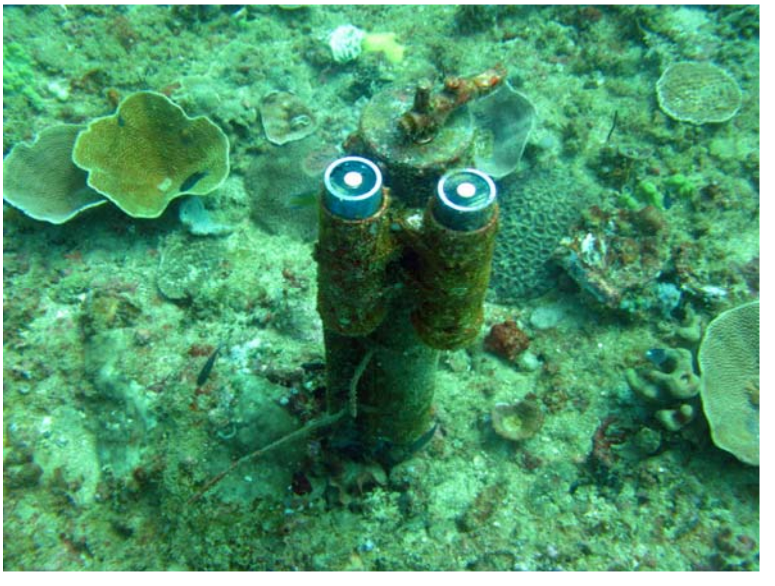
Port Hedland Outer Harbour Development



WATER QUALITY THRESHOLDS

- Revision 2
- WV03716-MV-RP-0029
- 05 April 2011

Port Hedland Outer Harbour Development

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- Revision 2
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- 5 April 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, which may result from the Outer Harbour Development, is the reduction in light available to benthic primary producers (BPPs) due to the increase in total suspended solids (TSS) released into the water column from dredging and spoil disposal activities.

There are no clearly defined and widely accepted impact thresholds for the level/s of TSS in the water column that would necessarily lead to mortality of corals, which are generally accepted to be the most sensitive of the BPPs present. The application of a number of different theoretical approaches in recent dredging projects in the Pilbara reflect attempts to define a set of impact thresholds for TSS and other water quality parameters. 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.

In the absence of definitive information on the actual set of relationships between water quality parameters such as turbidity and TSS and the potential health of each of the species of corals present in the areas under investigation, it is more useful to focus attention on light. It is recognised that the major potential effect of turbidity and TSS on corals is to reduce available light. SKM has considered that the modelling and monitoring of the potential impacts from the plume resulting from the dredging activities, may be better achieved utilising the light climate (light attenuation) as a key parameter to determine whether potential impact is possible and the potential level of impact.

The spatial scale and intensity of the depth averaged TSS and sedimentation patterns associated with the dredging and dredge spoil disposal activities for the project have been modelled. The model predictions were interrogated using light attenuation thresholds (based on a theoretical assessment that there is likely to be a severe impact on BPP) to further predict and plot specific zones of high and moderate impact. Only modelled data from the peak light period between 0800 and 1700 hours in which >95% of all light which falls on the coral communities are used for comparisons against thresholds.

The time scale chosen for setting light attenuation thresholds was 14 days. This corresponds with the present sampling period and the likely period of sampling and reporting during the dredging phase of the Outer Harbour Development.

Two factors that contribute to the total light attenuation thresholds are light attenuation due to suspended solids generated by dredging and light attenuation from background suspended solids. The threshold values set to delineate the zones of high impact are based on a total light attenuation in the water column that would prevent all light from reaching the coral community. The threshold values identified to delineate the zones of moderate impact are based on the total light attenuation in the water column that would prevent a significant proportion (40%) of light from reaching the coral community. Light attenuation values were converted to TSS values for the threshold plume modelling exercise.

If there are four consecutive "no-light" (high impact) or "low-light" (moderate impact) fortnights then impacts on the coral community are assumed to have occurred. Four consecutive fortnights was chosen based on information gained from baseline data and relevant literature.

The corresponding coral loss due to reduction in the light climate are summarised below:

- in the zones of high impact there is predicted to be 100% loss of coral for any period of "no light" four or more consecutive fortnights in a season;
- in the zones of moderate impact there is predicted to be a 0% loss of coral for any period of "low light" for four or more consecutive fortnights in a season; and
- in the zone of influence (areas which experience >5 mg/L at any time during the dredging program) there is predicted to be no loss of coral.

In addition to the potential impact of TSS on light attenuation and the light available to the coral BPP, there is the potential for some or all of the sediment in the water column to settle on coral BPP, which may compromise coral health leading to mortality as a consequence of smothering.

Sedimentation thresholds have been estimated from the baseline data sets on gross sedimentation rates. Best, most likely and worst case scenarios for the zones of high impact (100% coral loss) due to increases in sedimentation are summarised below:

- the best case is twice the maximum background mean daily gross sedimentation rates;
- the most likely case is for areas that experience 1.5 times the maximum baseline mean daily gross sedimentation rates; and
- the worst case predicted gross daily sedimentation rates that are 1.1 times the maximum baseline mean daily gross sedimentation rates.

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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
EPA	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
NATA	National Association of Testing Authorities
NTU	Nephelometric Turbidity Units
PAR	Photosynthetically Active Radiation
SKM	Sinclair Knight Merz
TSS	Total Suspended Solids
WIS	Weerdee Reef

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1. Introduction

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, which may result from the Outer Harbour Development, is the reduction in light available to benthic primary producers (BPPs) due to the increase in total suspended solids (TSS) released into the water column from dredging and spoil disposal activities.

Marine dredging programs can potentially have detrimental impacts upon the flora and fauna of surrounding sensitive marine habitats such as coral reefs (Brown *et al*. 1990; 2002) 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 light which in turn may lead to a reduction in photosynthetic production (Turner *et al*. 2006). Suspended particles can also settle and potentially smother marine organisms. Smothering can lead to the disruption of the organisms' photosynthetic rates, feeding and respiratory processes. These effects would immediately cause stress, and 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 thresholds based on physical attributes in the water column at which a biological impact is expected; which can then be used to predict the scale and spatial distribution of potential impacts. This document explains the methodology used to develop the water quality thresholds that have been used in the interrogations of modelling output to define the scale and spatial distribution of potential impacts.

Recent trends in the assignment of sensitivity to benthic marine habitats in Western Australia (EPA 2004) recognise the importance of benthic primary producer habitats (BPPH) in the support of ecological functions at the ecosystem level, and that corals are one of the most (if not the most) sensitive groups of BPP in terms of the potential impacts from dredging (Stoddart & Stoddart 2005). Hence the focus here is on the potential impact of dredging and dredge spoil disposal on corals, on the assumption that these are the most sensitive communities and therefore will act as sentinels for potential impacts on other BPP (e.g. macroalgae) that are present within the region.

Presently, there are no clearly defined and widely accepted criteria for the definition of the relationship between water quality parameters such as turbidity and coral health that would allow ready identification of thresholds for turbidity at which potential impact and stress of benthic coral communities in the Pilbara would certainly occur (Stoddart & Stoddart 2005), although a variety of theoretical models have been proposed for coral communities in general (e.g. McArthur 2002) and the Pilbara region (e.g. Gilmour *et al.* 2006).

There are no clearly defined and widely accepted impact thresholds for the level/s of TSS in the water column that would necessarily lead to mortality of corals, which are generally accepted to be the most sensitive of the BPPs present. The application of a number of different theoretical approaches in recent dredging projects in the Pilbara reflect attempts to define a set of impact thresholds for TSS and other water quality parameters. 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.

The development of thresholds for the modelling interrogations requires:

- collection and analysis of information (baseline data) on coral communities (depth distribution, percent cover, species, diversity, spatial extent) in the study area;
- collection and analyses of information (baseline data) on various water quality parameters (turbidity, light climate, light attenuation);
- investigation of relevant information from the published and grey literature on relationships between coral health and water quality parameters (such as turbidity, light attenuation and temperature); and
- formulation of relationship/s between water quality parameters and coral health for coral communities in the waters offshore from Port Hedland.

This report predominantly focuses on developing potential thresholds for water quality parameters that will be used in impact modelling analysis. The underlying basis for the threshold is that a significant risk of impact is assumed once the threshold has been exceeded, and the thresholds are also used as the upper bound of acceptable change for the development of reactive management triggers that can be applied for monitoring and management purposes.

1.1. 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.

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.

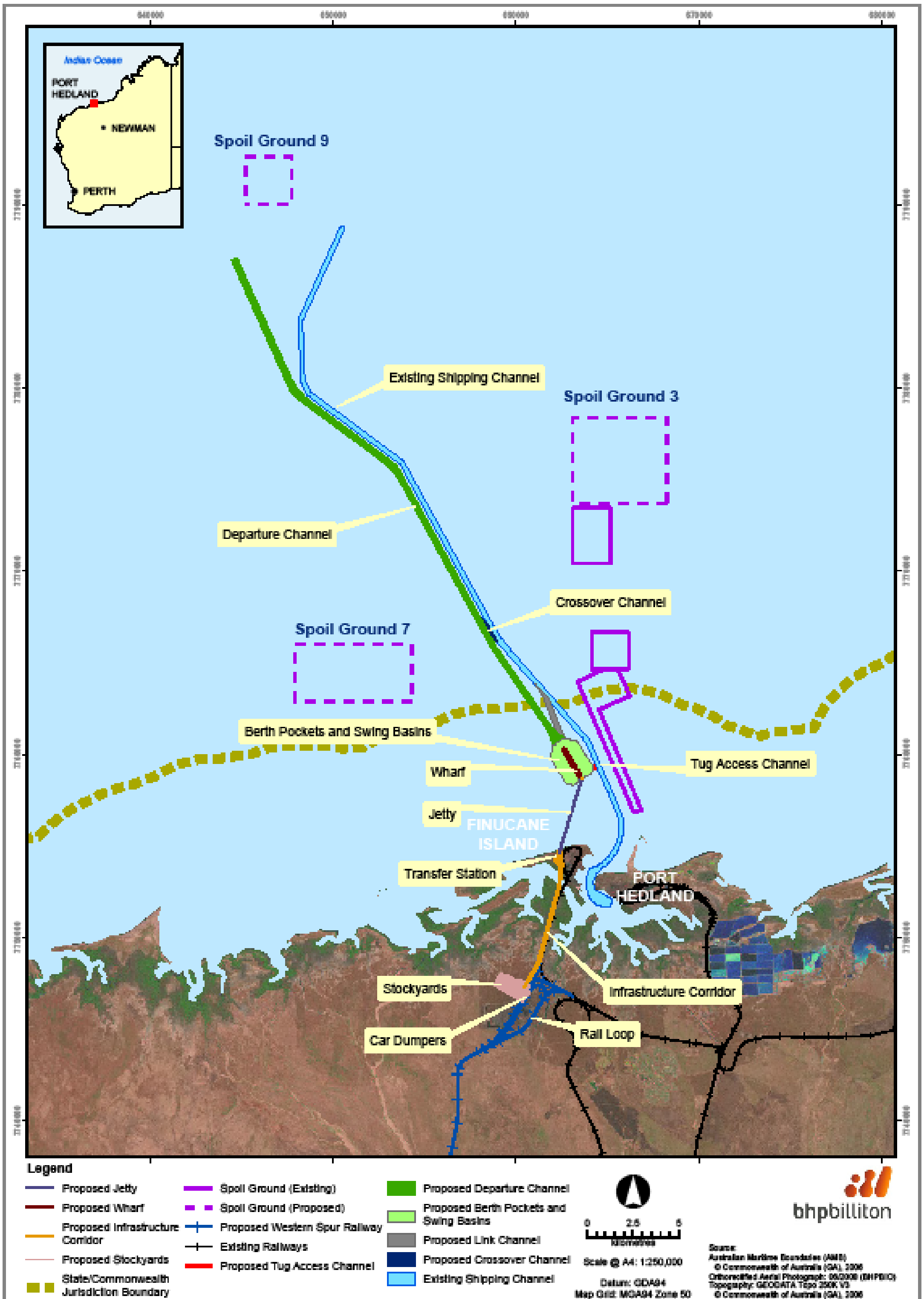


Figure 1.1 Proposed Outer Harbour Development showing construction, dredging and potential spoil ground locations.

- **Figure 1-1 Proposed Outer Harbour Development showing construction dredging and proposed spoil ground locations**

2. Benthic Communities and Water Quality

2.1. Benthic Communities

Surveys of the benthic habitats offshore of Port Hedland were undertaken between December 2007 and April 2008 (SKM 2009a). These surveys indicate that the benthic habitats offshore from Port Hedland are a mixture of predominantly extensive plains of sand/silt/rubble substrate and ridge lines of hard pavement (often covered in a layer of sand/silt). The hard substrate of the offshore ridge lines support occasional patches of sparse biota, including hard corals (BPP), macro-algal beds (BPP), and other biota such as sponges and soft corals (e.g. gorgonians, sea whips). Hard corals represented the most dominant BPP growing along these ridges, with the dominant corals from the genus *Turbinaria* and from the families Faviidae and Poritidae. Branching *Acropora* corals were found in numbers only at the offshore ridge lines in deeper water (>12 m).

Gilmour *et al* (2006) examined the water quality environment in the Pilbara region and identified a range of potential water quality stressors such as turbidity, sedimentation and reduced light. The susceptibility of a range of coral taxa to these stressors was characterised into three categories; High, Medium and Low. The dominant coral genus occurring in the Port Hedland area is *Turbinaria* which is described by Gilmour *et al* (2006) as having low susceptibility to these stressors. One study into the gradients of sedimentation with distance from a mud discharging river source and the coral communities across this gradient (Golbuu *et al.* 2008) found a decrease in the abundance of *Turbinaria* spp. moving away from the highest sedimentation zones located at the river mouth. Laboratory experiments using colonies of *Turbinaria mesenterina* that simulated extreme sedimentation events in a range of current flow rates (Sofonia & Anthony 2008) found that these events had no effect on the a 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).

Sub dominant genera in the Port Hedland region such as corals from the Faviidae and Poritidae family and branching corals of the genus *Acropora* were described by Gilmour *et al* (2006) as having medium susceptibility to major changes in the sedimentation and light regime.

The species richness of coral taxa at the six monitoring sites is very low in comparison to other studies carried out in the Pilbara region. A total of 51 species of coral from 19 genera were identified from areas offshore from Port Hedland which is considerably lower than the 120 coral species from 43 genera recorded in the Dampier Port and inner Mermaid Sound (Blakeway & Radford 2004).

Based on the low species richness and abundance of corals and the dominance of *Turbinaria*, coral communities that inhabit sub tidal habitats in the Port Hedland region can be described as predominantly high turbidity (low light) and high sedimentation adapted communities.

2.2. Water Quality

2.2.1. 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 Photosynthetically Active Radiation (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 Pluto, WA (MScience 2007), Hay Point, Qld (Koskela *et al*. 2002), Cape Lambert 85 Mtpa Port Upgrade, WA (SKM 2007a).

2.2.2. 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 concentrations 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.

2.2.3. 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. Marzalek 1981; Brown *et al*. 1990, 2002); 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 <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 re-suspension. If re-suspension 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 re-suspension 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.

2.2.4. Light Climate - Photosynthetically Active Radiation

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. 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 µmol /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.

The Western Australian Environmental Protection Authority (EPA) Guidance Statement 29 on Benthic Primary Producer Habitat Protection (EPA 2004) provides non-statutory advice on environmental management of BPPH. Thresholds for any dredge project should ultimately be established with the objective of survivorship of BPP.

As PAR relates directly to the biological processes of marine primary producers, 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 (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% of surface irradiance (Cooper *et al.* 2007). In the Gulf of Siam the lower limit for corals is in the range of 2 to 8% of surface irradiance (Titlyanov & Latypov 1991).

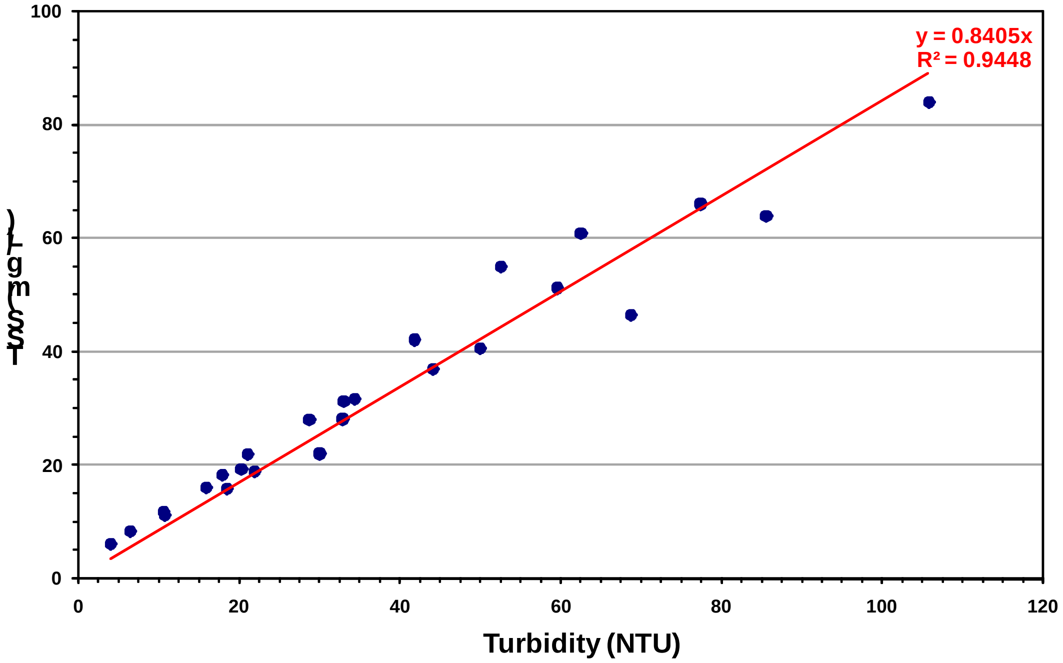
There is some detailed information in the literature on particular coral species and how they adapt to different light climates by altering their feeding strategies (Anthony 1999; Anthony & Fabricius 2000; Anthony & Connolly 2004). This is in contrast to studies on effects of turbidity and TSS on corals, 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 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.

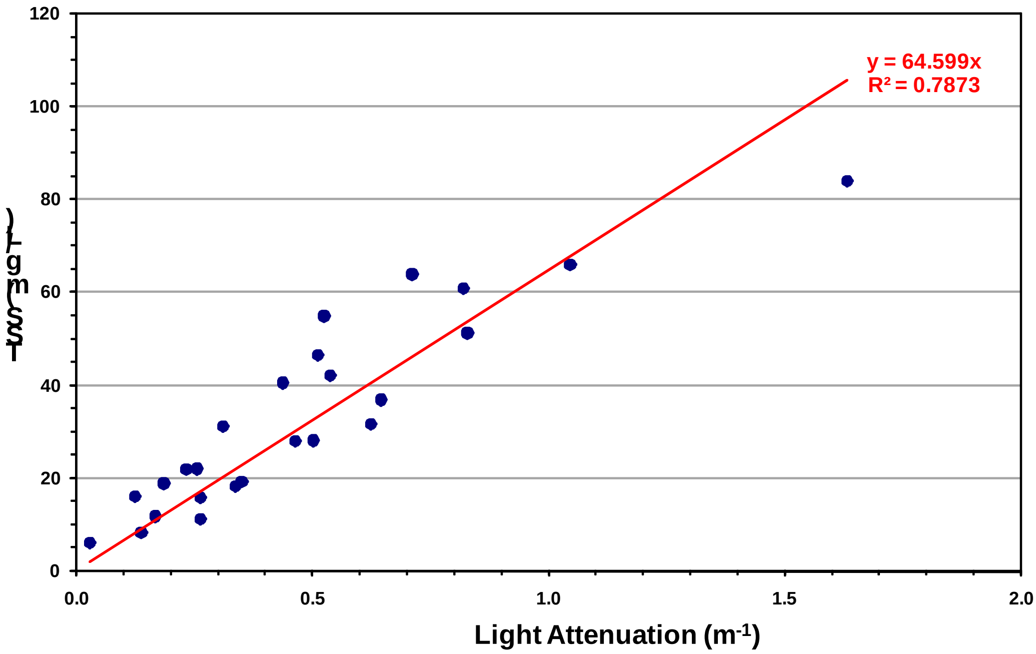
SKM has therefore considered that the modelling and monitoring of the impacts of a dredge plume may be better achieved using light and light attenuation in particular, as a key parameter to determine whether potential impact is possible and what the level of impact might be. The use of light attenuation allows decisions to focus on a single variable and removes the set of subjective decisions that would be required by the use of techniques such as constructing allowable fluctuations in the intensity-duration-frequency of TSS events (McArthur *et al*. 2002).

2.2.5. Water Quality Relationships

In 2007, SKM contracted the services of In Situ Marine Optics Pty Ltd (IMO) to estimate the relationships between turbidity, TSS and light attenuation (**Figure 2-2**, **Figure 2-2** and **Figure 2-3**) using cored seabed materials from the proposed Outer Harbour Development dredge footprint (SKM 2007b). The observed relationships were all comparatively strong (R^2 values > 0.78); any measurements of light attenuation that are transformed into TSS values using the IMO calculations to develop thresholds for modelling purposes are considered robust.



- **Figure 2-1 The relationship between turbidity and TSS from calculations provided by IMO from dredge footprint materials at Port Hedland**



- **Figure 2-2 The relationship between light attenuation and TSS from calculations provided by IMO from dredge footprint materials at Port Hedland**

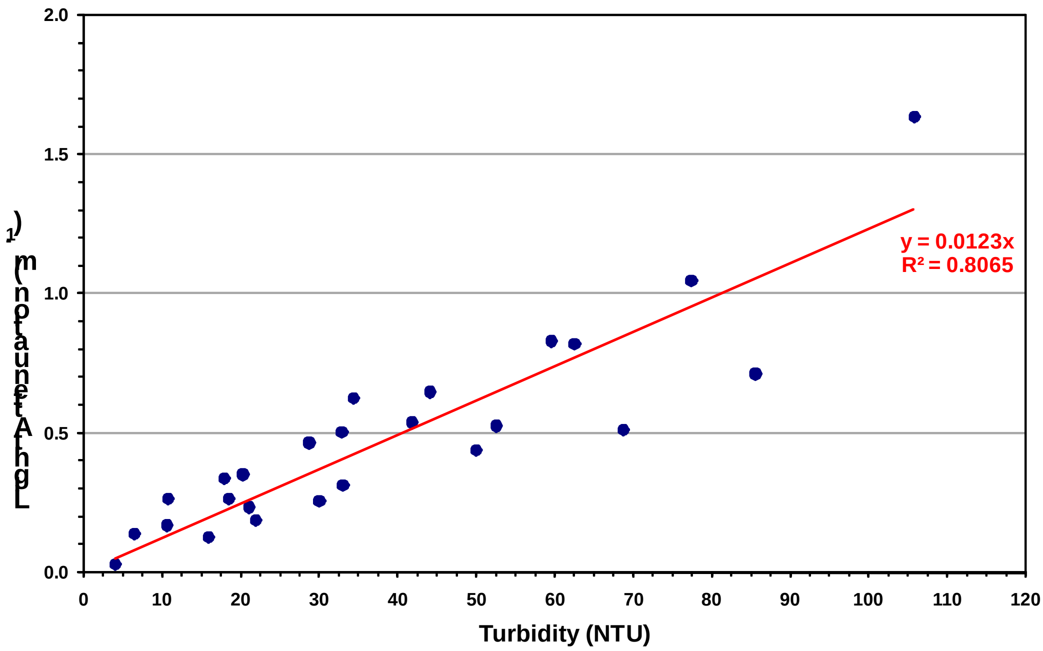


Figure 2-3 The relationship between light attenuation and turbidity from calculations provided by IMO from dredge footprint materials at Port Hedland

2.3. Recent Large Dredge Projects in Western Australia

Strong, predictive relationships between TSS (and turbidity) and coral health have yet to be conclusively established for data from the Pilbara. In part, this is because there have been no conclusive incidents where a decline in water quality as a result of dredging and spoil disposal activities has led to observations of corresponding declines in coral health.

Recently, extensive data sets for TSS/turbidity were collected and interrogated for the Cape Lambert 85 Mtpa Port Upgrade Project (SKM 2007a) and Cape Lambert Port B (SKM 2008a) development projects. To develop water quality thresholds for the Cape Lambert 85 Mtpa Port Upgrade dredge program, SKM originally used the theoretical thresholds developed by Gilmour *et al* (2006) to set the thresholds for delineation of the scale and spatial distribution of potential impacts upon corals. After a short term water quality (turbidity) baseline data set for monitoring sites at coral communities in the area became available, it became obvious that the theoretical thresholds developed by Gilmour were not applicable in this area primarily because the durations of turbidity elevations in the theoretical model are expressed in days, whereas the strong influence of semi diurnal macrotidal currents meant the real time scale likely for turbidity elevations was hours. The baseline data set also showed considerable variability in the levels of background turbidity measured at the same time between sites over quite small spatial scales. Therefore, the Cape Lambert Dredging and Spoil Disposal Management Plan (DSDMP) (SKM 2007a) was modified to establish locally relevant trigger levels for turbidity elevations for the purpose of reactive management by applying the techniques outlined by McArthur *et al*. (2002) to derive intensity/duration/frequency relationships for turbidity. The DSDMP implemented during the Cape Lambert 85 Mtpa Port Upgrade Project (SKM 2007a) was considered to be a success as no coral mortality was recorded during this project. It is important to note that the thresholds established using the approach of McArthur *et al* (2002) have two major potential problems and these are:

- assumption has to be made that corals can only tolerate the range of environmental fluctuations in turbidity (TSS) measured during the baseline period; and
- subjective decisions are required in terms of assigning levels of equivalent impact to different levels of intensity, duration and frequency (idf) events (e.g., 15 mg/L event for 3 hours twice a day = 25 mg/L event for 2 hours twice a day).

BPP thresholds developed for the Fremantle Port Authority port upgrade (SKM 2009d) project utilised predicted TSS values and the effect on light attenuation during dredging and spoil ground activities to define and delineate the zones of high and moderate impact and influence. Light attenuation thresholds for this project were primarily developed for seagrass beds in the vicinity of the project footprint. These thresholds were modified to also predict the impact on a small coral community located at Hall Bank, in close proximity to the dredging operations.

3. Methods

3.1. Water Quality Environments

Data from a range of baseline water quality parameters has been collected from six monitoring sites offshore from Port Hedland (**Table 3-1**) from 1 June 2008 to 31 May 2009 (SKM 2009b). Measurements of light climate, turbidity, gross sedimentation and temperature from each monitoring site indicate there are three distinct water quality environments; inshore (<5 m datum), mid-shore (5 to 10 m datum) and offshore (>10 m datum).

The inshore environment is characterised by highly variable turbidity and high gross mean daily sedimentation rates, highly variable light and sea temperatures. The mid-shore environment has fewer extremes of water quality parameters, but still experiences occasional high levels of gross mean daily sedimentation and variable turbidity, low light and variable temperatures. The offshore environment is much more stable in terms of all water quality parameters. A diagrammatical representation of the water quality environments and monitoring sites is presented in **Figure 3-1**.

- **Table 3-1 Coral monitoring sites offshore from Port Hedland**

Site Name	Code	Environment	Approximate distance from the mainland (km)	Approximate mid tidal water depth (m)	Latitude	Longitude
Weerdee Reef	WIS	Inshore	3	5	20° 17.414’ S	118° 28.893’ E
Cape Thouin	CTH	Mid-shore	10	8	20° 14.995’ S	118° 17.194’ E
Minilya Bank	MIB	Mid-shore	16	10	20° 09.002’ S	118° 38.157’ E
Little Turtle Island	LTI	Mid-shore	19	10	20° 01.081’ S	118° 47.991’ E
Cornelisse Shoal	COR	Offshore	33	12	20° 02.040’ S	118° 22.560’ E
Coxon Shoal	COX	Offshore	28	12	20° 03.998’ S	118° 27.485’ E

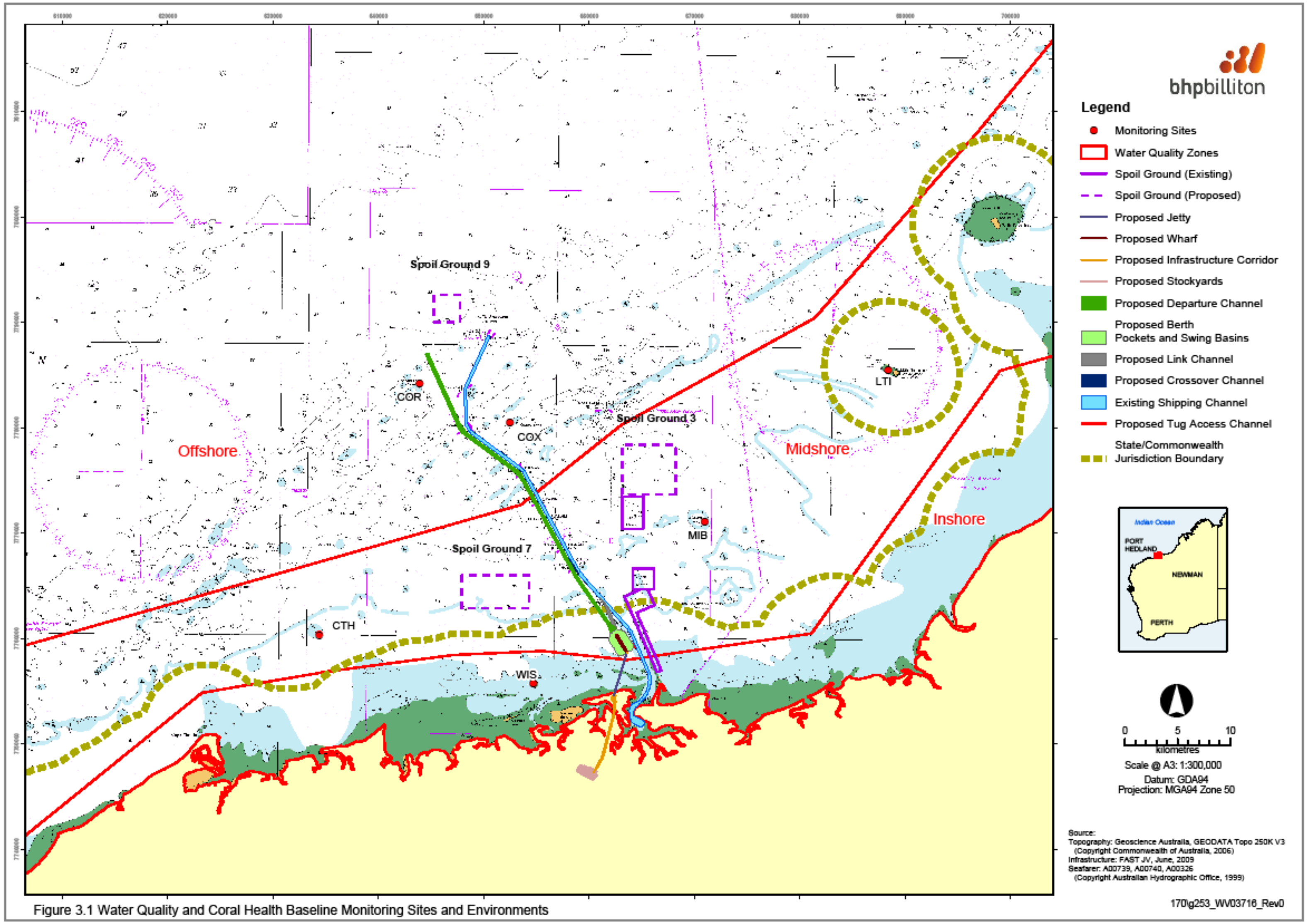


Figure 3.1 Water Quality and Coral Health Baseline Monitoring Sites and Environments

- **Figure 3-1 Water quality and coral health baseline monitoring sites and environments**

3.1.1. Seasons

Port Hedland lies in the arid subtropical zone (Bureau of Meteorology 1989). It is useful to split the seasons into ‘dry’ (June to November) and ‘wet’ (December to May) to reflect the change in the direction of prevailing winds and the potential for rainfall and cyclonic storms which are all factors that produce significant differences in all water quality parameters across the two seasons.

The dry season is characterised by lower sedimentation rates, lower turbidity events, high light levels due to lack of clouds (despite less light hours) and lower water temperatures.

The wet season may be characterised by sequential high sedimentation and turbidity events due to the passage of periodic storms and cyclones and in years where these events are relatively frequent (inter-annual variation in rainfall is high on this coastline) there may be a lower overall light climate. High temperatures during the wet season period can lead to coral bleaching events, typically when water temperatures exceed 32°C for extended periods.

3.2. Sedimentation

Three replicate sediment traps are deployed at each baseline monitoring site to measure gross sedimentation rates over a 14 to 16 day period. Every fortnight the sediment traps are capped underwater and replaced with new traps. The capped traps are brought to the surface and emptied into sample containers. Sample containers are then transported to the Marine and Freshwater Research Laboratory (MAFRL), a National Association of Testing Authorities (NATA) accredited laboratory, for drying and weighing. The total weight of material minus the organic component collected is divided by the number of days the trap was collecting *in situ* and equates to the mean daily gross sedimentation rate ($mg/cm^2/day$) for each monitoring site. The mean daily gross sedimentation rate within each environment is then calculated and this value is used for predictive sedimentation modelling.

During April 2009, sediment samples from each site together with the sediment collected from the adjacent trap were forwarded to the CSIRO for sediment particle sizing by laser diffraction. The sediment traps prevent the re-suspension of material and therefore provide a direct example of the size of material that is initially deposited as a result of suspended material in the water column. The sizes of sediment particles collected in the traps were compared to sediment samples collected at each site. This analysis determines if the size distribution of particles being deposited in the traps are similar or different from the size distribution of particles comprising benthic sediments in the immediate vicinity, thus providing some insight into the potential origin and fate of fine sediment susceptible to re-suspension.

3.3. Background Light Attenuation

Light was measured *in situ* every 30 minutes, 24 hours a day in units of PAR ($\mu moles/m^2/s$), using an Odyssey Integrating Light Sensor, calibrated by In Situ Marine Optics Pty Ltd (IMO) (SKM 2009b). Six units have been assigned to each site, with four deployed at any one time and two units held in reserve for each site. A wiper unit cleans the top of the light sensor every 30 minutes, offset from sensor measurement times, to remove any bio-fouling that may obscure the sensor, such as algal and barnacle growth. Two light sensors are located approximately 50 cm from the substratum. Light attenuation is measured using an additional two light loggers (*upper*) fitted with a wiper unit and placed on a star-picket at 2 m above the *lower* light loggers, but not as to shade the lower loggers. The light attenuation at the six monitoring sites was first measured in February 2009 and this data is used to calculate the wet season light attenuation (up to 31 May).

Light Attenuation coefficients (LAC) were calculated as the difference between the irradiance (I) values at each depth according to the equations (adapted from Kirk 1977):

$$\mathbf{K = \ln [I(\textit{upper})/I(\textit{lower})]/depth}$$

or

$$\mathbf{E = \log_{10} [I(\textit{upper})/I(\textit{lower})]/depth}$$

Using the base 10 logarithms to express the LAC (E instead of K) makes it easier to interpret the percentage of transmission of PAR. For example, when E=1 this represents 10% transmission per meter depth, when E=2 this represents 1% transmission per meter depth (Kirk 1977). The value of interest for setting coral mortality thresholds for the Port Hedland Outer Harbour project are when the total light attenuation for the water column is > 2, which equates to a ~100% light loss at the seafloor where the coral community grows.

Two assumptions are made regarding calculating the background E:

1) The background E in the 2 m layer closest to the substrate represents a close approximation of the depth average E (***E background (depth av.)*** for the entire water column.
2) Dry season E is calculated by using the relationship between dry and wet season NTU data and then adjusting the data collected on E for the wet season using this relationship as follows:

   E (dry season) = E (wet season) / [average NTU (wet season)/average NTU (dry season)]

3.4. Turbidity

Turbidity (NTU) was recorded *in situ* every 30 minutes, 24 hours a day, using an ANALITE NEP 495 turbidity and temperature logger. These devices were calibrated by the supplier, McVan Instruments, prior to deployment. They have been set to log NTU on a range from 0 to100. Further calibration checks are undertaken by MAFRL when required. Fifteen loggers have been acquired so that two units are available for each site with an additional three units held in reserve. The instruments were fixed by cable ties to a wooden spacer attached to star pickets approximately 50 cm above the substratum at each monitoring site.

3.5. Predicting the Zones of Impact and Influence

The spatial scale and intensity of the depth averaged TSS and sedimentation patterns associated with the dredging and dredge spoil disposal activities has been modelled. The model predictions have then been interrogated using light attenuation thresholds (at which it is assumed there is likely to be an impact on BPP) to further predict and plot specific 'areas' or 'zones' of interest. The time scale chosen for setting light attenuation thresholds was set at 14 days. This period corresponds with the present sampling period and the likely period of sampling and reporting during the dredging phase of the project. A summary of the descriptions for the two predictive areas defined in this project are given below.

3.5.1. Zones of High Impact

The zones of potential impact are expected to occur in close proximity to the dredging and spoil ground areas. The light attenuation in this area is likely to be affected due to increases in suspended particles, which may lead to significant impacts including mortality of the corals. The zones of high impact have been defined using the hourly periods of TSS (including background) in the water column in which 100% of all available light is occluded or 'no-light' events. The predicted plume model has been interrogated based on these 'no-light' light attenuation threshold values to predict the zones of high impact. The process by which the model is interrogated is as follows:

1) For each model cell, hourly depth and depth averaged TSS are estimated.

2) For the TSS value in that cell, the TSS-LAC relationship derived by IMO (SKM 2007b, **Figure 2-2**) is used to calculate light attenuation coefficient (E) for each hour for each cell.

3) This value represents the dredge component of light attenuation or ***E model *depth***.

4) ***E model*depth*** is divided by the depth of that cell to determine ***E model (depth av.)***.

5) ***E background (depth av.)*** is added to ***E model (depth av.)***.

6) The ***Attenuation(total)*** is calculated for each cell as

Attenuation (total) = [E model (depth av.) + E background (depth av.)] * depth of cell.

3) If ***Attenuation (total)*** >2, this cell is flagged.

3.5.2. Zones of Moderate Impact

The rationale used to predict these zones of moderate impact uses the hourly periods of levels of TSS in the water column which correspond to light attenuation (total) >1.6, or when 40% of all light is occluded. This value was chosen arbitrarily as the amount of light at which only sub lethal impact may occur. Similarly to the zones of high impact, the predicted plume model has been interrogated based on these light attenuation threshold values to predict the zones of moderate impact.

1) For each model cell, hourly depth and depth averaged TSS are estimated.

2) For the TSS value in that cell, the TSS-LAC relationship derived by IMO (SKM 2007b, **Figure 2-2**) is used to calculate light attenuation coefficient (E) for each hour for each cell.

3) This value represents the dredge component of light attenuation or ***E model *depth***.

4) ***E model*depth*** is divided by the depth of that cell to determine ***E model (depth av.)***.

5) ***E background (depth av.)*** is added to ***E model (depth av.)***.

6) The ***Attenuation(total)*** is calculated for each cell as

Attenuation (total) = [E model (depth av.) + E background (depth av.)] * depth of cell.

7) If ***Attenuation (total)*** >1.6, this cell is flagged.

3.5.3. Zone of Potential Influence

In previous large dredging projects, the zone of influence was defined as those areas which experience small changes in the sediment-related water quality (that are outside the natural ranges that may be expected) which are generated by dredging and dredge spoil disposal activities. The EPA Guidance Statement 29 describes these sediment related changes as causing 'no detectable effects on benthic biota or their habitats' (EPA 2004). The EPA has suggested that this represents an increase in TSS values of 1 mg/L or more above background in the surface layer at anytime throughout the dredging campaign for any duration in some recent dredging approvals documentation (SKM 2007a; SKM 2008b). Monitoring sites are then chosen outside these areas and classed as reference sites or sites where the dredging activities do not influence the biota for any length of time. There are a number of reasons why the recent definitions of these zones of influence are not practical. These reasons are outlined in the Cape Lambert Port B Project DSDMP (SKM 2008a) and summarised below with some additions:

- The current monitoring sites have in place turbidity meters (nephelometers) which measure NTU rather than TSS. The NTU to TSS relationship was developed in a laboratory which simulated a range of TSS environments in separate tanks and measured the corresponding NTU values recorded on nephelometers placed within these tanks. A line of best fit was calculated from this data to provide an approximate relationship between TSS and NTU. The measurement errors associated with the instrument and the conversion of NTU to TSS using the using the experimental TSS/NTU relationship developed in the laboratory are likely to make any measurement of 1 mg/L erroneous. This means the spatial scale of the zones of influence is grossly overestimated.

- Background turbidity varies considerably over very short time scales, sometimes in the order of hours, especially in the macro-tidal environment offshore from Port Hedland. To recognise that the 1 mg/L increase is actually due to dredging activities and not background variability in TSS is impossible, unless evidence of a visible plume extending from the dredge to the area in question is observed.
- The model used to predict the zones of potential influence is unlikely to be able to accurately predict increases in TSS at the lower end of the scale.
- The zones of potential influence for a sustained dredging campaign during which a large range of environmental conditions may occur, may extend over thousands of square kilometres and the prospect of finding ‘reference’ monitoring sites that are still within the same ecosystem is very difficult if not impossible.

For the proposed Outer Harbour Development, the zone of potential influence are defined to include areas within the dredge plume where the levels of turbidity due to elevated levels of TSS are sufficiently high to significantly alter the water quality above the background. Therefore, dredge plume predicted values of TSS greater than 5 mg/L are chosen to delineate the zone of potential influence.

4. Results

All data presented in this section were collected from the six monitoring sites (refer **Figure 3-1**) located off shore from Port Hedland from June 2008 to May 2009. These data are provided in the Port Hedland Outer Harbour Development: Baseline Water Quality Monitoring Report Periods 1–13 (SKM 2009b), and summarised below.

4.1. Daily Gross Sedimentation Rates

Based on the mean daily gross sedimentation rates collected from nine months of the water quality baseline survey data, three specific categories or environments relating to sedimentation regimes/rates were characterised. These three environments (**Figure 3-1**) were used in the threshold modelling process to delineate different areas of mean daily gross sedimentation rates. The first of the three environments is the inner environment, which surrounds Weerdee Reef (WIS) and is characterised by periodically high mean daily gross sedimentation rates over a 14 day period. For plume modelling interrogations, this high sedimentation environment was extended to include areas located above the 5 m bathymetry line along the coastline adjacent to Port Hedland.

Baseline surveys of inshore areas revealed that there is very little BPP growing on the BPPH that exists in this environment (SKM 2009a). Only at WIS and on hard ridges in the vicinity of WIS was there sufficient BPP to establish a monitoring site. The use of WIS sedimentation thresholds as a basis for thresholds in the entire inshore area appears to be very conservative, considering BPP exists here but is limited or non-existent in other inshore areas. This is potentially as a consequence (wholly, or in part) of higher mean rates of gross sedimentation. The second category is the mid-shore environment characterised by lower mean daily gross sedimentation rates and includes the three monitoring sites situated at Cape Thouin (CTH), Minilya Bank (MIB) and Little Turtle Island (LTI). These sites lie within the 5 m to the 10 m bathymetry contour and are situated within the area bounded by the outer ridge line. The third category is the outer environment which is characterised by lower mean daily gross sedimentation rates and includes the two monitoring sites at Coxon Shoals (COX) and Cornelisse Shoals (COR).

The range of mean daily gross sedimentation rates at each site was used to construct the mean daily gross sedimentation rate thresholds for each of the three environments (**Table 4-1**). In addition there were differences in the mean daily gross sedimentation rates in the dry season and wet season; the wet season mean daily gross sedimentation rates were typically three to four times as high as those in the dry season (**Table 4-1**).

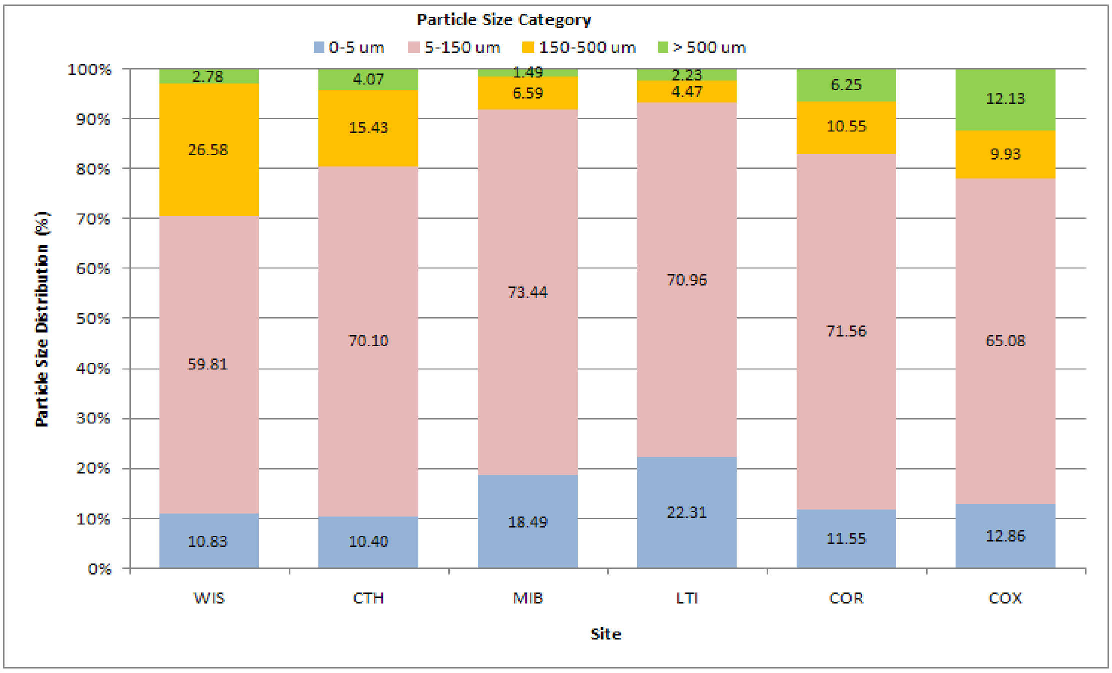
Particle size distribution analysis indicated the material in the sediment traps from each of the monitoring sites was mostly fine material (<150 µm**, Figure 4-1)** whereas, the material adjacent to the sediment traps was mostly coarse material (150 µm to >500 µm, **Figure 4-2**). This suggests that the fine material is re-suspended relatively quickly and does not remain at any of the sites. Also, as the material existing at each site is coarse, it can be concluded that the majority of fine sediment collected by the sediment traps is due to re-suspension of fine sediment elsewhere and subsequent transport into the monitoring site. The particle distribution of sediment from the traps was similar between sites. More information on particle size distributions at each monitoring sites is provided in SKM (2009b).

- **Table 4-1 Summary statistics for mean daily gross sedimentation rates within the three environments during the wet and dry season**

Sedimentation (mg/cm²/day)	Inshore(WIS)		Mid-shore(CTH/MIB/LTI)		Offshore(COX/COR)	
	DRY	WET*	DRY	WET*	DRY	WET*
n	23	20	71	62	47	42
Median	78	188	10	40	5	12
Max	220	2203	57	726	20	133
1.1 times max	242	2423	63	798	22	147
1.5 times max	331	3304	86	1088	29	200
2.0 times max	441	4406	114	1451	39	267

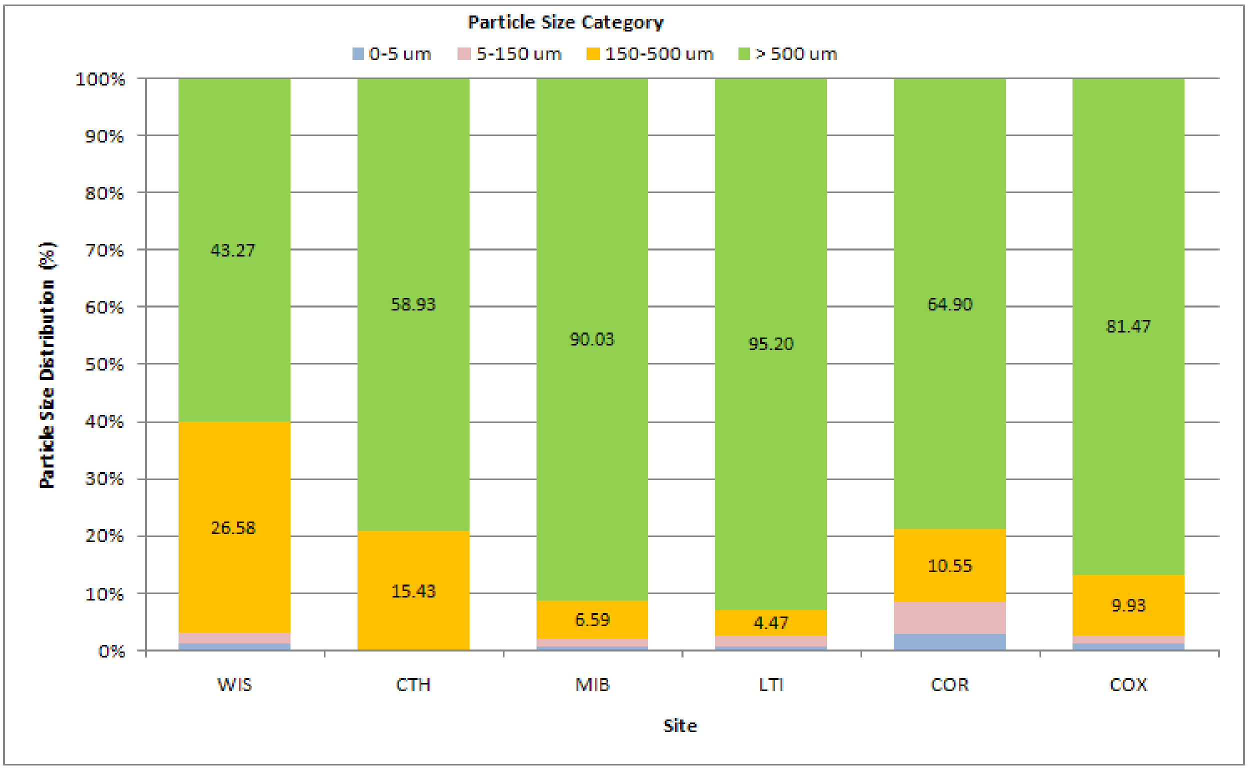
*3.5 months data

Source: SKM 2009b



Source: SKM 2009b

- **Figure 4-1 Particle size distribution (%) of sediment collected by sediment traps at each of the monitoring sites**



Source: SKM 2009b

- **Figure 4-2 The particle size distribution (%) of sediment collected from surrounding seabed at each of the monitoring sites**

4.1.1. Sedimentation Zones of High Impact

To model the sedimentation thresholds, median daily gross sedimentation rates predicted by the dredge plume over consecutive 14 day periods for the entire duration of the dredging program were evaluated to produce the zones of high impact for each season.

The predicted gross daily sedimentation rates that are 1.1 times the maximum background rates are placed in the zones of high impact as the worst case (**Table 4-1**) and assumes that the observed maximum daily gross sedimentation rates during the baseline period represent the upper limit of what could be tolerated by corals in the areas where sediment is settling. This is considered to be a very conservative estimate as there is no account taken of the very real potential for rapid re-suspension and transport elsewhere. The best case for the zones of high impact is set at twice the maximum background mean daily gross sedimentation rates (**Table 4-1**) and again this reflects a very conservative estimate of potential impact. The high impact zones are assumed to experience 100% loss of coral BPP and will be included in the final calculations of loss of coral for each of the management units in which they occur. These are indirect losses as the sediments that do settle and cause coral mortality are likely to be moved again by the process of re-suspension, therefore the areas of hard substrate will be available for re-colonisation.

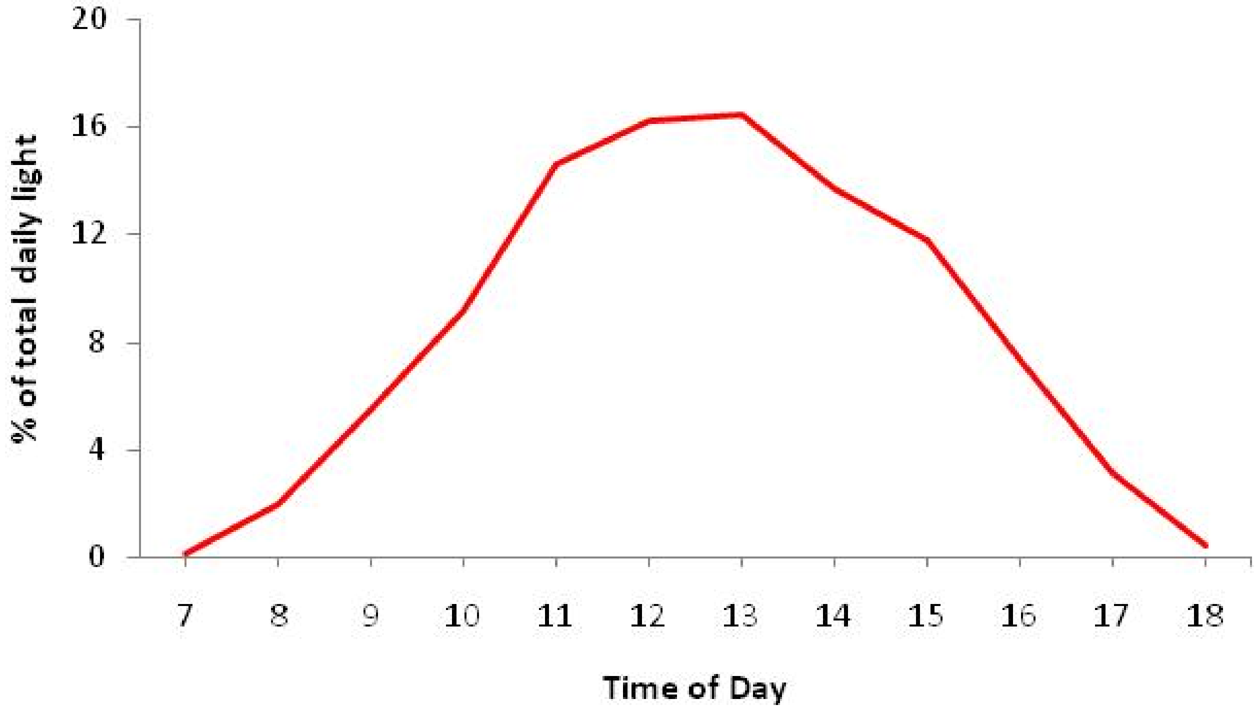
During the dredging program, exceedances of the maximum baseline mean gross sedimentation rate should be interpreted within each environment with respect to:

- the season in question;
- the mean daily gross sedimentation rate at the individual impact site; and
- the mean daily gross sedimentation rate at the corresponding reference site.

4.2. Light Climates

4.2.1. Background Light Climate

Analysis of the baseline light climate data indicates that over 95% of all light falls on the corals in the nine hours between 0800 hrs and 1700 hrs (**Figure 4-3**). Therefore attention is focussed on this period and all TSS data from outside the 0800 to 1700 hr periods are excluded from the modelling when applying the thresholds to predict the extent of the zones of high and moderate impact.



- **Figure 4-3 The percentage of daily light reaching the coral colonies during daylight between 0700 and 1800 hrs**

4.2.2. Background Light Attenuation

To calculate ***E (background depth av.,)*** the mean daily E was calculated from light data collected from the bottom 2 m of the water column at each monitoring site from 1 February 2009 to 31 May 2009. Only light data between 1000 hr and 1400 hr were used in the calculations for mean daily E as the surface reflectance is at a minimum during this period of the day (Kirk 1994). The LAC data from each site was averaged within each environment to provide an approximation of the background wet season E for each environment. The values of E were greatest in the inshore environment (0.181) followed by the mid-shore environment (0.132) and the offshore environment (0.105).

4.2.2.1. Preliminary Modelling Results

Preliminary model interrogations using the background measurements of E to identify the zones of potential impact and influence indicated severe problems with the assumption that these background values represent an accurate depth averaged E. The results indicated:

- in the offshore environment all areas where the depth was >15 m was predicted to have zones of high impact even though no plume sediments were predicted to occur there;
- this highlighted problems with applying the measured background E values to the deeper areas within each environment (the background E was triggering impacts);
- when converting the measured mean daily background E values to NTU (using the IMO relationship between LAC and NTU for dredge sediments), these values for background NTU were up to three times the measured background mean daily turbidity; and
- the different E values for each environment created large edge effects (anomalies) along the boundary between one environment and the next that extended across the entire study area.

Based on these results it was decided that the measurements of E in the bottom layer of the water column represented a gross overestimate of the depth averaged E and this approach was discontinued. Instead, turbidity measurements from each site were analysed to calculate a background turbidity value for the entire study area and this value was converted to E via the IMO relationship between turbidity and LAC.

4.2.2.2. Final Modelling Results

The median turbidity measurements from each environment are summarised in **Table 4-2**. The median NTU was used because the spread of the turbidity data was very strongly skewed and the majority of background NTU measurements were in the range of 0 to 1 NTU. The use of median turbidity is therefore more representative of the background turbidity experienced at least 50% of the time by coral communities off Port Hedland.

To add conservatism to the interrogation, a value of 2 NTU was chosen to represent background turbidity for the entire study area for both seasons. This removed the edge effect issue created in the preliminary model interrogations and represents a more realistic approximation of the background suspended sediments during the year. This value was then converted to LAC (E) using the IMO relationship (LAC (E) = 0.0123*NTU, **Figure 2-3**) and added into the calculations for ***Attenuation (total)*** as ***E (background depth av.)***. Therefore background E represented a constant value across the entire study area and in both seasons of 0.025.

- **Table 4-2 Median NTU within each environment for the dry and wet season**

Median NTU	Inshore	Midshore	Offshore
Dry	1.4	1.1	0.9
Wet	1.0	1.5	0.7
n Dry	8244	26034	15678
n wet	7474	23475	13534

Source: SKM 2009b

4.2.3. Predicting the Zones of High and Moderate Impact

Predicting the Zones of High Impact

The zones of high impact are defined as the area in which dredge related activities are likely to cause severe stress to corals with some level of mortality (whole colonies and/or partial mortality) evident. It is assumed that if all light is removed due to an over abundance of suspended particles in the water column from background plus dredging related activities, impacts on the coral community will occur. The thresholds for each environment are calculated as follows:

1) ***E (background depth av.)*** = 0.025.

2) If ***Attenuation (total)*** >2 then that cell has no light and is flagged.

3) If this cell has no light >125 times in a 14 day period (>90% light reduction in 14 days) there is an exceedence for that 14 day period (14 days x 10 TSS values (0800 to 1700) =125/140 = ~90%).

4) The consecutive fortnights of exceedences are counted.

5) If there are four or more consecutive fortnights of exceedences, this area is deemed to be impacted and is included as part of the zones of high impact.

An example of the TSS values in the water column (minus background) that would occlude 99% of light at a given depths are summarised in **Table 4-3** below.

- **Table 4-3 The TSS (minus background) that delineate the zones of high impact (E>2) and the zones of moderate impact (E>1.6) for each environment and season, at a range of depths**

Depth (m)	TSS (mg/L)	
	Zones of High impact	Zones of Moderate Impact
1	128	102
2	63	50
3	41	33
4	31	24
5	24	19
6	20	16
7	17	13
8	15	11
9	13	10
10	11	9
11	10	8
12	9	7
13	8	6
14	8	6
15	7	5
16	6	5
17	6	4
18	6	4
19	5	4
20	5	4

Predicting the Zones of Moderate Impact

The zones of moderate impact are defined as the area in which dredge related activities are likely to cause some stress to corals with some level of mortality (whole colonies and/or partial mortality) evident. It is assumed that if 40% of light is removed due to an increase in suspended particles in the water column then sub-lethal impacts on the coral community will eventually occur. To achieve the occlusion of approximately 40% of all light, the light attenuation due to the dredging related suspended particles plus the light attenuation due to the background suspended particles must combine to block 40% of all light from reaching the coral community. The thresholds for each environment and each season are calculated as follows:

1) ***E (background depth av.)*** = 0.025.

2) If ***Attenuation (total)*** > 1.6 the cell has a 40% light reduction.

3) If this cell has 40% light reduction for >135 times in a 14 day period there is an exceedence for that 14 day period (there are 140 TSS measurements in a 14 day period).

4) Count the consecutive fortnights of exceedences.

5) If there are four or more consecutive fortnights of exceedences, this area is deemed to be impacted and goes into the zones of moderate impact.

An example of the TSS values in the water column (background included) which would occlude 40% of all light at a given depth are summarised in **Table 4-3**.

5. Plume Model Interrogations

5.1. The Zones of High and Moderate Impact and Calculating Loss

The threshold values developed to delineate zones of high and moderate impact are based on TSS values that reduce the light climate available to the coral community. If these TSS values occur very frequently in a 14 day period then this period is termed a “no-light” (high impact) or “low-light” (moderate impact) fortnight. If the “no-light” or “low-light” fortnights are consecutive then impacts on the coral community are assumed to have occurred. The actual number of altered light climate fortnights that occur consecutively and the assigned loss of coral are examined using:

- the literature available on the length of “no-light” periods which correspond to coral mortality (**Section 5.1.1**); and
- the periods of “no light” the coral communities at Port Hedland experience from the baseline light climate data already collected, and the measures of mortality of these communities during and after the periods of “no-light” (**Section 5.1.2**).

5.1.1. Previous Studies on the Effect of TSS/NTU on Irradiance

A recent study examined the water quality parameters at coral reefs in the vicinity of a medium flooding event of the Tully River in North Queensland in February 2007 (Wolanski *et al*. 2008). At Dunk Island to the north of the Tully River mouth, the irradiance at 4 m depth was measured before, during and after the flood event. For a period of ten days during the flood there was almost no irradiance measured at 4 m depth. This study did not measure coral health and mortality before and after this event, however detailed measures of coral diversity and abundance, coral cover and recruitment are carried out frequently at a site within 1 km of the irradiance measurements. This site is situated on the southern flank of Dunk Island, North Queensland.

The coral community located on the southern flank of 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), therefore coral reefs growing in the vicinity of the mouth of the Tully River have frequently experienced high sediment loads and periods of total loss of irradiance in the last nine years. 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) recorded sustained periods of elevated turbidity (average: 9.2±0.2 NTU) at a monitoring site in Horseshoe Bay, North Queensland for a period of four weeks following a flood event in March/April 2007. The study suggested that turbidity levels >5 NTU result in ~94% light extinction in the water column. The resulting effect on the study coral, *Pocillopora damicornis,* was loss of colony brightness and a reduction in symbionts densities indicating a potential stress response. Once this period of "no-light" was over the colonies of *P.damicornis* recovered.

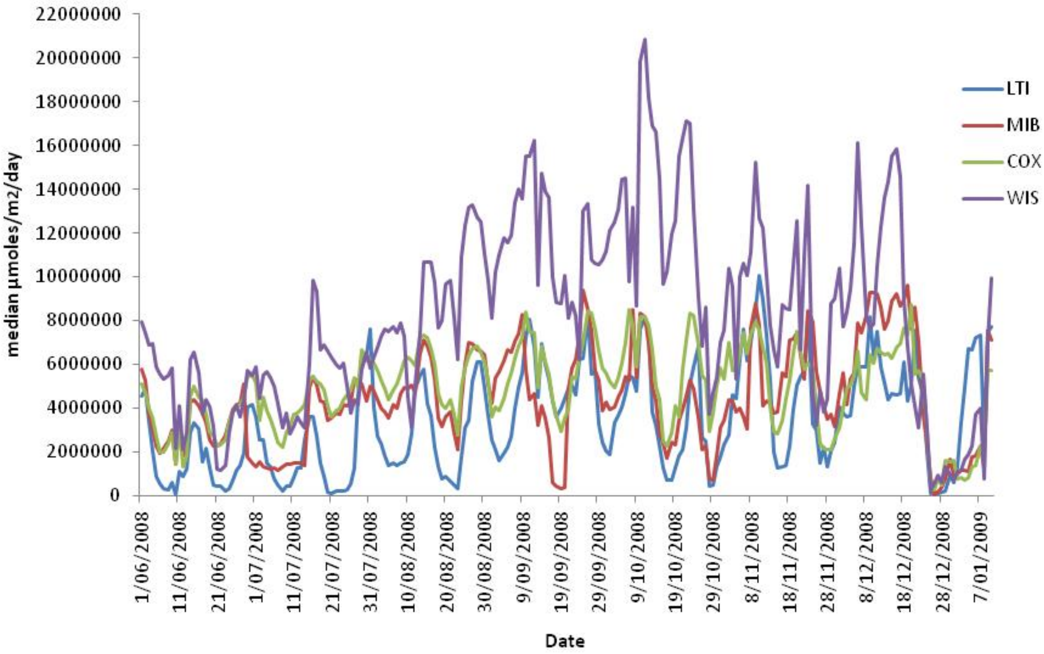
Additional studies into the effect of high TSS levels on coral species indicate there can be some beneficial elements to those species under low light situations (Anthony *et al*. 2007). These include increased reliance of feeding on food particles in the water column to offset photosynthetic energy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

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

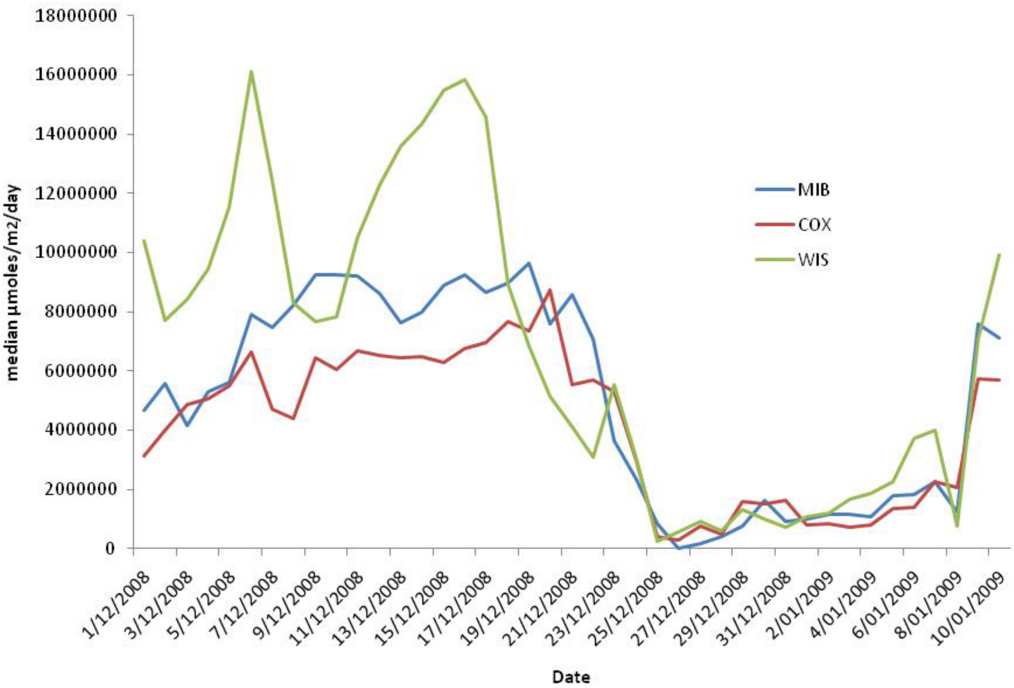
5.1.2. Baseline Data

Coral communities offshore from Port Hedland frequently experience periods of "no-light" throughout the year (**Figure 5-1**). 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 the 'normal' light situations (**Figure 5-2**). These sites have tagged coral colonies which are routinely monitored for partial mortality. During coral monitoring surveys at these sites subsequent to the periods of "no-light", there was no increase in partial mortality. In addition, coral communities at LTI frequently experience low light situations (>90% reduction for up to 10 days) throughout the year (see **Figure 5-2**) and yet the partial mortality at this site remains one of the lowest recorded at any monitoring site (SKM 2009c).

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.



- **Figure 5-1 Light climate at four monitoring sites offshore from Port Hedland between June 2008 and January 2009**



- **Figure 5-2 Light climate at three monitoring sites offshore from Port Hedland between December 2008 and January 2009**

5.1.3. Assigning Percentage Loss from Elevated TSS and Sedimentation

The information gathered from the literature, and baseline data (**Section 5.1.)** are outlined below:

- coral communities show no signs of mortality after periods of up to 10 to 28 days of "no light"; and
- coral communities at Port Hedland frequently experience "no light" for at least 14 days without any signs of increased mortality.

Four consecutive fortnights (i.e. 56 days) of >90% light reduction represents an event which has not been observed during the baseline surveys and it is assumed in this case that this period is likely to cause some mortality of coral colonies. Due to lack of information from baseline surveys and the literature on the effect of light loss on the coral community for periods of four fortnights or greater, a conservative approach is used and the coral loss predicted to occur in this circumstance is set at 100%.

If four consecutive fortnights (i.e. 56 days) of >40% light reduction is predicted, it is assumed that some mortality of coral colonies would occur. Due to a lack of information from baseline surveys and the literature on the effect of light loss on the coral community for periods of four fortnights or greater, a conservative approach is used and the coral loss predicted to occur in this circumstance is set arbitrarily at 30%.

The predicted gross daily sedimentation rates that are 1.1 times the maximum background rates are placed in the zones of high impact as the worst case (**Table 5-1**). This assumes that the observed maximum daily gross sedimentation rates during the baseline period represent the upper limit of what could be tolerated by corals in the areas where sediment is settling. The best case for the zones of high impact is set at twice the maximum background mean daily gross sedimentation rate. A most likely case is presented for areas that experience 1.5 times the maximum baseline sedimentation rate. Both the best case and worst case scenarios which define the zones of high impact for sedimentation predict a 100% loss of BPP which occur underneath these predicted zones.

- **Table 5-1 Predicted coral loss based on baseline gross sedimentation rates**

Gross sedimentation rates	Best case coral loss	Most likely coral loss	Worst case coral loss
1.1 times max baseline sedimentation	-	-	100%
1.5 times max baseline sedimentation	-	100%	-
2.0 times max baseline sedimentation	100%	-	-

6. Summary

The range of water quality and light climate data collected during the first 12 months of monitoring for the proposed Port Hedland Outer Harbour Development has provided the basis for development of water quality thresholds. The thresholds are based on the effect of TSS on light, and allow predictions of the spatial and temporal impacts to corals BPP by interrogating the dredge plume modelling output. The EPA Guidance Statement 29 emphasises the requirement to examine the effect on the light climate (reduction in photosynthetic capacity) due to increases in suspended solids in the water column brought about by dredging and spoil disposal activities. The formulation of thresholds for estimates of impacts on corals is always constrained by a lack of empirical data. The theoretical thresholds presented here are based on interpretations of the light requirements of sensitive receptors like corals and the likely changes to the existing light climate due to dredging and spoil disposal activities. Although this represents a relatively new approach to the development of impact thresholds, it is consistent with the expectations of the guidelines defined by the EPA (2004).

6.1. Coral Communities and Light Climate

The light climate thresholds are based primarily on changes to the minimum light climate required to maintain a viable coral community. A viable coral community can be described as a community that grows, reproduces and maintains species richness through time. Surveys of the coral communities in the sub-tidal areas adjacent to Port Hedland indicate a community dominated by the coral genus *Turbinaria.* This genus is common to areas that experience high turbidity and sedimentation and are adapted to low light environments.

The prevalence of such a coral community can be interpreted in two ways:

- the coral communities are already close to the point at which any reduction in the light climate could be detrimental to that community, or
- the marine environment located offshore from Port Hedland is such that the only genera that can flourish in such an environment are those that can withstand frequent storm and cyclonic disturbances, large tidal flows, high sedimentation and suspended solids, and these genera are essentially out-competing the less robust species.

Evidence for the latter argument is based on the large variation in light climates measured during the baseline monitoring that the coral communities at the different monitoring sites experience. At five of the six monitoring sites, the coral communities are dominated by the genus *Turbinaria* which suggests that this community can flourish in the range of light environments observed. *Turbinaria* spp (in particular *Turbinaria mesenterina)* are known to adapt to a range of water quality environments (including low-light environments) and their physiological responses to these environments are well documented (Anthony & Connolly 2004; Anthony 2006; Sofonia & Anthony 2008; Golbuu *et al*. 2008). Corals from the Faviidae family are ubiquitous on limestone ridges offshore from Port Hedland. Some species from this family are able to shift their mode of feeding from autotrophy to heterotrophy over a period of two months (Anthony & Fabricius 2000).

Predicting the Zones of High Impact

In order to be conservative, the coral communities under the predicted zones of high impact during the project are predicted to be severely impacted upon and potentially suffer 100% loss. This may not be the case. If there is a reduction in light available to the coral community of ~90% of available light in a given fortnight and there are four consecutive fortnights of this level of light loss, then potentially the amount of light the corals receive in the four fortnights period could range between 0 and 10% of available light. Depending on this value of available light, this may still be sufficient enough to ensure the survival of the coral community.

The percentage of surface irradiance at which a coral community can exist and reproduce in the Whitsunday region of the Great Barrier Reef is reported to be in the range of 6 to 8% (Cooper *et al.* 2007). Surveys of the species richness of coral communities on six Whitsunday reefs located in close proximity to the coastline produced estimates in the order of 100 to 120 species from a range of genera (Sweatman *et al.* 2006). The light climate in the zones of high impact due to the Outer Harbour Development will potentially be in the range of the 6 to 8% surface irradiance suggested by Cooper *et al* (2007) or just below. This may be sufficient light to maintain the existing coral community at Port Hedland.

In addition, it is highly unlikely that coral communities located at distance from the dredging and spoil disposal activities will experience ‘no light’ periods for long periods of time. Elevated TSS values that exceed the thresholds may occur in close proximity of the dredging and spoil disposal related activities for extended durations; however, it is very unlikely that in the macro-tidal environment of Port Hedland the plume created by these activities will remain stationary over a site for longer than the six hour tidal cycle. Light climates may therefore fluctuate between ‘no light’ and ‘full light’ in a matter of hours.

Predicting Coral Mortality in Zones of High Impact

The level of mortality within the zones of high impact is determined from information gathered from the literature and examination of baseline light climates. Assigning values of potential percentage loss is therefore based on a combination of information on what is known about the effect of low-light conditions on coral communities and assessment of the potential risk to the corals present at Port Hedland. It is logical to assume that coral communities that experience “no-light” light for two months or more and that are simultaneously impacted by severe sedimentation are likely to experience up to 100% mortality. Other areas that experience no sedimentation effects and are deprived of light for shorter periods are likely to be impacted to a lesser degree, if at all. For areas within this category, the proposed worst case scenario is based on the predictions of any occurrence of four or more consecutive fortnights of “no-light”.

Predicting Coral Mortality the Zones of Moderate Impact

Studies into the effect of periods of turbidity in the range of 5 to 10 NTU maintained over a long period concluded that significant impacts on coral health manifested as photosynthetic stress can occur under these conditions (Cooper *et al.* 2008). This study focused on *Pocillopora damicornis* which is known to be moderately susceptible to elevated turbidity and sedimentation (Gilmour *et al.* 2006). Only at the offshore site of COR were any colonies of *Pocillopora damicornis* found and according to the dredging turbidity plume modelling, this site is unlikely to be impacted by the plume arising from dredge and spoil related activities at any stage of the project. Despite this, the rationale for low turbidity events over long durations is incorporated into the modelling for the zones of moderate impact. These zones are defined as durations (four fortnights or greater) of elevated TSS which are predicted to generate modest reductions in the percentage of surface irradiation reaching the corals. This reduction in available light is predicted to cause sub-lethal stresses only. No coral mortality is predicted to occur with this zone.

6.2. Threshold Limitations and Assumptions

Background Light Attenuation

Kirk (1977) outlines two factors which influence the change in the value of the light attenuation coefficient with water depth.

These two factors are:

- light attenuation decreases with depth due to the progressive removal of more strongly absorbed wavelengths; and
- as light penetrates further into the water column the light becomes more scattered and therefore is more likely to be absorbed.

Kirk (1977) also found that in more turbid waters that these ‘two tendencies cancel each other out’ and that light attenuation coefficients in more turbid waters become linear. One vertical attenuation coefficient measurement may actually describe the light attenuation throughout the entire water column. This would certainly be the case in situations where the suspended solids were evenly spread throughout the water column. Model predictions of the dredge plume (APASA 2009) and *in situ* observations by divers at the six monitoring sites offshore from Port Hedland indicate that the lower layer in the water column is often the most turbid layer.

Although light is attenuated significantly in the upper layer through absorption, the light is potentially more highly attenuated in the lower layers due increased turbidity causing scattering, then absorption. This indicates that the assumption that the background light attenuation coefficient in the 2 m layer closest to the substrate does not represent a close approximation, but a gross over estimation of the depth average light attenuation coefficient for the entire water column.

Based on this, the background turbidity measurements from all sites for the baseline monitoring were used to approximate the effect on light attenuation. The background turbidity measured at 0.5 m above the seafloor at each site is assumed to be representative of the entire water column. This is a conservative approach given the modeling predictions and diver observations indicate that the most turbid layer is located near the seafloor. The conversion from turbidity to LAC for the modeling interrogations utilize the IMO relationships developed from potential dredge sediments between LAC and turbidity. This approximation using the IMO relationship is not ideal, however further field work on quantifying the relationship between background LAC and background turbidity at the six monitoring sites is underway.

Number of Fortnights

The number of consecutive 'no-light' fortnights is modelled to produce the zones of high impact. The worst case scenario of 100% coral loss is assumed when there are greater than four consecutive fortnights of "no-light" occurring **once** during the entire dredging campaign. The modelling does not examines the scenario in which there less than four consecutive "no-light" fortnights. Previous studies have indicated that periods of 10 to 28 days may cause some sub-lethal stress in particular genera that are not abundant at Port Hedland (e.g. *Pocillopora*). Four fortnights was chosen as an arbitrary value that is at least two to four times the measured periods of "no-light" gleaned from the literature or recorded in baseline surveys.

The development and refinement of water quality thresholds based on changes in light climate and the subsequent effect on coral communities is ongoing. Additional data on light attenuation profiles, light attenuation in the lower layer, total suspended solids, turbidity and coral health and mortality will be collected over the next year. These data will improve the accuracy of the thresholds used to predict the impact of dredging and spoil ground activities associated with the proposed Outer Harbour Development on coral communities located in subtidal areas offshore from Port Hedland.

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