspended sediment concentrations can potentially reach much higher background concentrations than those observed in the main Harbour as a result of turbulent mixing processes in the shallow areas, particularly during spring tides (McKinnon et al. 2006, Williams et al. 2006) (**Section 4.2.1**). Further, runoff from cyclone and monsoon events during the wet season can periodically increase sediment suspension to extreme levels in the upper reaches of tidal creeks. This demonstrates that mud crabs are frequently subject to episodes of naturally highly variable concentrations of suspended sediment in their natural habitats. Therefore mud crabs are likely to tolerate temporary events of elevated concentrations of suspended sediments generated by the dredging activities, which will be confined to East Arm and Shoal Bay and equates to only a minor proportion of the total habitat available for mud crabs in the Darwin Harbour area.

Nearshore dredging activities are predicted to cause patches of sedimentation in intertidal mangrove areas throughout East Arm (**Section 4.3.2**). Twenty-eight hectares of mangrove forest is predicted to accumulate >50 mm of fine sediments and an area of 2 ha is anticipated to receive over 100 mm of fine sediments during the first three years of dredging (**Section 4.3.2**). Ellison (1998) reviewed the available information on the potential impacts of sedimentation on mangroves and concluded that mangroves were vulnerable to sudden sedimentation events (e.g from cyclones and floods) that deposited more than 100 mm of sediment. However, as noted in Chapter 7 of the Draft EIS (INPEX 2010), the sediment burial events described by Ellison (1998) were the result of sudden sedimentation, therefore these threshold levels may be very conservative when applied to the sedimentation levels predicted in East Arm over the four-year dredge program. Based on an estimated total of 26 000 ha of mangrove forests within Darwin Harbour and Shoal Bay, this equates to less than 1% of mangrove forests receiving between 17 mm and 35 mm of elevated sedimentation during the first three years of the four-year dredging program and this is not considered likely to impact significantly on the overall health of the mangrove communities within the Harbour (Chapter 7 Draft EIS, INPEX 2010). In addition, the total area of mangroves that would be affected is very small in terms of total area of habitat available for mud crabs in Darwin Harbour and Shoal Bay.

Trapping of large amounts of fine sediments is a common phenomenon in tropical macrotidal estuaries (Wolanski et al. 1995, Wolanski and Spagnol 2003). Sedimentation rates have not been estimated in the Harbour or Shoal Bay. However, rates of sediment accretion in other mangrove forests have been found to range between 0.4 mm $year^{-1}$ to 72 mm $year^{-1}$ (Alongi 2009) and net fluxes of suspended sediment into upper estuary arms of the Darwin Harbour during the wet season can be in the order of 8.5 tonnes m^{-1} $d^{-1}$to 13.4 tonnes m^{-1} d^{-1}, indicating regular tidal trapping of large amounts of fine sediments (Williams et al. 2006). At least some of the suspended sediments are transported into the upper estuary arms within the Harbour and eventually settle out onto the areas of mangroves and adjacent tidal flats. The modelling predicts some areas will experience higher rates of sedimentation during the proposed dredging program and natural remobilisation of some sediment deposited into intertidal zones can be expected (**Section 4.3.2**). Semeniuk (1985) has noted a range of general mangrove habitat types present in Darwin Harbour and the main tidal flat habitat exhibits both sedimentation and erosion features. The creek bank habitat is maintained by erosion (Semeniuk 1985) and the small tidal channels across the tidal flats and the larger tidal creeks are also maintained by erosional features. Meandering channels of the tidal creeks are not fixed in space, showing regular changes in size and position through time with one bank accreting while the opposite bank erodes (Woodroffe 1992). In addition, any increase to net sedimentation caused by dredging is forecast to be relatively short-term as it is not expected to extend beyond the life of the dredging project (**Section 4.3.2**). At least some of the accreted sediment derived from the dredging activities is therefore likely to be eventually redistributed as a consequence of local changes in the patterns of sedimentation and erosion.

Tropical estuaries such as Darwin Harbour typically contain large areas of fine sediments that act as sinks for trace metals and other contaminants scavenged from the overlying water column by colloidal particles at the sediment/water interface (Luoma and Davis 1983). These particles are then often buried, trapping trace metals and contaminants at depth. The disturbance and re-suspension of large amounts of sediments during dredging activities therefore could lead to a release of trace metals back into the water column where they may become bio-available and subsequently concentrated up the food chain. Hanley and Couriel (1992) report some evidence of trace metal contamination in mud whelks in Darwin Harbour. As mud crabs predate on both filter feeders (bivalves) and deposit feeders (mud whelks), they are potential bioaccumulators of contaminants (van Dam et al. 2008, van Oosterom et al. 2009). However, to date, there have been no studies of the background levels of trace metals or other contaminants in mud crabs inhabiting Darwin Harbour and Shoal Bay. Further, the sediment to be dredged has been classed as uncontaminated (Chapter 3 and Appendix 9, Draft EIS, INPEX 2010) and consequently there is little risk of release of trace metals or other contaminant into the water column.

Another pathway whereby some trace metals could be mobilised into the water column is via acidification of PASS on exposure to air (**Section 4.3.3**). However, the risk of any formation of acid sulphate soils is small as the majority of material classed as PASS will be deposited offshore where it will be kept wet at all times. The only area where there could be drying of material sufficient to allow acid soils to form is in the pipeline shore crossing, but any production of acid leachate or release of trace metals will comprise small volumes that will be readily diluted on contact with sea water.

6.1.2. Migration

Elevated concentrations of suspended sediments and sedimentation are predicted to occur in areas of mud crab habitat in East Arm and Shoal Bay (**Section 4.3**) and this may potentially affect the natural migration patterns of mud crabs within these areas. However, based on typical natural sediment suspension and sedimentation regimes in Darwin Harbour as described in **Section 4.2**, it is reasonable to assume that mud crabs are adapted to live in and migrate within highly turbid environments experienced in Darwin Harbour.

In the unlikely event that concentrations of suspended sediments and sedimentation events exceeded the tolerances of mud crabs, adult and juvenile mud crabs may potentially exhibit avoidance behaviour and temporarily move away from the impact zones within East Arm and Shoal Bay. There are no data which could be used to infer whether there are limits to the levels of turbidity and sedimentation that can be tolerated by adult or juvenile mud crabs. However, given the scale of impact relative to the area of available habitat within Darwin Harbour and Shoal Bay and the temporary nature of the impact, any potential effect on migration patterns is likely to be both minimal and temporary.

6.1.3. Feeding

Dredging and dredge spoil disposal activities will potentially cause elevated concentrations of suspended sediments and sedimentation in some areas of East Arm and Shoal Bay (**Section 4.3**). This may have a direct impact on juvenile and adult mud crab feeding activity within East Arm and Shoal Bay as a result of altered light availability and smothering of prey items. This is speculative, however, since the effects of suspended sediments and sedimentation on adult and juvenile mud crab feeding activities have not been studied, and so there is no information that demonstrates elevations in suspended sediments and sedimentation would impinge on the feeding activities of these crabs.

Research has demonstrated that mud crabs generally feed more actively at night and predominantly use non-visual cues via contact, scent and chemoreceptors to detect and locate their food. The tips of crab legs (known as the dactyls) are the key chemoreceptor sites (Hill 1975, 1978, 1979). The highly efficient non-visual methods for locating food items are thought to be adaptations to feeding in muddy estuary waters at night where visual cues are not practical for feeding (Hill 1978). This means that mud crabs are able to successfully seek out food items in extreme low light conditions and a further temporary reduction in light availability or increase in sedimentation in the mud habitat within Darwin Harbour or Shoal Bay is therefore unlikely to have a significant adverse effect on mud crab feeding activities. Given that mud crabs forage at night, lowered light availability during daylight hours may even stimulate mud crab feeding activities outside of their regular patterns of feeding, although this is only speculation.

There is a possibility that mud crab feeding activity may also be indirectly affected by changes in the community composition, diversity, abundance and distributions of prey items. However, the epifauna and burrowing infauna associated with estuarine and mangrove habitats in Darwin Harbour and Shoal Bay are diverse (Hanley, 1988, 1993, Hanley et al. 1997, Metcalfe and Glasby 2007). The organisms include many species which are filter feeders, grazers or deposit feeders (Hanley 1993). All of these species are adapted to feeding in and on sediments where they are commonly exposed to high temperatures, high turbidity, high sulphide and polyphenolic acid concentrations, low dissolved oxygen levels and large variations in salinity (Alongi 1990). In addition, they are frequently subjected to burial (Alongi 1990). The natural hydrodynamic processes in Darwin Harbour and Shoal Bay include the accretion and redistribution of sediment; the additional sedimentation in East Arm and Shoal Bay as a consequence of the Project are not likely to exceed the tolerances of the benthic prey species present in those areas. In addition, mud crabs are able to adjust to changes in the distributions and abundances of prey species by switching to other species. Mud crabs are also capable of moving to other unaffected areas in order to forage for food.

6.1.4. Growth

The tendency of adult and juvenile mud crabs to bury themselves during critical growing phases (**Section 5.5**) and their affinity with habitats which are characterised by naturally high concentrations of suspended sediments and sedimentation, suggests that mud crabs can tolerate high concentrations of sediment suspension and rapid rates of sedimentation. The predicted elevated concentrations of suspended sediments and sedimentation rates will be, temporary and localised to small areas of intertidal and subtidal mud flats within East Arm (**Section 4.3**). Some infrequent (during spring tides only) elevations in concentrations of suspended sediments in Shoal Bay may also occur as a result of dredge spoil disposal (**Section 4.3.1**). However the temporary episodes of elevated suspended sediments and sedimentation in East Arm and Shoal Bay will likely fall within the natural ranges experienced within Darwin Harbour region. Therefore it is considered highly unlikely that any elevations in suspended sediments and sedimentation associated with dredging and dredge spoil disposal activities will have a significant impact on the growth of adult and juvenile mud crabs within Darwin Harbour or Shoal Bay.

Photograph: J. R. Hanley, SKM

- **Figure 6-1 Mud crab burrow in intertidal area of Darwin Harbour**

6.1.5. Mating

Temporary elevations in concentrations of suspended sediments and sedimentation in intertidal and subtidal habitats in East Arm and infrequent (during spring tides only) elevations in concentrations of suspended sediments in Shoal Bay associated with dredging activities are predicted (**Section 4.3**). This may have an impact on the reproductive behaviour of mud crabs by reducing the ability to seek out potential mates and mate successfully. However, as there is no information available on the effects of suspended sediment and sedimentation on the reproductive behaviour of mud crabs, it is difficult to anticipate whether increased levels will have an impact on mating activities although inferences can be made about the tolerances and adaptations which are likely to mitigate any such impacts. As stated in **Section 6.1.1**, mud crabs are adapted for living in an environment prone to high rates of suspended sediments and sedimentation. Aspects of their mating behaviour indicate that temporary elevations in suspended sediments and sedimentation are unlikely to impede on their mating activities. Firstly, as described in **Section 5.4** males can sense a potential mate using non-visual cues, so ability to locate mates is unlikely to be inhibited by lowered light availability associated with elevations in concentrations of suspended sediments. Secondly, mating typically occurs in burrows (**Section 5.4**), which suggests mud crabs are tolerant of sediment burial, and any increases in sedimentation are unlikely to interfere with reproductive activity. Lastly, sperm transfer and fertilisation occurs internally and females can mate more than once per season and store sperm (**Section 5.4**). Therefore, temporary changes to surrounding sediment regimes are unlikely to prevent successful mating and mating success is not reliant on a single mating event, which further reduces the likelihood of a significant affect to mating of mud crabs within Darwin Harbour and Shoal Bay.

Photograph: J. R. Hanley, SKM

- **Figure 6-2 Male mud crab protecting female in Darwin Harbour**

6.1.6. Activity

Mud crabs are predominantly more active at night than during the day (Hill 1976). Rates of activity have also been observed to increase outside of this diurnal pattern as a result of the presence of food. In laboratory experiments, Hill (1976) found that *S. serrata* activity levels were linked to the presence or absence of light and food. *S. serrata* spent significantly more time active under low light conditions (night simulation) compared to that of high light conditions (day simulation). In the presence of food items, mud crab activity was further increased under low light conditions. When inactive, mud crabs buried themselves in sediment. The stimulation of mud crab activity under low light conditions suggests that increased levels of suspended sediments in their habitats may stimulate increased activity levels of mud crabs. Therefore temporary elevations in concentrations of suspended sediments in intertidal and subtidal habitats in East Arm and infrequent (during spring tides only) elevations in concentrations of suspended sediments in Shoal Bay associated with dredging and dredge spoil disposal activities (**Section 4.3**) may have a positive effect on mud crab activity.

6.2. Potential impacts to mud crab eggs

Dredging activities are proposed to occur during both the dry season and wet season and will therefore coincide with mud crab spawning activity during the wet season (**Section 4.3**). However, dredge plume modelling has predicted that temporary elevations in concentrations of suspended sediments and sedimentation will occur predominately in the nearshore East Arm area surrounding the proposed facilities. Some low intensity, infrequent elevations in suspended sediment concentrations and sedimentation associated with dredge spoil disposal may also occur in Shoal Bay and the area surrounding the disposal ground (**Section 4.3**). On the basis of an offshore spawning migration (see **Section 5.3** and **Section 5.4**), berried females are unlikely to occur in nearshore areas of Darwin Harbour or Shoal Bay. It is therefore unlikely that berried females and development and survival of their eggs will be directly affected by temporary changes in concentrations of suspended sediment or sedimentation in these nearshore areas.

Since female mud crabs move large distances for spawning (**Section 5.4**) it is reasonable to assume that migrating females will be able to actively avoid regions where water quality is not optimal for egg development or larval dispersal (e.g. turbid dredge plumes). Additionally, the potential for smothering or adherence of sediments particles to mud crab eggs is likely to be minimal because, like other portunid crabs, female mud crabs brood their eggs and regularly groom and ventilate the brood to maintain oxygen levels and enhance egg survival (Baeza and Fernandez 2002, Samuel and Soundarapandian 2009).

6.3. Potential impacts to mud crab larvae

6.3.1. Dispersal

Runoff in the Darwin Harbour and Shoal Bay during the wet season can cause large vertical and horizontal fluctuations in salinity in the water column (Williams et al. 2006). The salinity levels within both the main Harbour and the upper estuary arms can fall to less than <5 ppt near both the surface and substrate during the wet season (McKinnon et al. 2006). Shoal Bay experiences fluctuations in salinity similar to that of the Harbour (Padovan 2003). Given that larvae survival is inhibited at salinities below approximately 32 ppt (Baylon et al. 2001, Hamasaki 2003), this suggests that female mud crabs in Darwin Harbour and Shoal Bay are likely to migrate to offshore locations to release zoea, where they can develop in a more stable environment.

On the basis of an offshore spawning migration by female mud crabs and subsequent offshore dispersal of larvae (zoea) (**Section 5.4**), the potential for zoea to be affected directly by the nearshore dredging activities in East Arm is likely to be minimal. However, some low intensity, infrequent elevations in suspended sediment concentrations may occur in the area surrounding the offshore dredge spoil disposal ground (**Section 4.3.1**). There is evidence that the larval phases of mud crabs move in response to light conditions in the water column, moving higher in the water column during higher levels of light (Webley and Connolly 2007) and that larvae have limited ability to move against strong currents to actively avoid areas of poor water quality (Webley 2008). Therefore the distribution of zoea within the water column may be affected by reduced light availability caused by suspended sediments derived from the offshore dredge spoil disposal ground. However, given the suspended sediments generated by disposal in the offshore spoil ground is expected to be infrequent, low intensity and will only temporarily affect a minor portion of the area available for dispersal of zoea (**Section 4.3.1**), the overall impact this will have on the dispersal of mud crab zoea is expected to be minor.

6.3.2. Growth

As discussed above in **Section 6.3.1**, on the basis of an offshore spawning migration by female mud crabs and subsequent offshore dispersal of larvae (zoea), the potential for zoea be significantly affected by the nearshore dredging activities in East Arm is likely to be minimal. The effect of offshore dredge spoil disposal ground is also likely to be insignificant given the temporary effect on a minor portion of area available for zoea.

After metamorphosis into the megalopae stage, the megalopae migrate into estuarine waters to settle (**Section 5.7** and **Section 6.3.4**). This means that a proportion of megalopae may potentially be subject to the elevated suspended sediment concentrations predicted to occur in East Arm and in Shoal Bay. There is no information in the literature on the potential effect of elevated suspended sediment concentrations on megalopae growth. However, megalopae are found in habitats where there are large fluctuations in suspended sediment concentrations and sedimentation which suggests that not only are megalopae tolerant of high concentrations of suspended sediment and sedimentation, but that they may respond positively to gradients in turbidity as such behaviour would enhance the capacity of megalopae to settle in the appropriate habitat type for juveniles and adults. Therefore the suspension of sediments caused by the proposed nearshore dredging and dredge spoil disposal activities is considered to be unlikely to have a significant impact on the megalopae stage of the life cycle of the two species of mud crab.

6.3.3. Feeding

Feeding activity of zoea and megalopae has been found to be directly affected by fluctuations in salinity and temperature (Li et al. 1999) but no information is available on whether there may be any direct affects on feeding activity from elevations of suspended sediment concentrations in the water column. In larval phases of other marine organisms, elevated suspended sediment concentrations have been found to reduce the ability of larvae to actively seek out and capture prey by reduced light intensity in the water column (Engstrom-Ost and Mattila 2008, Partridge and Michael 2010). Therefore reduced light availability caused by elevated concentrations of suspended sediment in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay and surrounding the offshore dredge spoil disposal ground (**Section 4.3**) could potentially impact directly on zoea and megalopae by reducing their ability to seek out and capture prey.

Additionally, the density and distribution of zooplankton is known to be indirectly affected by reduction in light intensity in the water column (i.e. by shifts in phytoplankton distribution and abundance) in both mangrove estuaries and the open ocean (Alongi 2009, Rothlisberg and Jackson 1982). In aquaculture studies, a reduction in prey density has been found to significantly reduce the feeding rates and consequently the survival of zoea and megalopae (Li et al. 1999). Therefore the suspension of sediments in the water column associated with dredging activities in East Arm and the dredge spoil disposal ground could potentially have an influence on the density and distribution of zoea and megalopae prey, which could in turn have an indirect adverse affect on larval feeding rates.

Given that mud crab zoea are likely to be dispersed offshore, they will be outside the nearshore area but may occur in the area of potential physical influence from the offshore disposal ground. Offshore dredge spoil disposal will, however, only cause infrequent, low intensity elevations in suspended sediment concentrations (**Section 4.3.1**) and will not affect a significant proportion of zoea. Therefore elevated concentrations of suspended sediments caused by dredging and dredge spoil disposal activities are unlikely to have a significant direct or indirect impact on the feeding rates of zoea.

A proportion of megalopae are likely to recruit to the nearshore intertidal areas of the East Arm and Shoal Bay where there will be temporary and localised elevations in suspended sediment concentrations caused by dredging activities. However high concentrations of suspended sediment are a natural phenomenon here, which suggests that megalopae and their prey items are likely to already be adapted to survive and feed under these conditions. Further, the ability of both zoea and megalopae to feed on a range of prey and prey sizes (**Section 5.6**) suggests a capacity to adapt readily to any changes in prey distribution or abundance.

6.3.4. Settlement and recruitment

The affinity of megalopae with habitats that are subject to naturally high concentrations of suspended sediment and sediment accretion indicate that temporary elevations in suspended sediment and sediment accretion are unlikely to deter them from settlement. In addition, the offshore spawning migration by females and the dispersal of pelagic larval phases that has been observed in other populations of *S. serrata* and *S. olivacea* in Northern Australia and other populations throughout the Indo-Pacific (Fielder and Heasman 1978, Hyland et al. 1984, Hill 1994, Vay 2001) indicates the likely interconnectivity of mud crab populations along large areas of coastline wherever there is suitable continuity of habitat such as estuaries, tidal rivers and creeks. The large-scale interconnectivity of mud crab stocks in the Northern Territory is supported by studies undertaken on the Northern Territory Commercial Mud Crab Fishery (Vay et al, Ward et al. 2007).

On the basis of one contiguous Northern Territory mud crab stock, Ward et al. (2007) suggested that interannual fluctuations in commercial catches (in the order of magnitude of 150 tonnes between successive years) across the Northern Territory Commercial Fishery (including the Boroloola, Roper and Darwin regions) reflect variability in recruitment to the fishery rather than fluctuations in fishing effort. Highly variable recruitment patterns have been recorded in mud crab populations elsewhere (Moser et al. 2005, Vay et al. 2006) and are believed to be influenced by a range of environmental and biological processes. Given the interconnectivity of mud crab stocks in Darwin Harbour and Shoal Bay to other areas in the Northern Territory, recruitment to these areas are unlikely to be dependent solely on the spawning patterns of the local population. Therefore the dredging program is considered unlikely to have a significant effect on mud crab recruitment. It should also be noted that given the natural range of variability apparent in recruitment (Ward et al. 2007), it would be difficult to attribute any apparent variations in recruitment of mud crabs to Darwin Harbour and Shoal Bay to dredging and dredge spoil disposal activities.

7. Risk Assessment

An environmental risk assessment was undertaken based on the risk assessment methodology described in Chapter 6 of the Draft EIS (INPEX 2010).

This risk assessment was undertaken to identify all potential impacts to mud crabs and identifies impacts to each life cycle phase of the mud crab. The adult and juvenile phases have been grouped together, since impacts and natural mitigating factors for these life cycle stages will be the same. Different aspects that could impact on each life cycle stage were identified, potential impacts described and natural mitigating factors identified. A residual risk was then determined for each aspect, using Figures 6-2, Table 6-2 and Table 6-3 from the Draft EIS (INPEX 2010). Natural mitigating factors are detailed in Section 6 of this report.

A significant impact has been defined as >25% loss of mud crab population or mud crab habitat within Darwin Harbour and Shoal Bay, based on the assumption that mud crabs are evenly distributed throughout the available habitat. Refer to **Section 6** for discussion on the rationale behind the level of significance and associated assumptions.

Table 7-1 below shows that all identified potential impacts to mud crabs were low residual risk, with the exception of one impact on migration of adult and juvenile mud crabs which was identified as a medium residual risk.

Table 7-1 Summary of impact assessment and residual risk for mud crabs in Darwin Harbour and Shoal Bay

Life cycle Stage	Aspect	Activity	Potential Impacts**	Mitigating Factors	Residual risk		
					C*	L†	RR‡
Adult and juvenile (**Section 6.1**)	Habitat	Nearshore dredging activities (which include shore crossing, jetty, module offloading facility, pipeline) and offshore dredge spoil disposal	Elevated suspended sediment concentrations and sedimentation above natural background levels in the intertidal and subtidal mangrove habitats of adult and juvenile mud crabs in East Arm and Shoal Bay leading to significant loss of suitable habitat.	Intertidal and subtidal habitats where mud crabs occur are areas which are naturally prone to high concentrations of suspended sediments and sedimentation (**Section 6.1.1**). Extensive areas of suitable mud crab habitat throughout the Harbour will be unaffected (**Section 6.1.1**). Episodes of elevated concentrations of suspended sediments above background levels are likely to be temporary and localised (**Section 6.1.1**). Predicted rates of net sedimentation are low and lie within the natural range of sedimentation events for Darwin Harbour (**Section 6.1.1**). If net sedimentation occurs at least some of it is likely to be eventually redistributed by natural processes of erosion and	E(B1)§	2	Low

				sedimentation (**Section 6.1.1**). Physical and chemical properties of sediment suspended by dredging are similar to that already found in the intertidal areas (**Section 6.1.1**).			
			Release of contaminants from suspended sediments into the water column near intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay. Potential for uptake and concentration of contaminants in prey items (filter feeding molluscs) leading to increased levels in mud crabs and thereby increased risk to human health.	Physical and chemical properties of sediment suspended by dredging are similar to that already found in the intertidal areas (**Section 6.1.1**). Sediment to be dredged is uncontaminated (**Section 6.1.1**). Tidal mixing will rapidly dilute any contaminants from the local area (**Section 6.1.1**).	E(B1)	2	Low
			Acid sulphate soils leaching during nearshore dredging activities may release acid, thereby reducing water quality of surrounding area. This may temporarily reduce suitability of habitat for mud crabs and have a negative effect on mud crab health.	Tidal mixing will rapidly dilute any leachates from the local area (**Section 6.1.1**).	E(B1)	2	Low

	Migration (local)		Elevated turbidity and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay may impact on mud crab migration patterns.	Mud crabs are adapted to live in and migrate within highly turbid environments. Therefore it is unlikely that elevated concentrations of suspended sediments and sedimentation will deter them from their local migration patterns within, into and out of the Darwin Harbour and Shoal Bay (**Section 6.1.2**). In the event that elevated concentrations of suspended sediment and sedimentation did reach levels the mud crabs do not tolerate (and there is no information available on what those levels might be), then they may exhibit avoidance behaviour and move away from the impact zones temporarily (**Section 6.1.2**).	E(B1)	3	Medium
	Feeding		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay may have a direct impact on juvenile and adult mud crab feeding activity, as a result of low light availability and smothering of prey. Thereby reducing their ability to seek out and capture prey.	Mud crabs are opportunistic omnivores with a highly varied diet which enables them to adjust to changes in the distributions and abundances of prey items (**Section 6.1.3**). The majority of prey species are also adapted to life in and on muddy substrates where sudden sedimentation events are normal (**Section 6.1.3**).	E(B1)	2	Low

			Mud crab feeding activity may also be indirectly affected by a reduction in prey abundance and/or changes in prey distribution due to elevated concentrations of suspended sediments and smothering by sedimentation.	Mud crabs are adapted to forage in turbid environments and do not use visual cues to seek out prey items (**Section 6.1.3**). Mud crabs can move to out of affected areas to forage in surrounding unaffected habitats and the area of potential impact is small relative to total habitat available (**Section 6.1.3**).			
	Growth		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay may have a detrimental effect on juvenile and adult mud crab growth.	Like other portunids, mud crabs rapidly bury themselves into the substrate to hide and also construct substantial burrows where they can hide, particularly during moulting. The crabs are therefore highly tolerant of high concentrations of suspended sediments and sedimentation (**Section 6.1.4**).	E(B1)	2	Low
	Mating		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay may reduce reproductive behaviour of mud crabs due to low light availability and thereby reducing their ability to seek out potential mates and mate	Mud crabs do not use visual cues to find mates (**Section 6.1.5**). Mud crabs are adapted to seek out potential mates in a turbid environment. They are equipped with sensitive chemical receptors and males can detect pheromones released by mature females which are about to moult	E(B1)	2	Low

			successfully.	(**Section 6.1.5**). Fertilisation is internal (**Section 6.1.5**). Females have the capacity to store sperm (**Section 6.1.5**). Reproductive behaviour may occur year round (**Section 6.1.5**).			
	Activity		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of juvenile and adult mud crabs in East Arm and Shoal Bay may have an effect on diurnal patterns and levels of mud crab activity.	Mud crabs are generally more active at night therefore reduced light levels caused by elevated concentrations of suspended sediments may have a positive effect on mud crab activity levels by stimulating increased activity (**Section 6.1.6**).	E(B1)	2	Low
Egg (**Section 6.2**)	Growth		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay and surrounding the offshore dredge spoil disposal ground may be detrimental to egg development and survival.	Females often migrate large distances offshore to spawn. Therefore eggs are spawned outside of the predicted nearshore impact zones (**Section 6.2**). Elevated concentrations of suspended sediments caused by dredge spoil disposal are predicted to be infrequent, low intensity (≤ 20 mg L^{-1}) and rapidly diluted (**Section**	E(B1)	1	Low

				6.2). Females brood eggs and can therefore actively avoid areas where water quality is not optimal for egg development. They can also groom eggs to reduce adhesion of sediments and maintain oxygenation (**Section 6.2**). Given female capacity to migrate large distances they are capable of avoiding areas of elevated concentrations of suspended sediments (**Section 6.2**).			
Larvae (**Section 6.3**)	Dispersal		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay may affect the distribution (horizontal and vertical) of zoea in the water column. Elevated concentrations of suspended sediments caused by the offshore disposal ground activities may affect the distribution (horizontal and vertical) of zoea in the	Zoea are dispersed offshore and therefore outside predicted nearshore impact zones (**Section 6.3.1**). Elevated concentrations of suspended sediments caused by offshore dredge spoil ground will affect a minor portion of area available for zoea dispersal and will be infrequent, low intensity (≤ 20 mg L^{-1}) and rapidly diluted by mixing processes (**Section 6.3.1**). Zoea stage of life cycle is short between ~12-	E(B1)	1	Low

			water column.	and 18 days (**Section 6.3.1**).			
	Growth		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay may have a detrimental effect on the growth of zoea and megalopae stages of mud crab development.	Zoea are dispersed offshore and therefore outside predicted nearshore impact zones (**Section 6.3.2**). Megalopae adapted for growing in a turbid environment (**Section 6.3.2**). Larval stages vary but are generally brief ~12–18 days and 6–7 days for zoea and megalopae, respectively **(Section 6.3.2**).	E(B1)	2	Low
	Feeding		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay and surrounding the offshore dredge spoil disposal ground may have a direct impact on zoea and megalopae feeding activity, as a result of low light availability. Thereby reducing their ability to seek out and capture prey. Feeding activity of zoea and megalopae may also be indirectly affected by a reduction in prey abundance and/or changes	Zoea are dispersed offshore and therefore outside predicted nearshore impact zones (**Section 6.3.3**). Elevated concentrations of suspended sediments caused by offshore dredge spoil ground will affect a minor portion of area available for zoea dispersal and will be infrequent low intensity (≤20 mg L^{-1}) and rapidly diluted by mixing processes (**Section 6.3.3**). Zoea are known to be sensitive to temperature and salinity, but there is no	E(B1)	2	Low

			in prey distribution due to elevated concentrations of suspended sediments and smothering by sedimentation.	evidence in the literature of sensitivity to suspended sediments and/or sedimentation (**Section 6.3.3**). Megalopae adapted for feeding in a turbid environment (**Section 6.3.3**). Megalopae are more capable swimmers than zoea and may move out of affected areas to forage in surrounding unaffected habitats if tidal conditions are favourable (i.e. neap tides) (**Section 6.3.3**). Megalopae are opportunistic feeders with a varied diet (**Section 6.3.3**).			
	Settlement and recruitment		Elevated concentrations of suspended sediments and sedimentation above natural background levels in the intertidal and subtidal habitats of mud crabs in East Arm and Shoal Bay may impact on megalopae settlement and recruitment.	Megalopae adapted for turbid environment (**Section 6.3.4**). Megalopae may avoid affected areas and settle in surrounding unaffected habitats if tidal conditions are favourable (i.e. neap tides) (**Section 6.3.4**). Spawning strategy (i.e. offshore spawning and pelagic larvae) suggests likely interconnectivity of populations in the	E(B1)	2	Low

				Northern Territory region. Therefore source of recruitment is unlikely to be dependent solely on spawning of local population (**Section 6.3.4**).			

**Significant impact defined here as >25% loss of mud crab population or >25% of mud crab habitat within Darwin Harbour and Shoal Bay, based on the assumption that mud crabs are evenly distributed throughout the available habitat.

*C = consequence.

†L = likelihood.

‡RR = risk rating.

§E – describes the level of consequence; B2 – describes the category of consequence.

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