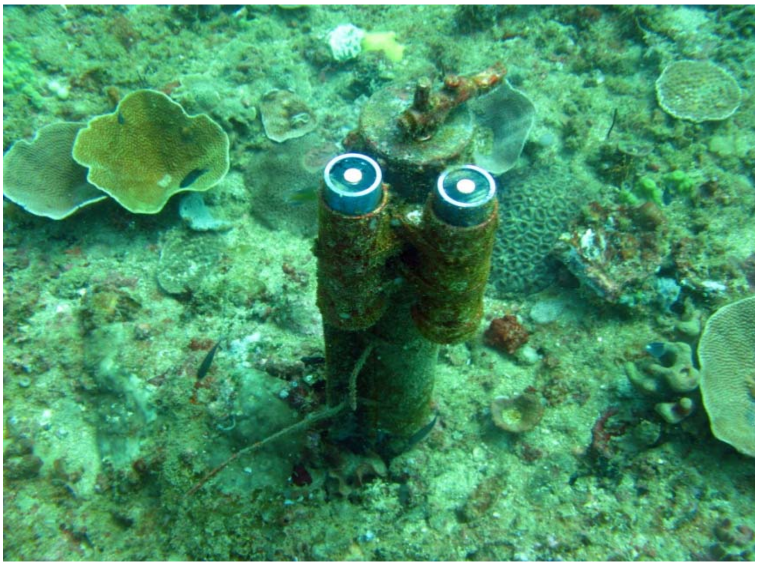
Port Hedland Outer Harbour Development



WATER QUALITY THRESHOLDS

- Revision 0
- October 2011

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Executive Summary

A key component of the environmental approval process for the BHP Billiton Iron Ore Port Hedland Outer Harbour Development is demonstration that potential impacts on the marine environment have been adequately investigated. One of the foremost potential impacts on the marine environment that may result from the Outer Harbour Development is altered water quality conditions from dredging and spoil disposal activities including increased turbidity, decreased benthic light conditions and increased sedimentation rates.

Environmental Assessment Guidelines (EAG) provided by the Environmental Protection Authority (EPA) of Western Australia outline processes by which potential impacts to marine benthic communities in State waters may be evaluated and quantified. In particular, EAG No. 7 *Marine Dredging Proposals* (EPA 2011) provides the following recommendation:

'*…'pressure thresholds' will need to be established for predicting mortality, sub-lethal effects and no measurable effects to biota. The thresholds are the numerical values for pressure (usually defined in terms of intensity and duration and sometimes frequency) that are used for interrogating the output produced by the modelling pressure fields. Pressure thresholds must therefore be in the same units as the model outputs or algorithms must be developed to allow conversion of thresholds units to the unit of output of the numerical models*.'

Biota classes comprising marine benthic communities present in the Outer Harbour Development area include benthic primary producers (BPPs; macroalgae, seagrasses and hard corals) and non-BPPs (sponges and soft corals). The primary impacts that may arise from altered water quality conditions due to dredging and disposal during the Outer harbour Development for benthic biota are as follows:

- **BPPs**: a reduction in Photosynthetically Active Radiation reaching the benthos causing reduced photosynthetic activity as well as scouring and burial due to elevated sedimentation rates; and
- **Non-BPPs**: increased suspended solid concentrations leading to reduced pumping rates in filter feeders and scouring and burial due to high sedimentation rates.

Using information from the baseline water quality and coral health monitoring and relevant literature, impact thresholds for BPPs and non-BPPs were developed to enable an impact assessment of benthic habitats in the Outer Harbour Development area to be undertaken. As recommended by EAG No. 7 (EPA 2011) thresholds incorporating intensity, duration and frequency in units applicable to the dredge plume modelling outputs were developed.

Also as recommended by EAG No. 7 (EPA 2011), thresholds applicable to the biotic component, BPP or non-BPP, were developed upon the organisms considered to be most sensitive/least tolerant of altered water quality conditions within this biotic component. In the case of the Outer Harbour Development area, the most sensitive organisms are hard corals, and these organisms are herein used as proxys to represent both the sensitivity and spatial representation for BPPs and non-BPPs.

Based on information gathered from the available literature, the impact thresholds for benthic biota in State waters of the Outer Harbour Development area are as per below.

Effect	Driver	Intensity	Duration	Frequency
Lethal	Light	≤1% Surface Irradiance (SI) at benthos	All daylight*	>40 days in a rolling 60 day period
	Sedimentation	110 $mg/cm^2/day$	Daily	>34 days in a rolling 50 day period
Sub-lethal	Light	Less than 60% SI at benthos[1]	All daylight*	>40 days in a rolling 60 day period
		Less than 45% SI at benthos[2]		
		Less than 30% SI at benthos[3]		
		Less than 15% SI at benthos[4]		
	Sedimentation	110 $mg/cm^2/day$	Daily	>15 days in a rolling 50 day period
No measurable change	TSS	Not more than 5 mg/L above background	All daylight*	>8 consecutive days
	Sedimentation	50 $mg/cm^2/day$	Daily	>15 days in a rolling 50 day period

*Refers to 10 daylight hours (0800 – 1800)

[1] Sensitivity analysis a

[2] Sensitivity analysis b

[3] Sensitivity analysis c

[4] Sensitivity analysis d

The impact thresholds for benthic biota in Commonwealth waters of the Outer Harbour Development area are presented in the following table.

Effect	Driver	Intensity	Duration	Frequency
Lethal	Light	≤1% SI at benthos	All daylight*	>7 days in a rolling 20 day period
	Sedimentation	50 mg/cm^2/day	Daily	>15 days in a rolling 30 day period
Sub-lethal	Light	Less than 60% SI at benthos[1]	All daylight*	>7 days in a rolling 20 day period
		Less than 45% SI at benthos[2]		
		Less than 30% SI at benthos[3]		
		Less than 15% SI at benthos[4]		
	Sedimentation	50 mg/cm^2/day	Daily	>7 days in a rolling 30 day period
No measurable change	TSS	Not more than 5 mg/L above background	All daylight*	>8 consecutive days
	Sedimentation	25 mg/cm^2/day	Daily	>7 days in a rolling 30 day period

*Refers to 10 daylight hours (0800 – 1800)
[1] Sensitivity analysis a
[2] Sensitivity analysis b
[3] Sensitivity analysis c
[4] Sensitivity analysis d

For the Zone of Moderate Impact (sub-lethal) assessment, if EAG #7 is followed and the most sensitive organism that may be present are used to develop thresholds then the use of a sub-lethal threshold of <60% Surface Irradiance (SI) is warranted on the basis that several species of *Acropora* have been reported to exhibit sub lethal stress if light is reduced past this level for any period of time, and *Acropora* is present at some sites but is rare. However, the use of this threshold is questionable as the modelling outputs reveal that background levels of TSS developed from baseline water quality monitoring produce exceedances of this threshold across large areas of the region. This information suggests that the reason *Acropora* species are rare on these reefs is because the natural light climate is often not suitable.

Therefore, a sensitivity analysis has been performed using different levels of %SI reductions (i.e. 45%, 30% and 15%) to better assess the likely impacts upon the more dominant components of the benthic communities.

Examination of the tables shows the major difference between the thresholds set for Commonwealth and State waters is that different frequencies have been used to predict areas of impact.

The use of 7 and 15 day periods in 20 or 30 days for Commonwealth waters is based on interpretation of evidence in the literature that suggests the coral communities located in the offshore region are likely to be more sensitive to light attenuation relative to the *Turbinaria*/ Faviid dominated communities of the inshore region. There is for example, more *Acropora* on the offshore reefs. Examination of the information available on a recent large scale dredging program elsewhere in the Pilbara suggests that periods of stress of about 7 days in 20 do lead to some mortality of corals, but these data are still to be properly investigated.

The coral communities in the deeper offshore areas located in Commonwealth waters also appear to be more stable relative to those in shallower State waters (as determined from larger colony sizes and percent cover of live coral) and this may be a consequence of greater protection from storm (cyclone) damage as depth increases. Of course, the greater the depth, the less light will penetrate to the substrate for a given level of TSS, and so while corals at these greater depths are protected from storm damage, they are likely to be more vulnerable to prolonged periods of low light.

The use of a 7 day period for estimates of mortality and sub lethal stress impacts is still considered to be conservative (e.g. baseline data suggests corals may routinely experience 14days of no light without mortality) . The thresholds will therefore predict overestimates of both coral mortality and stress because many of the offshore reef areas also support high proportions of *Turbinaria* and Faviid corals which are known to be much more resilient.

Once the benthic impact thresholds have been evaluated against the dredge plume modelling outputs to identify areas that experience lethal, sub-lethal and no measureable effects, this information is processed to generate indirect losses by overlaying effects areas with the benthic habitat map. Given that the benthic habitat map for the Outer Harbour Development area provides benthic subcategory components indirect loss estimates for BPPs and non-BPPs can be generated.

The application of lethal, sub-lethal and no measurable change thresholds to the dredge plume modelling outputs will be used to define the Zones of High Impact, Moderate Impact and Influence, respectively. Within the Zone of High Impact approved by the EPA, indirect losses of benthic habitat will be permitted, while in the Zone of Moderate Impact monitoring of benthic habitats may be required to evaluate if biota responses to water quality conditions are as predicted by the thresholds.

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Tables

List of Acronyms

Acronym	Full title
AIMS	Australian Institute of Marine Science
BPP	Benthic Primary Producer
BPPH	Benthic Primary Producer Habitat
COR	Cornelisse Shoal
COX	Coxon Shoal
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTH	Cape Thouin
EAG	Environmental Assessment Guidelines
EPA	Environmental Protection Authority
OEPA	Office of the Environmental Protection Authority
GBR	Great Barrier Reef
idf	intensity, duration, frequency
IMO	In Situ Marine Optics Pty. Ltd.
LTI	Little Turtle Island
MAFRL	Marine and Freshwater Research Laboratory
MIB	Minilya Bank
MLR	Minimum Light Requirements
Mtpa	Million tonnes per annum
NATA	National Association of Testing Authorities
NTU	Nephelometric Turbidity Units
PAR	Photosynthetically Active Radiation
SI	Surface Irradiance
SKM	Sinclair Knight Merz
TSS	Total Suspended Solids
WIS	Weerdee Island Site

Document history and status

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1. Introduction

1.1. Background

As part of the environmental approval process for the BHP Billiton Iron Ore Port Hedland Outer Harbour Development, it is required to demonstrate that potential impacts on the marine environment have been adequately investigated. One of the foremost potential impacts on the marine environment will be altered water quality conditions associated with turbidity-generating activities including dredging and disposal. Arising from altered water quality conditions is the potential for impacts and ultimately losses of benthic communities.

Marine dredging programs can have detrimental impacts upon surrounding sensitive marine habitats such as coral reefs (Brown *et al*. 1990; 2002; PIANC 2010) and seagrass beds (Onuf 1994). One of the main impacts of dredging is to increase the suspended particles in the water column; this may reduce the quantity and quality of available incident surficial light which in turn may lead to a reduction in photosynthetic production (Turner *et al*. 2006). Particles suspended in the water column can also settle and potentially smother benthic marine organisms. Smothering can lead to the disruption of the organisms' photosynthetic rates, feeding and respiratory processes. These effects would likely cause stress, that may reduce productivity and increase mortality if sustained (Turner *et al*. 2006).

An integral component of the successful management of potential impacts is the identification of effective impact thresholds based on physical attributes in the water column during turbidity-generating activities, and at which a biological impact is expected; which can then be used to predict the scale and severity of potential impacts to benthic communities. Impacts or pressure thresholds are defined in EPA (2010):

'Pressure thresholds signify a level of pressure (intensity, frequency and duration) that equates to a pre-defined level of impact in the biota of interest.

The EPA expects that pressure-response relationships and associated impact thresholds be given due consideration by proponents of proposed dredging projects, as the pressure-response relationships will vary according to the project design details and the biota potentially affected. The impact thresholds presented in this document are for benthic biota identified in State and Commonwealth waters of the proposed project area of the Outer Harbour Development at Port Hedland.

1.2. Project Overview

The Outer Harbour Development will provide an export capacity of approximately 240 Million tonnes per annum (Mtpa) of iron ore. This will be established in four stages, with incremental expansions brought on line to reach the maximum capacity. Expansion stages will occur through four separate modules, each with a nominal capacity of up to 60 Mtpa. Regulatory approvals are being sought for the infrastructure required to deliver the total capacity of 240 Mtpa. The Outer Harbour Development will involve the construction and operation of terrestrial and marine infrastructure (**Figure 1-1**) for the handling and export of iron ore.

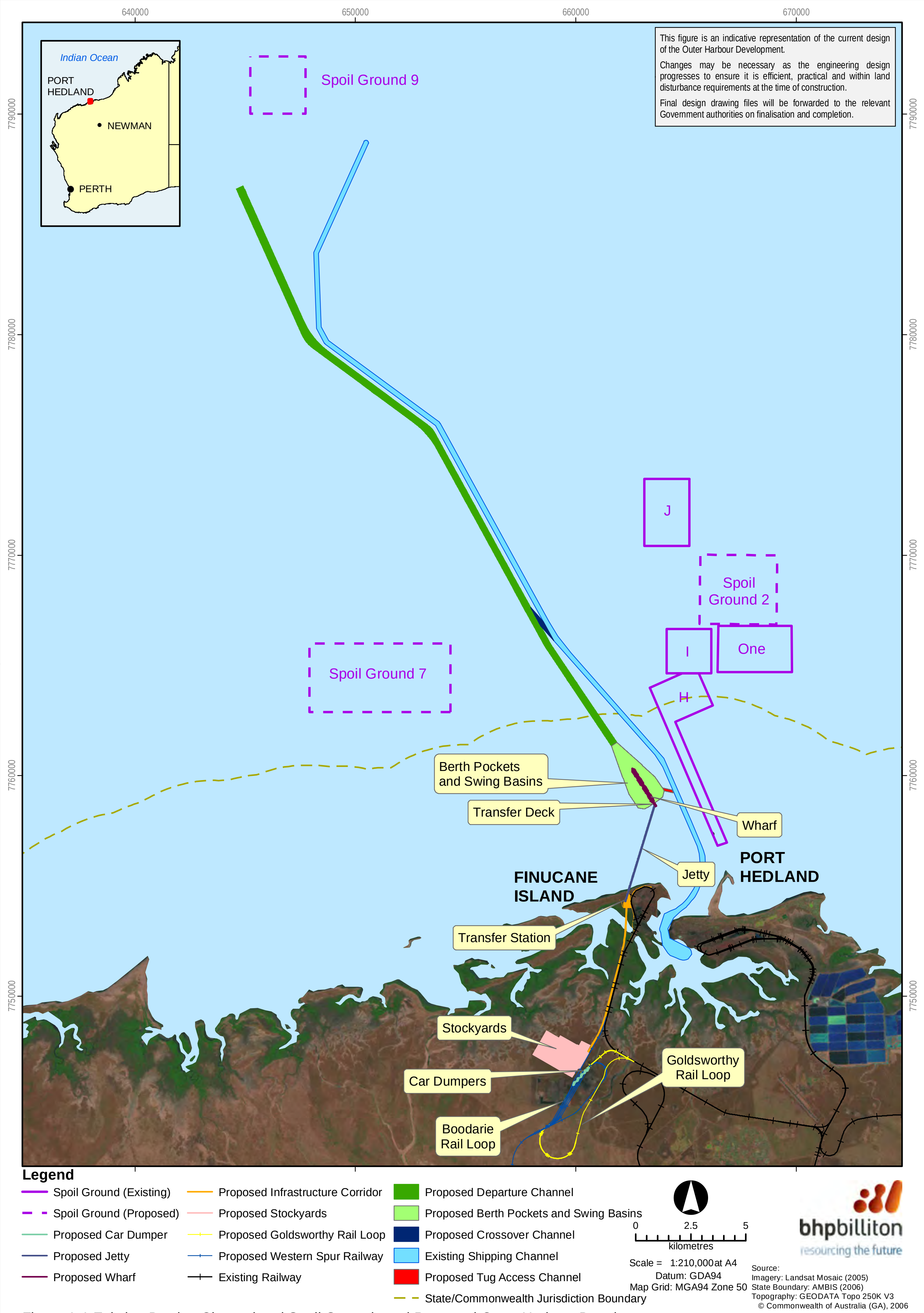


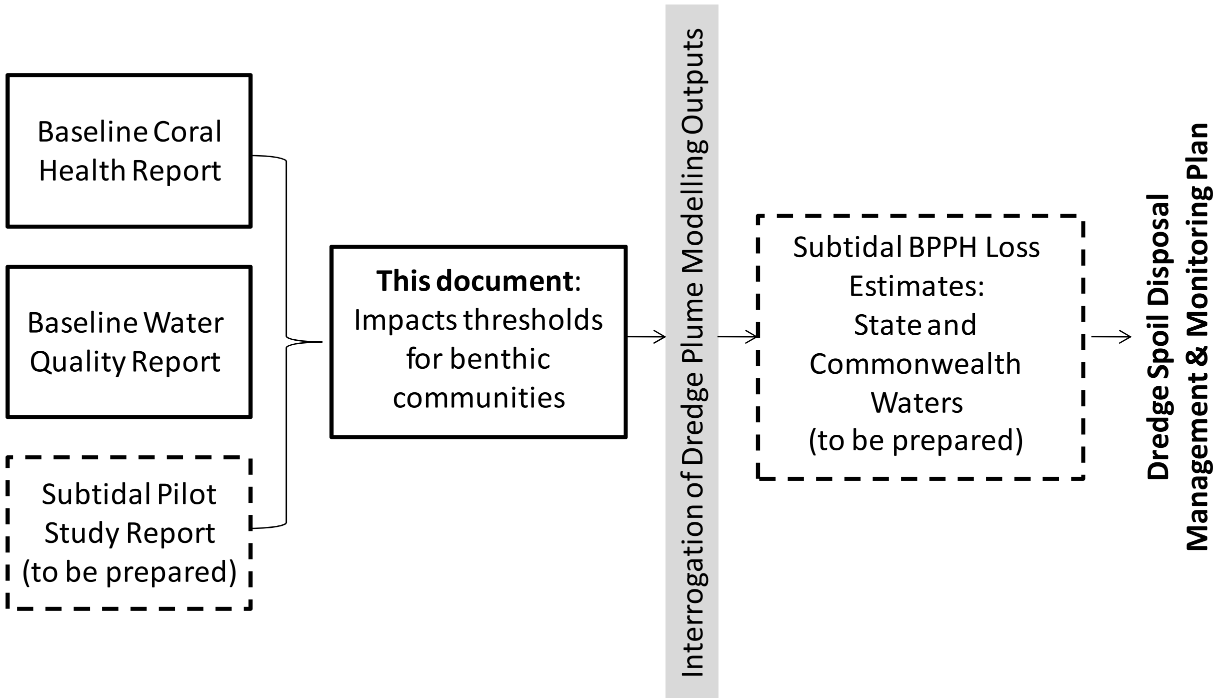
Figure 1-1 Existing Dredge Channel and Spoil Grounds and Proposed Outer Harbour Development

Marine development will include:

- an abutment, jetty and wharf;
- mooring and associated mooring dolphins;
- transfer station and deck;
- associated transfer stations, ore conveyors and shiploaders;
- dredging for berth pockets, basins and channels; and
- aids to navigation.

1.3. Report Structure

This document explains the approach used to develop water quality impact thresholds, their intended spatial application, and the process by which dredge plume modelling outputs are interrogated to quantify the scale and severity of potential impacts to benthic communities in the project area. There are a number of other associated documents that either provide information to support this approach or are dependent on the outputs. **Figure 1-2** illustrates the relationship of this document to these others.



- **Figure 1-2 Approach to Setting Water Quality Thresholds**

The following sections provide the structure of the report:

- **Section 2**: an overview of government environmental assessment guidelines relevant to the impacts thresholds presented here;
- **Section 3**: a summary of baseline data on benthic habitats and water quality collected for the Outer Harbour Development;
- **Section 4**: an overview of benthic communities and potential impacts arising from altered water quality conditions due to dredging and spoil disposal activities; and
- **Section 5**: the proposed impacts thresholds for benthic habitats for the Outer Harbour Development project.

2. Relevant Guidelines

2.1. State Waters

The Environmental Protection Authority (EPA) issues Environmental Assessment Guidelines (EAGs) which assist in the protection and management of sensitive environments in Western Australia. There are two EAGs relevant to the water quality threshold approach for State waters outlined in this report:

- EAG No. 3 *Protection of Benthic Primary Producer Habitats in Western Australia's Marine Environment* (EPA 2009) provides guidance on assessing potential impacts, including cumulative irreversible loss and serious damage to, benthic primary producer habitats in Western Australia's marine environment; and
- EAG No. 7 *Marine Dredging Proposals* (EPA 2010) has been designed to impart clarity and consistency to the information presented to the EPA for the environmental impact assessment of marine dredging proposals through the provision of a single assessment framework.

A brief summary of each EAG is provided in the sub-sections below.

2.1.1. Environmental Assessment Guideline No. 3

The geographic scope of EAG No. 3 covers all coastal waters of Western Australia, from the highest water mark of the intertidal zone associated with the mainland, islands and emergent reefs to the depth maxima for benthic primary producer habitats in the subtidal zone of these waters.

In applying the intent of EAG No. 3 and ensuring that impact assessment is undertaken as intended by the EPA, a clear understanding of a number of terms is required:

- Benthic primary producer habitats are functional ecological communities that inhabit the seabed within which algae (e.g. macroalgae, turf and benthic microalgae), seagrass, mangroves, corals or mixtures of these groups are prominent components. Benthic primary producer habitats also include areas of seabed that can support these communities;
- Loss of benthic primary producer habitat would commonly be associated with activities such as excavation or burial. In almost all cases, these activities directly modify benthic primary producer habitat so significantly that impacted habitat would not be expected to recover to the pre-impact state and therefore the impact is irreversible; and
- Serious damage refers to damage to benthic primary producer habitat that is effectively irreversible or, where recovery is predicted, it is not predicted to occur within a five year timeframe.

2.1.2. Environmental Assessment Guideline No. 7

The direct and indirect impacts of dredging on benthic communities and habitats are the primary concerns of EAG No. 7. Specifically, the main focus of EAG No. 7 is:

- direct loss of benthic habitats and communities by removal or burial; and
- indirect impacts on benthic habitats and communities from the effects of sediments introduced to the water column by the dredging.

At a minimum, direct losses will occur within the footprint of dredged areas and some spoil grounds, and may extend to areas immediately surrounding infrastructure where acute or ongoing sediment-related impacts are expected to occur (e.g. sedimentation). Direct losses are considered irreversible unless a scientifically-sound case can be made for recovery within a timeframe of five years or less.

Indirect impacts generally occur as a consequence of the intensity, duration and frequency of sediment-related pressure imposed on benthic biota such as:

- Sediment in the water column (turbidity): reduces quality and quantity of light available at the seabed for photosynthesis, can clog feeding apparatus of filter feeders and deposit feeders and inhibit key ecological processes that occur in the water column (e.g. fertilisation of pelagic gametes, survivorship and competency of propagules); and
- Sediment deposited on the benthos (sedimentation): smothers biota, can cause abrasion of exposed tissues, can alter sea bed load or produce other effects similar to those caused by turbidity.

A summary of the definitions used in EAG No. 7 to describe impacts to benthic communities and habitats is provided in **Table 2-1**.

- **Table 2-1 List of Terms used to Define Impacts to Benthic Communities and Benthic Habitats**

Term	Definition
Loss	Direct removal or destruction of BPPH. Considered to be irreversible.
Damage	Alteration to the structure or function of a community.
Serious damage	Timeframe for full recovery is expected to be longer than five years.
Minor damage	Timeframe for full recovery is expected to be less than five years.

2.2. Commonwealth Waters

The Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) is responsible for the management of the marine environment in Commonwealth waters and for the management of threatened marine species listed under the *EPBC Act 1994.* There are presently no specific guidelines relevant to the determination of water quality thresholds for prediction of impacts to marine benthos in Commonwealth waters and the EAGs described above apply only to State waters. For the sake of consistency, the guidance outlined for State waters has been applied herein to the development of thresholds for Commonwealth waters. Whilst there are no guidelines for acceptable loss, or otherwise, of benthic habitat in Commonwealth waters, impacts to these habitats may affect listed marine species (since they may be used as refuge or as foraging habitat) and therefore habitat loss has been reported and assessed in these terms in the impact assessment report (Appendix B2 of the PER/EIS).

3. Baseline Data

In June 2008, surveys of benthic habitats and collection of baseline water quality data within the Outer Harbour Development project area commenced. Provided here is a summary of the program's findings. For further detail, the reader is referred to the following reports:

- SKM (2009). *Port Hedland Outer Harbour Development – Baseline Benthic Marine Survey*. Prepared for BHP Billiton Iron Ore by Sinclair Knight Merz, Perth;
- SKM (2011b): *Port Hedland Outer Harbour Development – Baseline Water Quality Monitoring Report: June 2008–March 2010*. Prepared for BHP Billiton Iron Ore by Sinclair Knight Merz, June 2011; and
- SKM (2011d) *Port Hedland Outer Harbour Development – Baseline Coral Health Monitoring Report: Periods 1–23*. Prepared for BHP Billiton Iron Ore by Sinclair Knight Merz, June 2011.

3.1. Benthic Habitats

3.1.1. Benthic Surveys

Baseline surveys of subtidal marine benthic habitats in the Port Hedland region were undertaken between December 2007 and May 2008 (SKM 2009). The area surveyed was extensive covering approximately 365,000 ha. This was ground-truthed using a number of survey techniques and included 734 discrete observations to provide a high level of confidence in the mapping. LiDAR investigations highlighted seabed relief likely to support benthic habitat. Habitat information was collected either by divers making observations and taking replicated 50 m video transects, or by towing video cameras over longer transects. The locations were selected after examining the detailed LiDAR seabed bathymetry, bathymetric charts and aerial photographs of inshore areas.

The survey work undertaken to establish the baseline habitat map and subsequent surveys to establish the natural variability have revealed that the area is subject to high levels of natural variability, particularly within the inshore zone. The results of the subtidal surveys show that benthic habitats offshore of Port Hedland comprise extensive plains of sand/silt, and limestone pavement and ridges (SKM 2009). The distribution of benthic primary producers (BPP) is strongly associated with either hard substratum, which provides surfaces for attachment or areas that provide the necessary shelter for colonisation of seagrasses or algae within a sediment substratum. Many of the offshore limestone ridges run parallel to the coastline and those areas of ridges surveyed up to depths of 25 m, support sparse hard corals, macroalgae, soft corals, gorgonians, sea whips and sponges. The extensive plains surveyed are often bare of any large marine flora or fauna (such as coral and macroalgae), and mainly support smaller sediment dwelling invertebrates and very sparse sponge and soft coral assemblages.

Hard corals were the most dominant BPP growing along the ridgelines that may be affected by dredging activities, and the dominant corals present are from the genus *Turbinaria* and from the families Faviidae and Poritidae. Branching *Acropora* corals were found in numbers (low abundance) only at the offshore ridge lines in deeper water (greater than 12 m, lying in Commonwealth waters). Based on the low species richness and abundance of corals and dominance of *Turbinaria*, coral communities that inhabit subtidal habitats in the Port Hedland region are high turbidity, high sedimentation adapted communities. In addition, the species and habitats affected are considered typical of the broader marine environment of the Pilbara region, and no new species have been recorded on these reefs. Cover of hard corals was also assessed as part of the ground-truthing survey work. The results showed that within State Waters the coverage of corals was between 0 and 21.6% cover.

Macroalgae occur on both hard and soft substrata and their abundance varies among different habitats and according to season. Macroalgal cover varied between 0 and 71% of the substratum at Weerdee Reef, 11 km west of Port Hedland Harbour in State waters, with *Caulerpa*, *Halimeda* and *Sargassum* among the most common macroalgae at this site (SKM 2009). The shallow subtidal limestone pavement at Weerdee Island has around 30 to 40% macroalgal cover; common genera included *Caulerpa*, *Halimeda* and *Sargassum* (SKM 2009). At Little Turtle Island, 40 km north-east of Port Hedland Harbour, macroalgal cover on subtidal pavement was lower (0 to 15%, but generally less than 5%). The intertidal pavement of the island also had sparse algal cover although species diversity was higher; 35 species comprising 17 red, 13 green and 5 brown algal species (SKM 2009).

One of the most prolific of the macroalgae (in terms of biomass) in the Pilbara region is the brown alga genus *Sargassum* (Huisman 2004). These plants exhibit a pattern of annual growth and reproduction followed by senescence, with individual plants appearing during late winter and rapidly attaining lengths of up to 3 m during spring before breaking off above the holdfast in early summer (pers. com. Gus Paccani 2009, previously of SKM). These algae are known to occur on the shoals offshore from Port Hedland and have been observed at four of the six water quality monitoring sites (SKM 2009).

Seagrasses are not common in the Port Hedland area and those that do occur are ephemeral species such as *Halophila ovalis* and *Halodule uninervis* that form patches of low density. Field investigations reported sporadic observations of seagrasses. A sparsely inhabited area (approximately 5 x 5 m) of *Halophila decipiens* was observed offshore of Weerdee Island. A similarly small and sparse stand of *Halophila ovalis* was observed at North Turtle Island. In addition, drop video investigations identified patches of seagrass, predominantly *Halophila ovalis*, in the shallow protected embayment between Weerdee and Downes Islands. The seagrass was mapped to cover approximately 86 ha in beds of sparse (5–25% cover) density, and was most commonly present with macroalgae and sponges forming a mixed assemblage. Given the field effort undertaken and the temporal breadth of these studies, it is likely that the distribution of seagrass, specifically *Halophila* spp., throughout the Port Hedland region is spatially and temporally dynamic. In addition, it appears that seagrasses in the study area are preferentially located in areas that offer shelter from prevailing metocean conditions (e.g. in the lee of islands).

3.1.2. Benthic Habitat Mapping

A benthic habitat map for the project area was produced using models based on methods developed by Holmes *et al*. (2007). Modelling from LiDAR[1], field observations and underwater video of marine benthic habitat distribution was used to predict habitat distribution within the surveyed areas.

The modelling included two types of substrata, soft (sediment) and hard substratum, and the biota that may be present on the substrata types. Estimates of the accuracy of the modelled habitat distribution were made and compared against actual ground truthing sites. Final categories of hard substratum presence and sediment were predicted with high (97%) overall accuracy and the correct classification rates for each of the habitat categories were generated.

The area and proportion of hard substrate and sediment in State and Commonwealth derived from habitat modelling is presented in **Figure 3-1**.

- **Table 3-1 Substrate Areas within State and Commonwealth waters of the Proposed Outer Harbour Development**

Habitat Category	Area (in ha)	Proportion (%)
State waters		
Sediment	79,591	92
Hard substratum	3,843	4
Sediment covered hard substratum	2,248	3
Undefined substrata	1,139	1
Total	**86,821**	**100**
Commonwealth waters		
Sediment	242,204	86
Hard substratum	21,603	8
Sediment covered hard substratum	8358	3
Undefined substrata	7703	3
Total	**279,867**	**100**

Five biotic habitat categories were included in the habitat model including BPP (hard corals and macroalgae) and non-BPP (soft corals, invertebrates and sponges).The majority of the biotic habitat categories were predicted to occur on the areas of topographic complexity also associated with hard substratum and sediment covered hard substratum; essentially the limestone ridgelines and shoals visible on LiDAR imagery. These areas therefore comprise most of the Benthic Primary Producer Habitat

[1] LiDAR stands for light detection and ranging. It is a technique used to construct an image representing the terrain of an area by firing rapid pulses of light at the landscape and a sensor measures the return of light once it bounces off the landscape surface. The time taken for the light to return to the sensor allows distances and therefore topography to be measured (http://www.csiro.au/resources/LightDetectionLidar.html).

(BPPH) within State and Commonwealth waters. Hard substratum comprised 4 and 8% of the total area in State and Commonwealth waters, respectively while sediment covered hard substratum comprised 3% of the total area within both State and Commonwealth waters (**Table 3-1**).

In order to be able to develop robust models for predicting distributions, the habitat class must have been observed with sufficient prevalence (at least 5% of the area of interest). Models developed for habitat classes that were observed with lower prevalence will not be robust as there would be insufficient presence data to train the models. In essence, the model would be trained to predict where the biota class would not be found and it would have extremely poor ability to predict presences.

Observations of seagrasses in the study area were very sporadic, and were concurrent with the presence of intertidal areas (**Section 3.1.1**). As a result, seagrass distribution could not be predicted using benthic habitat modelling.

3.1.3. Subtidal Pilot Program

Previous mapping undertaken in the subtidal waters in the vicinity of Port Hedland (SKM 2009) has revealed that subtidal habitats that may be affected by the dredging and spoil management activities comprise mosaic benthic communities present on hard substrata including benthic primary producer (e.g. hard corals and macroalgae) and non-benthic primary producers (e.g. filter feeders including soft corals, gorgonians, sea whips and sponges). The OEPA (Office of the Environmental Protection Authority) set out guidelines to ensure that impacts, both direct and indirect, are minimised and to advise on how benthic communities should be monitored and managed during dredging programs as part of a Dredging and Spoil Disposal Management Plan (DSDMP).

To ensure the suitability of non-diver methods to monitor subtidal benthic communities in State waters, as part of the DSDMP and in accordance with EAG No. 7 (EPA 2010), a pilot study has been implemented. The pilot study has the following overarching objectives:

- To refine sampling and statistical analysis based on real data so that benthic community monitoring is conducted in a scientifically rigorous and cost-effective way;
- To determine natural levels of spatial and temporal variation to inform ecologically relevant Effect Sizes that could be used for statistical analysis in a monitoring program; and
- To investigate the time and resources required to undertake a benthic community monitoring program and to ensure that such a program could be conducted, analysed and reported on within agreed deadlines.

The pilot study comprised three initial sites each with an area of 200 x 200 m. The sites were located over predominantly hard substratum areas supporting mixed benthic communities comprising BPPs and non-BPPs. The pilot study involved the investigation of the spatial and temporal variability in benthic communities (percent cover) measured by random towed video transects, with a sufficiently high level of replication. The high level of replication allowed an accurate assessment of natural variation that in turn provided rigorous information on the parameters and sample sizes needed to achieve sufficient statistical power for each site over time. Results of the pilot study have been used to inform the design of a broader marine monitoring approach in State waters.

3.2. Baseline Water Quality

Baseline water quality monitoring undertaken fortnightly at six monitoring locations within the Outer Harbour Development project area (**Figure 3-1**) commenced in June 2008 (SKM 2011b). In general, the majority of light, turbidity, temperature and sedimentation water quality data were weather dependent and showed a strong seasonal transition from the dry to the wet seasons. The tidal regime appeared to be an influential factor determining variations in the light climate, turbidity and water temperature on a fortnightly basis. On a seasonal basis, these water quality variables appeared to be influenced by climate (air temperature), storms and cyclone events.

Of the six locations, the sites at Weerdee Island (WIS) and Little Turtle Island (LTI) lie within State waters, while the sites at Cape Thouin (CTH), Minilya Bank (MIB), Coxon Shoal (COX) and Cornelisse Shoal (COR) lie within Commonwealth waters. At all monitoring sites there was a distinct seasonal transition in light, turbidity and sedimentation rates from the dry to the wet seasons, with turbidity increasing at the onset of the wet season (November) and the light climate, measured as Daily Photosynthetically Active Radiation (PAR) subsequently decreasing (**Figure 3-2** and **Figure 3-3**). Turbidity fluctuations and sedimentation rates were greatest at WIS (ranging from 0.1 to 124 NTU and a maximum of 1,559 mg/cm^2/day, respectively) followed by Cape Thouin, Minilya Bank and Little Turtle Island.

Of the six sites monitored for baseline water quality data, light was the most variable at WIS, which fluctuated on a daily basis and had the greatest range (<0.01 – 20.85 moles/m^2/day) compared to the remaining five sites (**Figure 3-2** and **Figure 3-3**). PAR at LTI followed a regular oscillating pattern that coincided with the tidal regime, however, there appeared to be no regular pattern in PAR recorded at WIS that coincided with the tidal phase.

All of the results observed to date were within the expected range of previous water quality observations made during other studies within the Pilbara region and were all reliably explained by reference to weather conditions and seasonal trends.

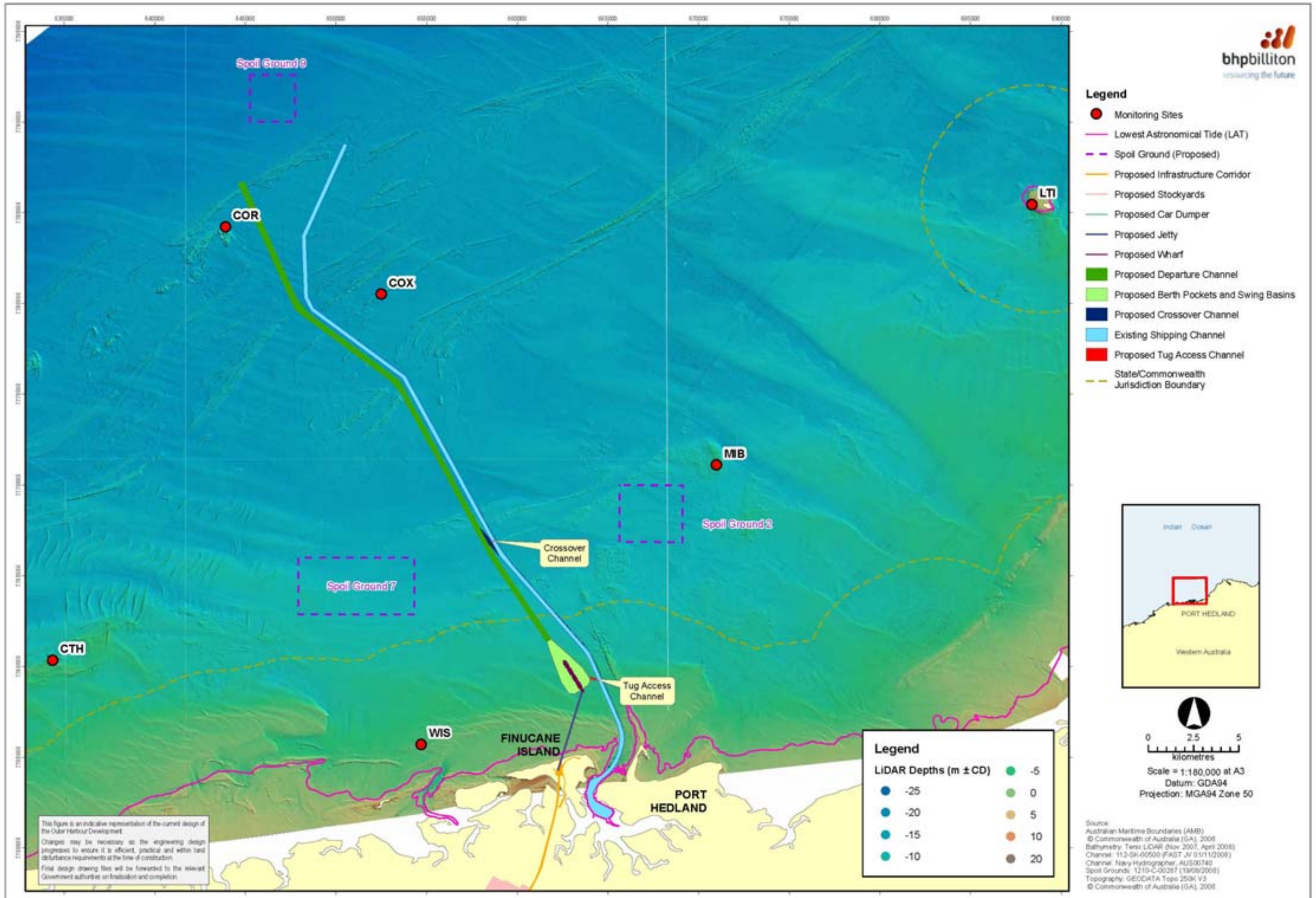
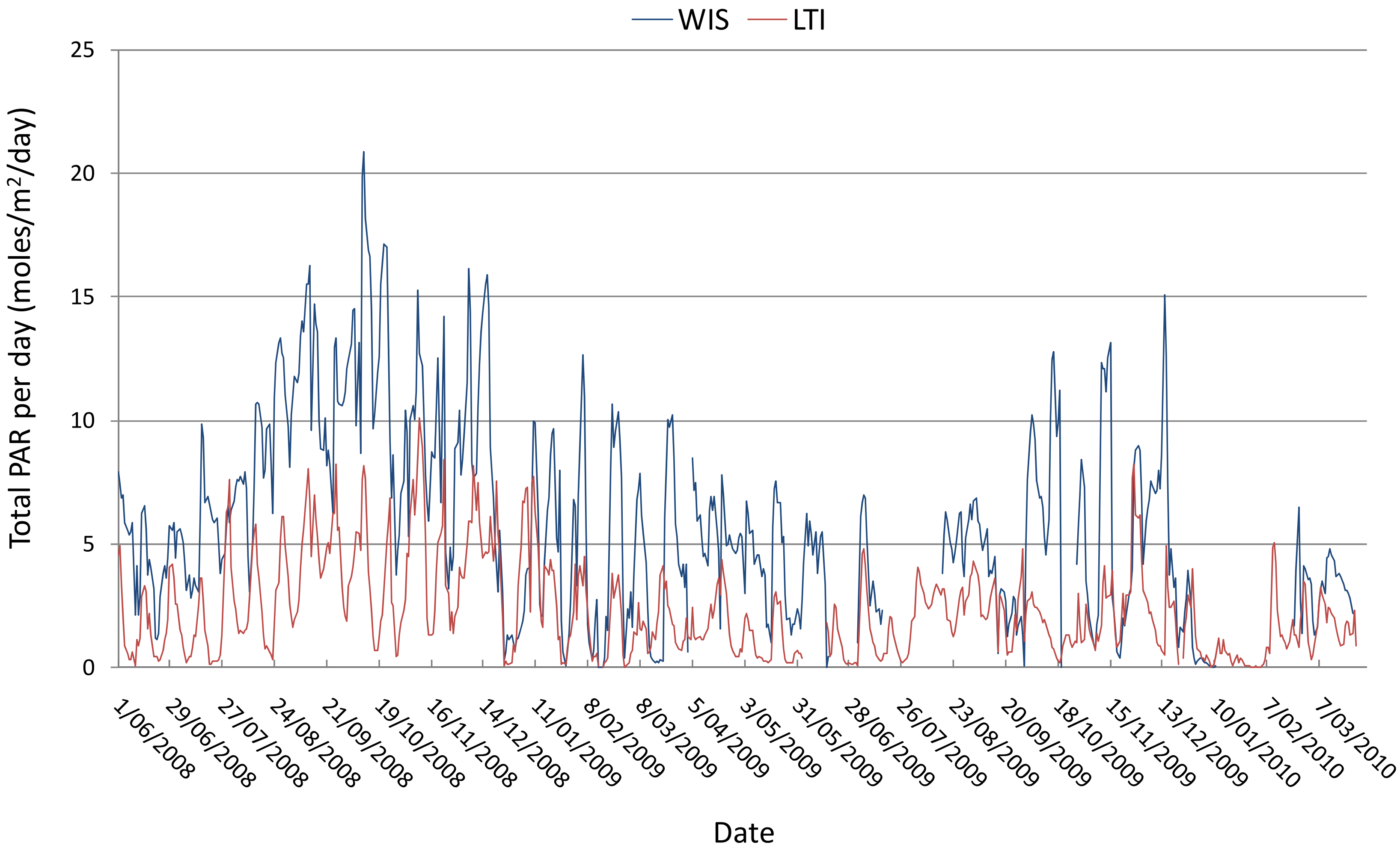
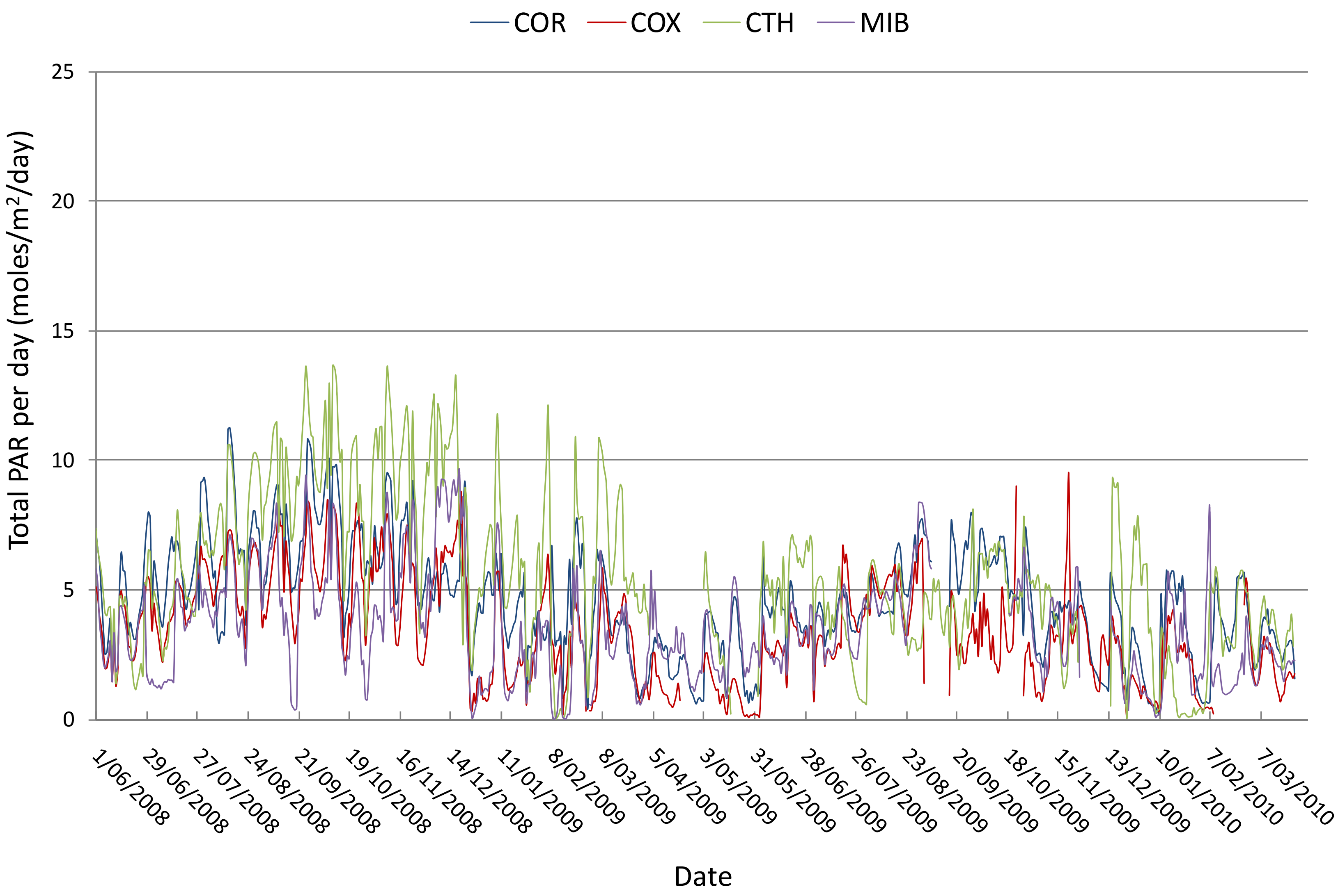


Figure 3-1 Water Quality and Coral Health Baseline Monitoring Sites

- **Figure 3-1 Locations of the Water Quality and Coral Health Baseline Monitoring Sites**



- **Figure 3-2 Light climate at Port Hedland State waters sites (WIS and LTI) between June 2008 and March 2010**



- **Figure 3-3 Light climate at Port Hedland Commonwealth waters sites (COR,COX, CTH and MIB) between June 2008 and March 2010**

3.3. Light Conditions for Hard Corals

Coral monitoring was undertaken at the six baseline WQ monitoring sites between June 2008 and April 2011 (**Figure 3-1**). Corals at these sites frequently experienced periods of 'no-light' (very low PAR), or high turbidity conditions (**Figure 3-2** and **Figure 3-3**). For example, between 24 December 2008 and 5 January 2009 there was a period where the light levels at three of the six monitoring sites (MIB, COX and WIS) were between 0 and 5% of background light conditions. These sites have tagged coral colonies, which were routinely monitored for partial mortality before, during and after this time (SKM 2011d). Coral health monitoring at these sites showed no increase in mortality in the subsequent weeks to months. In addition, coral communities at site LTI frequently experienced low light conditions (greater than a 90% reduction in light for up to 10 days) throughout the year (see **Figure 3-2**) and yet the partial mortality at this site (0–11%) remained one of the lowest recorded at any monitoring site (SKM 2011d).

The natural occurrence of light deprivation can be used as a guide to the period/s of light deprivation which may correspond to severe stress or mortality of coral colonies. An absence of light in the baseline surveys for 14 days does not appear to lead to mortality.

4. Water Quality and Benthic Communities

4.1. Water Quality and Impact Drivers

4.1.1. Turbidity

The measurement of turbidity is relevant to coral health in that increased turbidity influences the light attenuation characteristics of the water column, and therefore influences the amount of PAR available to primary producers. Turbidity also reflects the level of Total Suspended Solids (TSS) within the water column, although the relationship between the two parameters can vary widely depending on the nature of the particles constituting suspended sediment. Turbidity (measured as Nephelometric Turbidity Units (NTU)) is a widely utilised parameter, particularly for the reactive monitoring of dredge plume impacts on water quality, because of the impact on a biologically important physical parameter (light). The measurement of turbidity is also favoured because with modern instrumentation it is easily and robustly measured simultaneously at many sites (multiple loggers deployed), continuously (entire dredging and spoil disposal program), over varying small temporal scales from seconds to days.

As the measurement of turbidity can be influenced by changes in particle size, the relationships between turbidity and light attenuation (PAR) or TSS (a key means to mathematically model sediments behaviour within a dredge plume) can vary widely. The turbidity scale is also problematic as changes in turbidity often occur over orders of magnitude resulting in data that is log distributed. Despite these known problems, turbidity has been successfully utilised as a measure of water quality in and adjacent to dredge plumes in numerous locations and projects such as the Pluto LNG Development, Western Australia (MScience 2007), Hay Point Departure Channel Dredging, Queensland (Koskela *et al*. 2002), and Cape Lambert 85 Mtpa Port Upgrade, Western Australia (SKM 2007a).

4.1.2. Total Suspended Solids

One of the most robust and repeatable water quality measurements is the TSS concentration measurement. This measure is critical in dredge plume modelling. The common models used for predictions of plume behaviour, work on the basis of particles measured as excess levels of TSS moving over varying spatial and temporal scales in response to the activities of dredging and dredge spoil disposal and prevailing metocean conditions.

The accurate measurement of TSS relies upon laboratory analysis of water samples. This means there are severe logistical and economic constraints in the use of this method for the assay of water quality over large spatial scales in both baseline and reactive monitoring programs. In light of these constraints, the favoured approach is the collection and use of turbidity data. Because TSS is used to characterise the behaviour of particles in modelling of dredge plume behaviour, the use of water quality thresholds based on turbidity requires an understanding of the locally relevant relationship/s between TSS and NTU in order to use the baseline and reactive monitoring datasets (NTU) to predict the potential impact of the dredge plume (TSS) upon the environment. Therefore, the development of the thresholds for modelling interrogations typically hinges upon the development of a reliable relationship between TSS and turbidity.

4.1.3. Sedimentation Rate

Marine organisms have physiological or behavioural ways of dealing with sediments that settle on or around them, ranging from avoidance (such as fish, marine mammals and sea turtles) to tolerance and clearing of clogged pores (such as filter feeders). Above certain thresholds, small changes in net sedimentation rates may adversely affect organisms, resulting in stress and eventually mortality, particularly for sessile organisms or those confined to specific territories.

The majority of observed detrimental impacts of dredging relate to high sedimentation (e.g. Marsalak 1981; Brown *et al*. 1990, 2002; PIANC 2010); however, the alteration of the background net sedimentation rate(s) due to deposition of sediment from a dredge plume is likely to be on a smaller spatial scale compared to any changes in the water quality induced by a dredge plume. This is primarily because the heavier particles in the plume will fall out of the water column relatively close to the site where the dredge is working, or where spoil material is disposed. Fine particles (typically those less than 75µm), on the other hand, often travel large distances in the water column until eventually settling out of the water column wherever local conditions (waves and currents) are sufficiently calm, and these particles may be re-suspended again (repeatedly) if local conditions (waves and currents) change. Consequently, the modes of impact and the receptors affected by sedimentation are often different when compared to impacts induced by reduced light or suspended sediments. It is therefore appropriate that sedimentation be considered separately for the interrogations of the dredge plume modelling output and separate thresholds for the process of sedimentation need to be developed.

There is an important distinction between gross sedimentation rate and net sedimentation rate where the former does not incorporate the removal of some (or all) sediment by resuspension. If resuspension is frequent, as is likely in high energy environments (where wave action and/or tidal currents are strong), then the net sedimentation rate, which measures the actual rate of accumulation of sediment on the bottom, can be significantly lower than the gross sedimentation rate. Insight to the potential resuspension regime offshore of Port Hedland is provided by comparison of the particle size distributions of sediment from sediment traps and the adjacent substrate. However, this information cannot be used to calculate net sedimentation rates, and so the focus remains on the use of gross sedimentation rate as a measure of potential sedimentation at a site.

4.1.4. Light Climate

Thresholds for any dredge project should ultimately be established with the objective of survivorship of BPP (EPA 2010).

Turbidity and TSS are typically used as proxies for the measurement of potential impact on biological processes due to attenuation or extinction of light. The spectrum of light available for photosynthesis (approximately 400 to 700 nanometres (nm)) is approximated using the parameter PAR. Photosynthetically Active Radiation (PAR) is defined in terms of photon (quantum) flux, which is the number of moles of photons in the radiant energy (usually measured in the unit $\mu mol/m^2/s$). PAR is an important measure of light within an ecosystem or habitat as the photosynthetic response of an organism is well correlated with the number of photons rather than with the light energy.

As PAR relates directly to the biological processes of BPPs, it is commonly used as a key measure in managing environmental impacts (Turner *et al*. 2006). There is a good understanding of the impacts of variable light on *hermatypic* corals (*hermatypic*-reef-building corals characterized by the presence of symbiotic algae within their tissue) and it is generally accepted that they will not live in conditions of less than 2 to 0.5% of Surface Irradiance (SI) (e.g. Falkowski & Dubinsky 1981; Titlyanov & Latypov 1991). The lower limit for coral communities to maintain integrity in the Whitsunday region of the Great Barrier Reef (GBR) is reported to be in the range of 6 to 8% SI (Cooper *et al.* 2007). In the Gulf of Siam the lower limit for corals is in the range of 2 to 8% SI (Titlyanov & Latypov 1991). There is also some detailed information in the literature on particular coral species and how they adapt to different light climates by altering their feeding strategies (Anthony 1999; Anthony & Fabricius 2000; Anthony & Connolly 2004).

This is in contrast to studies on effects of turbidity and TSS on corals, where there is a considerable variation in the potential levels of thresholds of these parameters that are known to have effects on corals (Anthony 1999; Gilmour *et al*. 2006), and an uncertainty as to what these levels may mean in different environments (i.e. high versus low water movement).

In review of the information above and in the absence of definitive information on the actual set of relationships between turbidity, TSS and the potential health of each of the species of corals present in the area offshore from Port Hedland, it is more useful to focus attention on light as it is recognised that the major potential effect of turbidity and TSS on corals is to reduce available light.

Modelling of the impacts of a dredge plume may be better achieved using light and light attenuation in particular, as a key parameter to determine whether potential impact is possible and what the level of impact might be. The use of light attenuation allows decision trees based on a single variable, thereby removing many of the subjective decisions required by the use of techniques based on fluctuations in the intensity-duration-frequency of TSS events (McArthur *et al*. 2002).

4.2. Sensitivities and Resilience of Benthic Community Components

As detailed in **Section 3.1.2**, the subtidal benthic habitat components of macroalgae, seagrasses, hard corals and filter feeders have been identified in State waters of the Outer Harbour Development project study area. Due to the varying life strategies and stages between and within these component groupings, the altered water quality conditions generated during dredging and spoil disposal activities will elicit different effect responses according to their related sensitivities and resilience.

Recently, a literature review considering impact thresholds relevant to a range of benthic community components – seagrass, macroalgae and microphytobenthos, (hard) corals and filter feeders – was prepared by Woodside Energy Ltd as part of the *Browse Liquefied Natural Gas Precinct Dredging and Spoil Disposal Assessment* on behalf of the State government’s Department of Sustainable Development

(DSD 2010). The literature review was comprehensive and recent, providing a temporally and thematic information source that is directly relevant to this document.

In the sub-sections below, summaries of the environmental conditions that have been found to generate an effect in benthic community components have been drawn from DSD (2010). Where additional information has become available since release of the report, or was not included in the review, this information has also been presented.

4.2.1. Macroalgae

Within State waters of the Outer Harbour Development project area macroalgae (**Section 3.1.1**) have been identified as a benthic community component that may be at risk from altered water quality conditions due to dredging and disposal activities. Impacts to macroalgal components of the benthic community may arise from reduced quality and quantity of light available and/or smothering due to increased sedimentation rates.

As noted in DSD (2010, pp. 110–111) the main points relating to macroalgae and altered water quality conditions are:

- Increased turbidity and sedimentation can influence macroalgal abundance and community composition;
- Increased turbidity will result in reduced photosynthetic productivity and potentially mortality if sustained over extended durations;
- Increased sedimentation can result in smothering, scouring, and changes to local structure and assemblage diversity;
- Impacts to macroalgal communities may be positive, negative or not detectable;
- Macroalgal light requirements vary among species and morphologies;
- Generally, macroalgal species with an extended reproductive period are most tolerant to sedimentation;
- Minimum light requirement varies according to morphology (**Table 4-1**);
- Compensation irradiance[2] values for various macroalgal species range from 1.8–140 $\mu mol/m^2/s$ (**Table 4-2**); and
- There are no definitive values documented in the literature for levels of sedimentation known to cause a negative impact on macroalgae.

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[2] The light level at which respiration losses equal productivity. As light decreases with depth, a depth is reached at which the productivity which is gained from sunlight is equal to what is needed for respiration (this level is known as the compensation irradiance). Beyond this depth, abundance of seagrass and growth decreases as productivity generated from sunlight is not sufficient to meet the needs of respiration.

- **Table 4-1 Minimum Light Requirements (in mol/m^2/d) of the Major Macroalgal Functional Groups**

Functional Group	Range	Mean
Filamentous	0.1082–2.63	1.4
Slightly corticated filamentous	0.9289–2.63	1.95
Corticated foliose	0.0483–2.49	0.87
Corticated	0.0317–2.63	0.93
Foliose	0.0842–0.25	0.13
Leathery	0.0277–1.53	0.5
Articulated calcareous	0.011–2.92	0.65
Crustose	0.0001–0.5	0.42
Undefined	0.0019–4.42	1.16
All	0.0001–5.0	0.81

Source: DSD (2010)

- **Table 4-2 Compensation Irradiance Points (I_c in µmol/m^2/s) for Macroalgae**

Species	I_c
Avrainvillea amadelpha	30
Codium sp.	80
Dictyosphaeria cavernosa	140
Dictyota acutiloba	26.1
Dictyota menstrualis	30–48
Dictyota pulchella	25–31
Gracilaria cornea	27.8
Gracilaria crassa	60
Gracilaria multifurcata	70
Halimeda copiosa	1.8 ± 0.7
Halimeda lacrimosa	7.1 ± 1.3
Halimeda tuna	4.8 ± 0.6
Halimeda sinulans	4.7 ± 1.3
Laminaria abyssalis	9
Padina japonica	14.5
Stypopodium hawaiiensis	19.8
Udotea orientalis	140

Source: DSD (2010)

4.2.2. Seagrasses

Within the State waters of the Outer Harbour Development project area seagrasses have also been identified as a benthic community component that may be at risk from altered water quality conditions due to dredging and disposal activities. Impacts to seagrass may arise from reduced quality and quantity of light available and/or smothering due to increased sedimentation rates.

As noted in DSD (2010, pp. 93–109), the main points relating to seagrasses and altered water quality conditions are:

- Increased turbidity and sedimentation can influence seagrass abundance and survival;
- Sensitivity of seagrasses to light reduction and sedimentation vary widely among species; seagrass species that have well-developed rhizome systems with significant below-ground reserves are most tolerant, while smaller pioneering species such as *Halophila* spp. are most sensitive;
- Minimum light requirements (MLR) for seagrasses (expressed as % of SI) vary widely between seagrass species, with mean values ranging from 2 to 30 % SI (**Table 4-3**);
- Compensation irradiance values for seagrasses range from 0.7–3.5 $\mu mol/m^2/s$ for smaller *Halophila* species and from 4.3–29.4 $\mu mol/m^2/s$ for mixed seagrass meadows dominated by larger climax species (**Table 4-4**);
- Increased turbidity will result in reduced photosynthetic productivity and potentially mortality if sustained over extended durations;
- Laboratory experiments have shown that seagrasses can survive low light conditions (below their minimum light requirement (MLR)) for periods ranging from a few weeks to several months, with *Halophila ovalis* being the most sensitive species (surviving only 16–38 days of light deprivation) (**Table 4-5**).
- Increased sedimentation over sustained periods of time can result in smothering and shoot mortality of seagrasses;
- In some smaller species, mortality following burial can be extremely rapid while other larger species (with vertical shoots) can survive burial for prolonged periods of time; and
- Maximum levels of sedimentation that seagrasses can survive range from 2 to 13 cm per year (**Table 4-6**), while short-term sedimentation occurring over periods of less than 2 months should not exceed 5 cm for most seagrasses.

- **Table 4-3 Minimum Light Requirements (MLR) (% of Surface Irradiance) for Seagrass Species – Determined using a Variety of Methods and Sources of Irradiance**

Species	Location	MLR (% SI)	Reference
Halodule wrightii	Alabama, USA	14	Shafer (1999)
	Laguna Madre, USA	15–20	Burd and Dunton (2001)
	Texas, USA	16	Onuf (1996)
	Florida, USA	17.2	Dennison *et al*. (1993)
	Texas, USA	17.5	Onuf (1991)
	Laguna Madre, USA	18	Dunton (1994)
	Corpus Christi Bay, USA	18	Dunton (1994)
	San Antonio Bay, USA	18	Dunton (1994)
	Indian River Lagoon, USA	20	Steward *et al*. (2005)
	Corpus Christi Bay, USA	20	Czerny and Dunton (1995)
	Indian River Lagoon, USA	24–37	Kenworthy and Fonseca (1996)
	Florida, USA	29.5	Beal and Schmit (2000)
Halophila decipiens	Hobe Sound, Florida, USA	2.5	Dennison (1987)
	St Croix, USA	4.4	Williams and Dennison (1990)
	Florida Bay, USA	5	Fourqurean *et al*. (2003)
	Cuba	8.8	Duarte (1991)
Halophila engelmanni	Cuba	23.7	Duarte (1991)
Halophila ovalis	Zanzibar, Tanzania	16	Schwarz *et al*. (2000)
Halophila spinulosa	Moreton Bay	6	Udy and Levy (2002)
Halophila spp.	Sub tropical seas	5	Dennison *et al*. (1993)
Heterozostera tasmanica	Westernport, Victoria	4.7–13	Bulthuis (1983)
Syringodium filiforme	Florida, USA	17.2	Dennison *et al*. (1993)
	Florida, USA	18.3	Dennison *et al*. (1993)
	Cuba	19.2	Dennison *et al*. (1993)
	Indian River Lagoon, USA	24–37	Kenworthy and Fonseca (1996)
Thalassia testudinum	Florida Bay, USA	13	Fourqurean and Zieman (1991)
	Corpyus Christi Bay, USA	14	Lee and Dunton (1997)
	Florida, USA	15.3	Dennison *et al*. (1993)
	Corpus Christi Bay, USA	20	Czerny and Dunton (1995)
	Cuba	23.5	Dennison *et al*. (1993)
	Puerto Rico	24.4	Dennison *et al*. (1993)
Zostera capricorni	Moreton Bay, Queensland	30	Longstaff *et al*. (1999)

Source: DSD (2010)

- **Table 4-4 Summary of Available Parameters for Tropical *Halophila* spp.**

Species	Location	Depth (m)	LAC	I_o	I_z	%SI	MLR	I_c	Reference
H. decipiens	Cuba	24.3	0.1	42.97	3.8	8.8	8.8		Duarte (1991); Buesa (1975)
H. decipiens	Hobe Sound, Florida, USA					2.5	2.5		Dennison (1987)
H. decipiens	Florida, USA	56				5	5		Fourqurean *et al*. (2003)
H. decipiens	St Croix, USA	40	0.08			4.4	4.4		Williams and Dennison (1990)
H. decipiens	US Virgin Islands, USA	16		224–293	33.7–64.6	15–22			Williams and Dennison (1990)
H. decipiens	US Virgin Islands, USA	24		224–293	18.0–32.3	8–11			Williams and Dennison (1990)
H. ovalis	Gulf of Carpentaria, Australia	1.5 above LAT		63.0	30.0	47			Longstaff and Dennison (1999)
H. ovalis	Gulf of Carpentaria, Australia	1.5 above LAT		63.0	0.1	0.2			Longstaff and Dennison (1999)
H. ovalis	Zanzibar, Tanzania	10				16	16		Schwarz *et al*. (2000)
H. ovalis		15						2.9	Erftemeijer and Stapel (1999)
H. ovalis	Canning Estuary, Australia						2	3.5	Hillman *et al*. (1995)
H. ovalis	Negeri Sembilan, Malaysia							0.7–1.1	Jamaludin *et al*. (2006)
H. spinulosa	Moreton Bay, Australia	28				6	6		Udy and Levy (2002)
H. spinulosa		50						1.7–3.5	Beer and Waisel (1982)
Mixed species		<15						4.3–29.4	Erftemeijer *et al*. (1993)
Mixed species					30.0–44.7			10.2–17.7	Erftemeijer *et al*. (1993); Gattuso *et al*. (2006)

Source: DSD (2010)

- **Table 4-5 Time and light Levels where Decline or Mortality was Observed in Seagrass**

Species	%SI	Days to Decline	Time to Death	Location	Reference
Halophila ovalis	0	0	38 days	Karumba, Queensland	Longstaff and Dennison (1999)
	0	3–6	30 days	Moreton Bay, Queensland	Longstaff *et al*. (1999)
	1	14	25 days	Magnetic Island, Queensland	Collier and Waycott (2009)
	7	15	16–22 days	Moreton Bay, Queensland	Longstaff *et al*. (1999)
Halodule pinifolia	0		100 days	Karumba, Queensland	Longstaff and Dennison (1999)
Halodule wrightii	13–16		9 months		Czerny and Dutton (1995)
Heterozostera tasmanica	2		2–4 months		Bulthuis (1983)
	9		10 months		Bulthuis (1983)
Posidonia sinuosa	12		24 months		Gordon *et al*. (1994)
Thalassia testudinum	10		11 months		Czerny and Dutton (1995)

Source: DSD (2010)

- **Table 4-6 Critical Thresholds of Seagrass for Sedimentation (cm/y)**

Species	Location	Sedimentation (cm/y)	Reference
Cymodocea nodusa	Mediterranean (Spain)	5	Marba and Duarte (1994)
Cymodocea rotundata	Phillipines	1.5	Vermaat *et al*. (1997)
Cymodocea serrulata	Phillipines	13	Vermaat *et al*. (1997)
Enhalus acoroides	Phillipines	10	Vermaat *et al*. (1997)
Halophila ovalis	Phillipines	2	Vermaat *et al*. (1997)
Posidonia oceanica	Mediterranean (Spain)	5	Manzanera *et al*. (1995)
Zostera noltii	Mediterranean (Spain)	2	Vermaat *et al*. (1997)

Source: DSD (2010)

4.2.3. Filter Feeders

Filter feeders, including sponges and octocoral (i.e. soft corals, gorgonians and sea whips), are present within State waters of the Outer Harbour Development project area and may be at risk from altered water quality conditions due to dredging and disposal activities. Impacts to filter feeder components of the benthic community may arise from increased suspended solid concentrations and increased sedimentation rates.

Sponges

As noted in DSD (2010, pp. 129–130), and additional references cited below, the key points in relation to the effect of altered water quality conditions on sponges are:

- Sedimentation and turbidity can play a significant role in determining sponge species distribution, diversity and abundance;
- Increases in turbidity and sedimentation can obstruct filter feeding capacities resulting in reduced flow rates and negative energy balances;
- There have been few studies on how sedimentation and turbidity affect sponges and there are no widely accepted threshold levels;
- Gerrodete and Flechsig (1979) found that for *Verongia lacunosa* the observed pumping rate significantly declines when a clay suspension of TSS greater than 11 mg/L was applied for four hours. A continual decline (cumulative impact) was only observed when a TSS concentration of 95 mg/L was applied for four days (**Table 4-7**);
- Tompkins-MacDonald and Leys (2008) found that two species of hexactinellid (glass) sponges temporarily arrested pumping at TSS concentrations of 15 and 36 mg/L, respectively (**Table 4-7**);
- Some sponges are phototrophic meaning they contain symbiotic algae within sponge tissue and the level of PAR can influence their abundance and diversity;
- Increased sedimentation can result in smothering and scouring of sponges and affect their respiration and/or filter feeding capacity;
- There are no widely accepted thresholds for the impact of sedimentation on sponges;
- Carballo *et al*. (1996) found tolerance to sedimentation varies with species and that some species inhabit environments of less than 2.8 g/m^2/month whilst others inhabit environments where the sediment load is 15.8 g/m^2/month (**Table 4-8**);
- Rutzler *et al*. (2007) found that for reef and mangrove inhabiting sponge species mortality for all species occurred after 96 hours of complete burial (**Table 4-8**); and
- Wulff (1997) found that 50% burial of sponges resulted in up to 56% biomass death after six weeks of burial (**Table 4-8**).

- **Table 4-7 Published TSS effects on sponges**

Author	TSS Level	Effect
Gerrodete and Flechsig (1979)	11 mg/L for 4 hours	Temporarily reduced *Verongia lacunosa* pumping rate
	95 mg/L over 4 days	Continual decline in *Verongia lacunosa* pumping rate
Tompkins-MacDonald and Leys (2008)	15 and 36 mg/L	Initiated arrest of pumping rate in two hexactinellid sponges

- **Table 4-8 Published sedimentation effects on sponges**

Author	Sedimentation Level	Effect
Carballo *et al*. (1996)	2.8 – 15.8 g/m^2/mo	Tolerance ranges between these levels depends on species
Wulff (1997)	50% burial	Biomass death ranged from 25–56% after 6 weeks
Rutzler *et al*. (2007)	Complete burial	All sponges died after 96 hours

Octocorals (soft corals, gorgonians and sea whips)

As noted in Chevron (2010) and additional references cited, key points relating to the effects of altered water quality on octocorals include:

- Most soft corals in sub-tropical Indo-pacific waters are heterotrophic with only 31 of the 90 genera containing zooxanthellae and therefore having the ability to be phototrophic;
- The presence of phototrophic soft corals decrease when turbidity increases;
- Relatively few studies have investigated impacts to soft corals from sedimentation;
- Some studies (i.e. Anthony and Fabricus (2000), Riegl and Branch (1995)) suggest that soft corals are more able to tolerate higher suspended sediment than hard corals;
- Riegl (1995) found that tissue necrosis of soft corals resulted after a week of applying sediment at 200 mg/cm^2 (**Table 4-9**); and
- Gorgonians growing in areas subject to high sedimentation (14.1 mg/cm^2/d) had growth rates similar to other regions (Goh and Chou 1995) (**Table 4-9**).

- **Table 4-9 Published sedimentation effects on octocorals**

Author	Sedimentation Level	Effect
Riegl (1995)	200 mg/cm^2/week	Tissue necrosis appeared
Goh and Chou (1995)	14.1 mg/cm^2/day	No discernible effect on 'normal' growth rates

4.2.4. Hard Corals

Hard corals have been identified as a benthic community component within State waters of the Outer Harbour Development project area that may be at risk from altered water quality conditions due to dredging and disposal activities. The direct impact to hard corals, other than direct removal during dredging, is considered to be smothering due to elevated sedimentation. Indirect impacts to hard coral components of the benthic community may arise from reduced quality and quantity of light available affecting their ability to photosynthesise and increased turbidity reducing the success of feeding and gamete fertilisation.

The susceptibility of a range of coral taxa to the stressors of turbidity, sedimentation and reduced light was characterised by Gilmour *et al.* (2006) into three categories: high, medium and low. The dominant coral genus occurring in the Port Hedland area is *Turbinaria* (**Section 3.1.1**), which is described by Gilmour *et al.* (2006) as having low susceptibility to these stressors. Ongoing studies of the benthic communities in State waters (i.e. within 3 nm from shore) around Port Hedland confirm this with *Turbinaria* being the dominant component of the hard coral community within the inshore benthic community mosaic (SKM 2011c).

Drawing upon published results on the effect of TSS and sedimentation on hard corals, summaries are presented in **Table 4-10** and **Table 4-11**.

- **Table 4-10 Published effects of TSS on hard corals (*Turbinaria mesenterina* study highlighted)**

Species	Location	TSS (mg L^{-1})	Effect	Reference
Faviids (e.g. *Goniastrea retiformis)*	Orpheus Island, GBR, Australia	41	Feeding saturation	Anthony and Fabricus (2000)
Acropora digitifera	Coral Bay, Ningaloo Reef, Australia	≥50	Reduced larval settlement and survival	Gilmour (1999)
Acropora millepora	Orpheus Island, GBR, Australia	>30	Feeding saturation	Anthony and Fabricus (2000)
Acropora millepora	Davis Reef, GBR, Australia	≥100	Reduced fertilisation by 50%	Humphrey *et al*. (2008)
Montipora verrucosa	Kanehoe Bay, Hawaii	8	Reduction of photosynthetic production by 28%	Te (1997)
		20	Negative energy production	
Pocillopora damicornis	Guam	≥100	Reversed metamorphosis “polyps bail-out” by planulae	Te (1992)
Porites cylindrica	Orpheus Island, GBR, Australia	4 - 8	Feeding saturation	Anthony (1999)
Turbinaria mesenterina	**GBR, Australia**	**~50**	**Feeding saturation**	**Anthony and Connolly (2004)**
Montipora aequituberculata		30	Whole mortality after 12 week exposure	Negri *et al*. (2008)
Acropora millepora		100	Whole mortality after 12 week exposure	

Source: Table adapted from Chevron (2010) and DSD (2010)

Laboratory experiments using colonies of *Turbinaria mesenterina* that simulated extreme sedimentation events (i.e. >100 mg^{-1} cm^{-2} day^{-1} over 34 days) in a range of current flow rates (Sofonia & Anthony 2008) found that these events had no effect on the range of physiological variables relating to coral colony stress over a five week period. This reflects the ability of some corals to change the mode of feeding in high sedimentation environments from reliance on the provision of nutrients from photosynthetic processes (autotrophy) to feeding on suspended particulate matter (heterotrophy) (Anthony 1999; Anthony & Fabricius 2000).

- **Table 4-11 Published effects of sedimentation on hard corals (*Turbinaria mesenterina* study highlighted)**

Species	Location	Sedimentation ($mg/cm^2/d$)	Effect	Reference
Acropora millepora	Ningaloo Reef, Australia	1–11.7	Reduced recruit survival	Babcock and Smith (2002)
Acropora cervicornis	Jamaica	200	No effect	Dallmeyer (1982)
Acropora palmata	Caribbean	200	Death of underlying tissue	Rogers (1983)
Montastrea peltiformis	GBR, Australia	≥109	Death	Philipp and Fabricus (2003)
Montastrea annularis	Jamaica	800	Death of underlying tissue	Dallmeyer (1982)
Montastrea cavernosa	Panama	13.8	Death	Lasker (1980)
Porites asteroids (bgreen morphs)	St Croix, United States Virgin Islands	3.6–4.0	Reduction in sediment clearing	Gleason (1998)
Porites asteroids (brown morphs)	St Croix, United States Virgin Islands	5.0–5.4	Reduction in sediment clearing	Gleason (1998)
Porites sp.	Bolinao, Philippines	1–5 cm over 68 hours	90% bleached tissue; recovery after 4 weeks	Wesseling *et al*. (1999)
Turbinaria mesenterina	**Magnetic Island, GBR, Australia**	**110 maintained for 34 days**	**No effect on any physiological variables. Able to clear sediment in 4-5 hours**	**Sofonia and Anthony (2008)**

Source: Table adapted from Chevron (2010)

The severity of the impact is a function of the intensity, duration and frequency of the impacting process. Within the Pilbara, coral communities are adapted to natural regular (tides and winds) and episodic (cyclones) processes which increase sediment loads and turbidity over relatively short periods (days). Gilmour *et al*. (2006) suggest that impacts of elevated turbidity and sedimentation over a period of weeks are likely to cause more stress and mortality than significantly high increases over periods of days.

The inshore coral community located in the Wet Tropics of the Great Barrier Reef at Dunk Island has been monitored by the Australian Institute of Marine Science since 2004 (Schaffelke *et al*. 2007). In 2006, the coral cover at 2 m depth was approximately 17% and dominated by *Acropora* spp. At 5 m depth the coral cover was 36%, which is above average for the reefs in the Wet Tropics region, and the community was dominated by Poritidae and Faviidae coral colonies. The coral community was represented by 30 different genera at 5 m depth. Major and moderate flooding of the Tully River has occurred six times since 2000 (Bureau of Meteorology 2008), and a recent study has found that coral reefs growing in the vicinity of the mouth of the Tully River frequently experience high sediment loads and periods of total loss of irradiance during flood events (Wolanski et al. 2008). The data collected on the coral communities located at the southern flank of Dunk Island suggest that this coral community is flourishing despite frequent periods of total loss of irradiance of at least ten days duration.

Cooper et al. (2008) in a study of the potential of *Pocillopora damicornis* as a bioindicator recorded periods of sustained elevated turbidity over a two year study period including one event (average: 9.2 ± 0.2 NTU) at a monitoring site in Horseshoe Bay, North Queensland for a period of four weeks (28 days) following a flood event in March/April 2007. The study concluded that at about 3 NTU there was typically loss of 88%SI at the site which was at 3.5m depth. During the four week period of elevated turbidity, benthic irradiance averaged a low 5.8±0.9 mol photons m−2 day−1 The observed effects on the study coral, *Pocillopora damicornis*, included loss of colony brightness and a reduction in symbionts densities during periods of low light induced by turbidity >3NTU, indicating a potential stress response. Once this period of low light was over the colonies of *P. damicornis* recovered. While most low light events observed were of shorter duration (5-14 days) the *P.damicornis* subjected to the elevated turbidity associated with the four week event in Horseshoe Bay were stressed but apparently recovered from this event.

Additional studies into the effect of high TSS levels on coral species indicate there can be some beneficial elements to those species under low light situations (Anthony *et al*. 2007). These include increased reliance of feeding on food particles in the water column to offset photosynthetic energy loss and protection from high solar irradiance during summer months by the high concentration of particles in the water column potentially reducing bleaching related stress on the coral colonies.

These studies suggest that the almost complete loss of light for periods ranging from 10 up to 28 days may cause sub-lethal stress to the studied coral species but not lead to mortality of those species.

5. Impacts Thresholds

Provided in this section is an overview of the objectives, information and considerations that have guided the development of the impacts thresholds used for the proposed Outer Harbour Development. Provided at the end of the section are the thresholds recommended for evaluating impacts to subtidal benthic communities, and thereby the derivation of the Zone of High Impact, Zone of Moderate Impact and Zone of Influence required for the dredging management framework.

5.1. Spatial Application

The impact thresholds must be defined such that they can be applied to the delineation of the predicted scale and spatial distribution of potential impacts in the study area offshore from Port Hedland through interrogations of the plume modelling outputs.

Specifically, the impact thresholds presented here will be used to identify benthic community impact areas in State waters of the project footprint, and in turn will allow the Zone of High Impact to be derived and proposed.

In recognising the different functional groups generally represented by BPPs and non-BPPs (i.e. traditionally autotrophs and heterotrophs, respectively), and thereby the differing cause-effect pathways that may arise from altered water quality conditions and biota responses, consideration of both BPPs and non-BPPs has been given.

5.1.1. Benthic Primary Producers

Within the Outer Harbour Development area, primary producers present in the benthic communities include seagrasses (although uncommon), macroalgae and hard corals (**Section 3.1.1**). Given that BPPs are autotrophic and rely on PAR to generate carbohydrates, the parameter most likely to cause stress and mortality is a reduction in PAR. In addition, deposition of suspended sediments (i.e. sedimentation) can result in stress and potentially mortality if the rate of sedimentation is heavy.

Recent EPA determinations have accepted that scleractinian (hard) corals are likely to be among the most sensitive receptors for impacts of elevated suspended solids concentrations and sedimentation (DSD 2010). Based on the literature reviewed in **Sections 4.2.1**, **4.2.2** and **4.2.4**, it is posited that of the primary producers present in benthic communities of the Outer Harbour Development area hard corals are the BPP most sensitive to both light reduction and sedimentation.

Using the data reviewed in the previous sections, the impacts thresholds proposed for BPPs are provided in **Section 5.2** and **Table 5-1** and are based on the premise that hard corals are the most sensitive BPP to altered water quality conditions. In addition to the lethal effect thresholds, sub-lethal effect thresholds have also been proposed as the point where sub-lethal stress in BPPs may arise (e.g. increased mucous production in hard corals; increased above-ground biomass height in seagrasses).

The literature review has not examined in any specific detail the role of durations in turbidity events in determining the potential impact upon benthic primary producers. This is a consequence of a lack of information about whether the observed increases in turbidity that led to measurable impacts were based on continuous turbidity events or on shorter duration pulses. The literature reviewed rarely states the whether the elevated levels of turbidity (or shading reductions in % SI) were continuous. The absence of clear statements about whether the stresses imposed on corals and other benthic organisms were continuous for the stated periods of time implies that the stresses were continuous. In the past on a number of other dredging projects in the Pilbara where thresholds have been developed (Hanley 2011), the durations of stresses have typically been associated with tidal oscillations and therefore set at 6 hours. As there is no evidence these thresholds correctly predicted coral mortality (Hanley 2011) at these low durations, for this project a decision has been made to use durations of stress events (TSS elevations and sedimentation), which occur for the entire period of daylight each day. In the Pilbara this has been assumed to be the period between 0800 to 1800 (i.e. 10 hours).

5.1.2. Non-Benthic Primary Producers

Given that filter feeders are primarily heterotrophic[3], the parameters most likely to cause stress and mortality are those that interfere with feeding and respiration processes by smothering and/or clogging polyps and feeding apparati. Therefore TSS and sedimentation, as opposed to incident light, appear to be the most appropriate parameters that may be used as impacts thresholds for non-BPPs.

While little information exists that directly focuses on sponges or filter feeding communities and their response to increased suspended particulate material or sedimentation, the bulk of the information that is available describes responses in sponges. Thus, the majority of information presented here is for sponges rather than soft corals.

The Pluto LNG Project established photo transects in an area in which the most intensive dredging was to be undertaken in May 2006. Benthic cover was recorded prior to commencement of dredging (MScience 2010), with measures including live sponge cover expressed as a percentage cover of the area of the transect (Stoddart *et al*. 2005). Initial post-dredging surveys in August 2008 revealed that almost all cover estimates had decreased. A subsequent recovery survey undertaken in February 2010 however revealed that where declines in sponge cover had been observed considerable recovery of sponge density was evident in the February 2010 survey, including some regrowth to near original size.

Based on the literature reviewed in **Section 4.2.3**, and that provided above, the thresholds for filter feeders to be used in the Outer Harbour Development benthic community impact assessment for State waters are as per those prescribed for BPPs.

[3] Sponges typically filter fine organic material out of the water column for their primary source of energy (Reiswig 1971) and are heterotrophic in this function. Phototrophic sponges are able to photosynthesise due to the presence of symbiotic algae in the sponge tissue. Phototrophic sponges are adapted to maximise photosynthetic potential thorugh morphological flattening to maximise light interception and surface area to volume ratio (Wilkinson 1983).

5.2. Impacts Thresholds for State and Commonwealth Waters

Evident in the sections on both BPPs and non-BPPs is the common impact units of suspended solids (and thereby changes in the light climate) and sedimentation. Also clear when comparing the recommended intensity, duration and frequency aspects of the impacts thresholds for BPPs and non-BPPs that of the two groups, hard corals are the most sensitive benthic community component present in State and Commonwealth waters of the Outer Harbour Development area.

As such, it is proposed here that the impacts thresholds for BPPs (hard corals) are also adequately representative for non-BPPs due to their conservatism, spatial applicability and suitability of units used. The thresholds for BPPs and non-BPPs of the Outer Harbour Development area in State and Commonwealth waters are summarised in **Table 5-1** and **Table 5-2**, respectively.

- **Table 5-1 Thresholds for the Outer Harbour Development Benthic Impact Assessment in State Waters**

Effect	Driver	Intensity	Duration	Frequency
Lethal	Light	≤1% SI at benthos	All daylight*	>40 days in a rolling 60 day period
	Sedimentation	110 mg/cm^2/day	Daily	>34 days in a rolling 50 day period
Sub-lethal	Light	Less than 60% SI at benthos[1]	All daylight*	>40 days in a rolling 60 day period
		Less than 45% SI at benthos[2]		
		Less than 30% SI at benthos[3]		
		Less than 15% SI at benthos[4]		
	Sedimentation	110 mg/cm^2/day	Daily	>15 days in a rolling 50 day period
No measurable change	TSS	Not more than 5 mg/L above background	All daylight*	>8 consecutive days
	Sedimentation	50 mg/cm^2/day	Daily	>15 days in a rolling 50 day period

*Refers to 10 daylight hours (0800 – 1800)

[1] Sensitivity analysis a

[2] Sensitivity analysis b

[3] Sensitivity analysis c

[4] Sensitivity analysis d

- **Table 5-2 Thresholds for the Outer Harbour Development Benthic Impact Assessment in Commonwealth Waters**

Effect	Driver	Intensity	Duration	Frequency
Lethal	Light	≤1% SI at benthos	All daylight*	>7 days in a rolling 20 day period
	Sedimentation	50 mg/cm^2/day	Daily	>15 days in a rolling 30 day period
Sub-lethal	Light	Less than 60% SI at benthos[1]	All daylight*	>7 days in a rolling 20 day period
		Less than 45% SI at benthos[2]		
		Less than 30% SI at benthos[3]		
		Less than 15% SI at benthos[4]		
	Sedimentation	50 mg/cm^2/day	Daily	>7 days in a rolling 30 day period
No measurable change	TSS	Not more than 5 mg/L above background	All daylight*	>8 consecutive days
	Sedimentation	25 mg/cm^2/day	Daily	>7 days in a rolling 30 day period

*Refers to 10 daylight hours (0800 – 1800)
[1] Sensitivity analysis a
[2] Sensitivity analysis b
[3] Sensitivity analysis c
[4] Sensitivity analysis d

For the Zone of Moderate Impact (sub-lethal) assessment, if EAG #7 is followed and the most sensitive organism that may be present are used to develop thresholds then the use of a sub lethal threshold of <60%SI is warranted on the basis that several species of *Acropora* have been reported to exhibit sub lethal stress if light is reduced past this level for any period of time (Jaap and Hallock 1990), and *Acropora* is present at some sites in the study area but is rare. However, the use of this threshold is questionable as the modelling outputs reveal that background levels of TSS developed from baseline water quality monitoring regularly produce exceedances of this threshold across large areas of the region. This information suggests that the reason *Acropora* species are rare on these reefs is because the natural light climate is often not suitable.

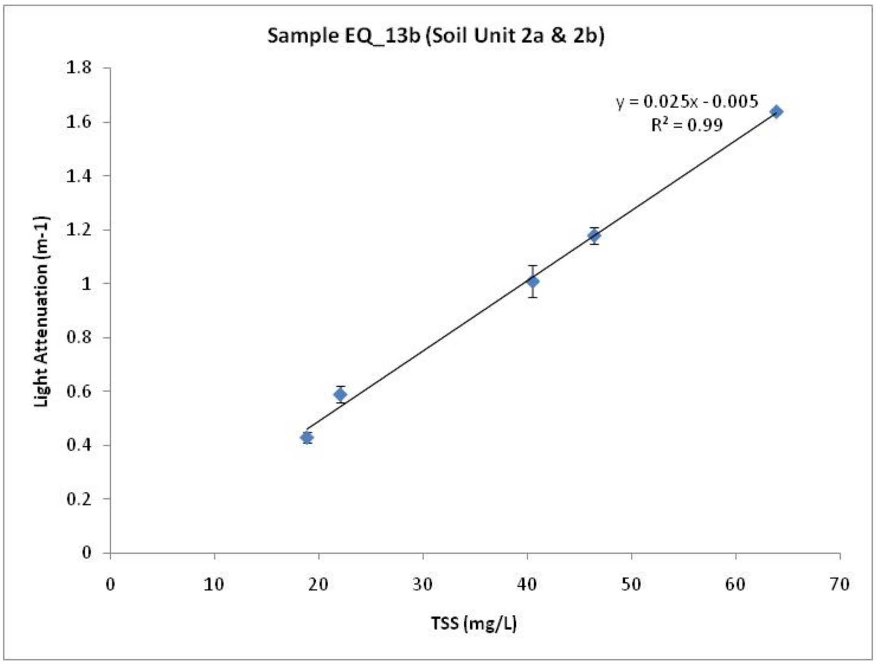
Therefore, a sensitivity analysis has been performed using different levels of %SI reductions to better assess the likely impacts upon the more dominant components of the benthic communities. As light decreases, the potential effect on constituent components of the benthic community can be expected to increase.

5.3. Application of Thresholds to the Plume Model

5.3.1. Total Suspended Solids Thresholds

The light component of the threshold units proposed for BPPs are in % SI. It is noted that these units are not directly aligned with output units of the dredge plume modelling (TSS concentrations and sedimentation rates). To enable reconciliation between the threshold units proposed and units of the dredge plume modelling outputs, SKM contracted the services of In Situ Marine Optics Pty Ltd (IMO) to estimate the relationships between turbidity, TSS and light attenuation using cored seabed materials from soil units 2a and 2b from the proposed Outer Harbour Development dredge footprint (**Figure 5-1**; SKM 2007b). The observed relationships were strong (R^2=0.99). The particle size distributions of the cored seabed materials used to develop this relationship were very similar to those reported in the Outer Harbour Development Geotechnical Survey (Worley Parsons 2011).

Any measurements of light attenuation that are transformed into TSS values using the IMO calculations to develop thresholds for modelling purposes are considered robust. It is these relationships that are used to integrate the impacts thresholds proposed for BPPs in State waters and plume modelling outputs.



- **Figure 5-1 The relationship between light attenuation and TSS from calculations provided by IMO from dredge footprint materials from soil units 2a and 2b at Port Hedland**

(Source: IMO 2008)

Thresholds are based on Allowable Total TSS = background TSS + dredging-derived TSS. In order to allow for background contribution to Allowable Total TSS, the 50 percentile (%ile) monthly TSS values were derived for three zones:

- Inshore (State waters; based on baseline data collected from the WIS monitoring site);
- Little Turtle Island (State waters; based on baseline data collected from the LTI monitoring site) ; and
- Offshore (Commonwealth waters; based on baseline data collected from the CTH, MIB, COR, COX monitoring sites).

This zoning classification was chosen due to the difference in water quality between the inshore and offshore environments (SKM 2011b); however, Little Turtle Island (LTI) did not fit into either classifications and was considered to be a zone of its own. Note that the inshore zone is conveniently delineated by the State waters boundary, and the State waters boundary around Little Turtle Island delineates that zone as well (**Figure 3-1**). The setting of boundaries is necessary to account for the widely different levels of background TSS observed in the baseline water quality datasets (SKM 2011X).

The 50%ile monthly TSS values for each zone were derived from calculating the mean 50%ile NTU values from the baseline water quality monitoring dataset, spanning 22 months of data collection from June 2008 to March 2010 (SKM 2011b). These values were calculated as site-specific for WIS and LTI; pooled for offshore sites CTH, MIB, COR and COX, then converted to TSS using the TSS/NTU relationship reported by GHD (2011; y = 0.87 x) (**Table 5-3**). This relationship was derived using baseline TSS and NTU data collected from February to August 2011 (~7 months) at a range of sites (both inshore and offshore) throughout the Port Hedland Outer Harbour project study area (n = 124) and is considered the best to describe the 'background' TSS rather than using the relationship between TSS and NTU (based on the materials to be dredged) developed by IMO (**Figure 5-1**).

The 50%ile monthly background TSS values in **Table 5-3** are representative of 'near bottom' due to the location of the turbidity loggers that the data were collected from. No attempt was made to define depth-dependent background TSS levels for any of the zones as this would have added an additional layer of complexity into the modelling. Although background TSS levels vary throughout the water column (GHD 2011), a number of substantial errors inherent in the application of zone-wide bottom monthly averages exist, given that these are based upon a small number of sites. Hence, no improvement in the accuracy of predictions would result from the introduction of depth-dependent background TSS.

- **Table 5-3 50%ile Monthly Background TSS (mg/L) derived for the Inshore, Little Turtle Island and Offshore Zones from baseline NTU data collected from June 2008 – March 2010**

Month	Inshore (WIS)	Offshore (CTH, MIB, COR, COX)	LTI
January	4.14	0.84	1.70
February	2.16	0.65	0.88
March	0.53	0.61	0.96
April	0.44	0.57	1.57
May	0.17	0.35	1.74
June	1.04	0.28	2.18
July	1.07	0.35	1.41
August	0.68	0.33	0.82
September	0.87	0.35	0.96

Month	Inshore (WIS)	Offshore (CTH, MIB, COR, COX)	LTI
October	0.78	0.44	0.80
November	1.04	0.48	1.01
December	1.14	0.51	0.68

The relationship (s) between % SI, depth and TSS

The 1% SI defined as critical for corals (described in **Section 4.2.4**) is also often defined as the limit of the euphotic zone (z). The following calculations based on the Beer-Lambert law were used to calculate the level of TSS sufficient to reduce light to % SI at a given depth for each time step, for each cell. A set of TSS levels that would produce x% SI for a given depth has been derived from the two basic equations for LAC (K_{par}) as follows:

$K_{par} = (\ln I_{(0)} - \ln I_{(Z)})/z$ *(Formula 1)*

Where K_{par}= the vertical attenuation coefficient of PAR. This allows K_{par} to be calculated for any euphotic zone depth (z). Thus, once a K_{par} has been defined for each depth, then the following equation is used to calculate the corresponding TSS value using the specific relationship generated by IMO for TSS and LAC provided in **Figure 5-1**:

$K_{par} = 0.025TSS - 0.005$

or

$TSS = (K_{par} + 0.005)/0.025$ *(Formula 2)*

This is the equation of a fitted line $y=0.0205x - 0.005$.

So for any particular LAC derived from the IMO TSS/LAC data it must be true that:

$0.025TSS - 0.005 = (\ln I_{(0)} - \ln I_{(z)})/z$

Therefore it must satisfy both the specific equation for the IMO/TSS data plot and also the general equation based on the Beer Lambert law.

As the natural log of 1 is 0, the equation becomes:

$0.025TSS = (-\ln I_{(z)}/z) + 0.005$

or

$$TSS = \frac{(-\ln I_{(z)}/z) + 0.005)}{0.025}$$

- **Table 5-4 Equations used to define the level of TSS for lethal, sub-lethal and no measurable change effect**

Effect	Test (Total TSS)
Lethal (1% SI)	$\frac{(4.6052/z) + 0.005)}{0.025}$
Sub-lethal sensitivity analysis a (60% SI)	$\frac{(0.5108/z) + 0.005)}{0.025}$
Sub-lethal sensitivity analysis b (45% SI)	$\frac{(0.7985/z) + 0.005)}{0.025}$
Sub-lethal sensitivity analysis c (30% SI)	$\frac{(1.2040/z) + 0.005)}{0.025}$
Sub-lethal sensitivity analysis d (15% SI)	$\frac{(1.8971/z) + 0.005)}{0.025}$
No measurable change	Background >5*

z = any nominated depth (m)

There are no fixed levels of TSS other than those used to calculate the background level of TSS in any particular month. With the exception of TSS values, which vary both by depth for the dredged component and monthly zone 50%ile for background, the remaining parameters are fixed.

Lethal Effect - Zone of High Impact in State waters (Inshore and LTI)

Zone	Intensity		Duration	Frequency
	% SI	TSS (mg/L)		
Inshore and LTI	≤1% SI at benthos	Depth dependent + background	All daylight	>40 days in a rolling 60 day period

Durations are daily; defined as 10 hours of daylight (0800 – 1800). Shorter time steps of 2-6 hours have been used on previous occasions but there is no evidence that such short time periods of exposure lead to mortality in *Turbinaria* spp. or any other species of coral in the Pilbara (Hanley 2011). Thus, it is considered that light must be extinguished for the entire daylight period. Whilst non-BPPs are susceptible to elevated TSS during all hours (i.e. not only daylight hours), hard corals are considered the most sensitive receptor, hence a conservative approach has been used to set thresholds.

The review of the literature (**Section 4.2.4**) indicated that an extinction of light over 42 consecutive days are considered necessary to produce an impact on coral mortality. The 40 days a rolling 60 day period is considered to be conservative, as it has entailed reducing the total number of days of stress from 42 (3 x 14 days) to 40, and extended the total number of days over which cumulative stress would be calculated to 60 (from 42).

Lethal Effect – Zone of High Impact in Commonwealth (Offshore) waters

Zone	Intensity		Duration	Frequency
	% SI	TSS (mg/L)		
Offshore	≤1% SI at benthos	Depth dependent + background	All daylight	>7 days in a rolling 20 day period

Examination of **Table 5-1** and **Table 5-2** shows the major difference between the thresholds set for Commonwealth and State waters is that different frequencies have been used to predict areas of impact.

The use of 7 and 15 day periods in 20 or 30 days for Commonwealth waters (**Table 5-2**) is based on interpretation of evidence in the literature that suggests the coral communities located in the offshore region are likely to be more sensitive to light attenuation relative to the *Turbinaria*/ Faviid dominated communities of the inshore region. There is for example, more *Acropora* on the offshore reefs. Examination of the information available on a recent large scale dredging program elsewhere in the Pilbara suggests that periods of stress of about 7 days in 20 do lead to some mortality of corals, but these data are still to be properly investigated.

The coral communities in the deeper offshore areas located in Commonwealth waters also appear to be more stable relative to those in shallower State waters (as determined from larger colony sizes and percent cover of live coral) and this may be a consequence of greater protection from storm (cyclone) damage as depth increases. Of course, the greater the depth, the less light will penetrate to the substratum for a given level of TSS, and so while corals at these greater depths are protected from storm damage, they are likely to be more vulnerable to prolonged periods of low light.

The use of a 7 day period for estimates of mortality and sub lethal stress impacts is still considered to be conservative (e.g. baseline data suggests corals on these reefs may routinely experience 14 days of no light without mortality) (**Table 5-2**). The thresholds used in Commonwealth waters will therefore predict overestimates of both coral mortality and stress because many of the offshore reef areas also support high proportions of *Turbinaria* and Faviid corals which are known to be much more resilient.

Sub-lethal Effect - Zone of Moderate Impact in State waters (Inshore and LTI)

Zone	Intensity		Duration	Frequency
	% SI	TSS (mg/L)		
Inshore and LTI	<60% SI at benthos[1]	Depth dependent + background	All daylight	>40 days in a rolling 60 day period
Inshore and LTI	<45% SI at benthos[2]	Depth dependent + background	All daylight	>40 days in a rolling 60 day period
Inshore and LTI	<30% SI at benthos[3]	Depth dependent + background	All daylight	>40 days in a rolling 60 day period
Inshore and LTI	<15% SI at benthos[4]	Depth dependent + background	All daylight	>40 days in a rolling 60 day period

[1] Sensitivity analysis a
[2] Sensitivity analysis b
[3] Sensitivity analysis c
[4] Sensitivity analysis d

The Zone of Moderate Impact thresholds are based on the same approach as the Zone of High Impact, including the durations and frequencies for each zone, and background TSS loadings. The only difference is in the level of SI reduction that would produce sub-lethal stress but not mortality. The level of percentage SI considered likely to produce stress but no mortality in the most sensitive species of corals is set at <60% SI (sensitivity analysis a), however, these species are uncommon to rare and are not likely to exist in the turbid inshore zone. Therefore, a sensitivity analysis approach has been used to provide a better indication on the likelihood of sub-lethal stress without mortality for the dominant components of the benthos, whereby the SI has been reduced at increments of 15%, with increasing numbers of organisms and community types likely to experience stress as the percentage of SI decreases.

Sub-lethal Effect - Zone of Moderate Impact in Commonwealth (Offshore) waters

Zone	Intensity		Duration	Frequency
	% SI	TSS (mg/L)		
Offshore	<60% SI at benthos[1]	Depth dependent + background	All daylight	>7 days in a rolling 20 day period
Offshore	<45% SI at benthos[2]	Depth dependent + background	All daylight	>7 days in a rolling 20 day period
Offshore	<30% SI at benthos[3]	Depth dependent + background	All daylight	>7 days in a rolling 20 day period
Offshore	<15% SI at benthos[4]	Depth dependent + background	All daylight	>7 days in a rolling 20 day period

[1] Sensitivity analysis a
[2] Sensitivity analysis b
[3] Sensitivity analysis c
[4] Sensitivity analysis d

No Measurable Change Effect - Zone of Influence in State (Inshore and LTI) and Commonwealth (Offshore) waters

Zone	Intensity		Duration	Frequency
	% SI	TSS (mg/L)		
Inshore, LTI and Offshore	N/A	Background + 5 mg/L	All daylight	>8 consecutive days

The use of a 5 mg/L addition to background has been used to define the Zone of Influence as a zone where water quality changes substantively from background (i.e. a discernable signal from the dredged material in the water quality data). Thus, durations have been set as daily, which for the majority of occasions would remove natural elevations above average background that are driven by tide and wind. There are cyclonic events that may lead to daily durations well above average background for an extended period but these are unlikely to persist for weeks at a time, with the majority of data suggesting 3-7 days (SKM 2011b).

5.3.2. Sedimentation Thresholds

The dredge-sourced net daily sedimentation rate has been used to define thresholds based on the specifications provided below.

Lethal Effect - Zone of High Impact in State waters (Inshore and LTI)

Zone	Intensity (net sedimentation rate)	Duration	Frequency
Inshore and LTI	110 mg/cm^2/day	Daily	>34 days in a rolling 50 day period

The literature review in **Section 4.2.4** indicated that *Turbinaria* spp., were remarkably resilient to sediment loading with no apparent ill effects after 34 days of a loading of 110mg/cm^2/day. Furthermore, the corals were able to clear sediment within 4-5 hours. Therefore setting a sedimentation threshold of 110 mg/cm^2/day for inshore areas that are dominated by *Turbinaria* spp., is acceptable because it assumes that increases above this level may cause mortality. The duration has been 'daily' as even short periods of 4-5 hours are apparently sufficient for *Turbinaria* corals to clear sediment. The frequency limit has been set to >34 days in a 50 day period, which is considered conservative given the observed capacity of these species to clear sediment.

Lethal Effect - Zone of High Impact in Commonwealth (Offshore) waters

Zone	Intensity (net sedimentation rate)	Duration	Frequency
Inshore and LTI	50 mg/cm^2/day	Daily	>15 days in a rolling 30 day period

Sub-lethal Effect - Zone of Moderate Impact in State waters (LTI and Inshore)

Zone	Intensity (net sedimentation rate)	Duration	Frequency
Inshore and LTI	110 $mg/cm^2/day$	Daily	>15 days in a rolling 50 day period

Setting of thresholds in this zone is arbitrary as there is very little evidence to base it upon from the literature. The intensity and duration has been set as the same for that of the Zone of High Impact but the frequency has been reduced from >34 days to >15 days in a 50 day period.

Sub-lethal Effect - Zone of Moderate Impact in Commonwealth (Offshore) waters

Zone	Intensity (net sedimentation rate)	Duration	Frequency
Inshore and LTI	50 $mg/cm^2/day$	Daily	>7 days in a rolling 30 day period

As was applied in State waters, the Zone of Moderate Impact in Commonwealth waters was based on roughly halving the frequency for the High Impact Zone from >15 days to >7 days in a rolling 30 day period.

No Measurable Change Effect - Zone of Influence in State waters (LTI and Inshore)

Zone	Intensity (net sedimentation rate)	Duration	Frequency
Inshore and LTI	50 $mg/cm^2/day$	Daily	>15 days in a rolling 50 day period

Setting the boundary for a Zone of Influence is problematic as there is no data available on the typical net background rate of sedimentation for any area in the region. Therefore, the same durations and frequencies for Zone of Moderate Impact were used, but reduced the intensity by half.

No Measurable Change Effect - Zone of Influence in Commonwealth (Offshore) waters

Zone	Intensity (net sedimentation rate)	Duration	Frequency
Inshore and LTI	25 $mg/cm^2/day$	Daily	>7 days in a rolling 30 day period

As was applied for State waters, the same durations and frequencies for Zone of Moderate Impact in Commonwealth waters were used, but reduced the intensity by half.

5.4. Calculation of Benthic Losses

Once the benthic impacts thresholds have been evaluated against the dredge plume modelling outputs to identify areas that experience lethal, sub-lethal and no measureable effects, this information is processed by the SKM spatial unit to generate the areas of indirect losses. Indirect losses are derived by overlaying effects areas with the benthic habitat model and where areas of effect and presence of benthic community intersect a loss calculation is made.

Given that the benthic habitat model for the Outer Harbour Development area provides benthic subcategory components (i.e. macroalgae, hard corals, soft corals and sponges) indirect loss calculations for both BPPs and non-BPPs can be generated. In addition, the boundaries for the zones of impact and influence may also be defined by GIS.

In the instance of seagrasses, if a zone of impact is proposed to encroach upon areas known to support seagrass, a manual loss calculation will be undertaken. Indirect loss calculations for seagrasses will apply the impact thresholds as recommended above given their apparent conservatism and spatial relevance, also applicable to seagrasses for the Outer Harbour Development, in combination with the maximum areas and densities previously recorded.

It should be noted that the thresholds for mortality no longer attempt to define a percentage of mortality. Recent evidence from current dredge monitoring programs is demonstrating that this is not possible with any degree of certainty and therefore should be avoided.

5.5. Thresholds for Management and Monitoring

As per EAG No. 7 (EPA 2011), the threshold effect categories of lethal, sub-lethal and no measurable change allow the proponent to define the Zones of High Impact, Moderate Impact and Influence, respectively. Within the Zone of High Impact approved by the EPA, indirect losses of benthic habitat will be permitted, while in the Zone of Moderate Impact monitoring of benthic habitats may be required to evaluate if biota responses to water quality conditions are as predicted by the thresholds. Finally, the Zone of Influence is an extent in which no discernable impacts occur.

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