Port Hedland Outer Harbour Development

BASELINE WATER QUALITY MONITORING REPORT: JUNE 2008 – MARCH 2010

- WV03716-MV-RP-0037
- Revision 2
- June 2011

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SKM derived the data in this report primarily from the data collected during the baseline water quality monitoring programme. The passage of time, manifestation of latent conditions or impacts of future events may require further exploration at the site and subsequent data analysis, and re-evaluation of the findings, observations and conclusions expressed in this report.

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Executive Summary

Background

A key component in the environmental approval process for the BHP Billiton Iron Ore Port Hedland Outer Harbour Development is to demonstrate to the regulatory authorities that potential impacts on the marine environment have been adequately investigated. A major potential impact 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 during construction.

In order to quantify the effects of increased TSS produced by dredging, it is necessary to first determine the baseline light conditions that BPPs are exposed to under natural conditions prior to dredging.

Purpose

SKM was engaged by BHP Billiton Iron Ore to undertake a baseline water quality monitoring programme to:

- determine existing water quality conditions to gain an understanding of:
    i. natural seasonal variation within the proposed development area; and
    ii. existing tolerances of BPPs, both theoretical and observed, to changes in water quality (a requirement of Environmental Protection Authority Guidance Statement No. 29) (EPA 2004).
- provide site specific information, from which it can then be demonstrated to regulatory authorities/agencies that the basis for predicting potential impacts on the marine environment is robust and based upon site measured data; and
- allow for comparisons of water quality conditions and BPPs health within the Port Hedland region with other locations where similar data have been collected.

This report provides a baseline summary of several water quality variables at six sampling sites during the period from June 2008 to March 2010 and completes 22 months of baseline monitoring.

Methods

Six water quality monitoring sites were selected based on the existing information provided by preliminary plume modelling results, pilot field surveys of benthic primary producer habitat (BPPH) and field observations of environmental characteristics. The six sites were stratified across inshore, mid-shore and offshore environments. Sites within each environment were recognised as having similar water quality characteristics. This was done in order to capture the full range of environmental characteristics within the study area. The site function (impact versus reference) of all water quality monitoring sites will be determined based on the revised plume modelling results.

At each site, instruments were installed to measure and record turbidity in nephelometric turbidity units (NTU), water temperature in degrees Celsius (ºC) and light or photosynthetically active radiation (PAR) in units of µmoles/m^2/s, every 30 minutes. In addition, sedimentation data (sedimentation rates as mg/cm^2/day) were collected using three sediment traps at each monitoring site deployed for successive two week time periods.

Water quality thresholds are being developed based on the minimal light requirements to maintain a viable coral community, these are described in the Water Quality Thresholds Report (SKM 2009b). TSS is the variable used to characterise the behaviour of particles in modelling of dredge plume behaviour. The use of water quality thresholds based on light or sedimentation requires an understanding of the locally relevant relationship(s) between TSS and these water quality variables in order to use the baseline and reactive monitoring datasets to predict the potential impact of the dredge plume (TSS) upon the environment.

Summary of Results

The results collected during baseline monitoring demonstrated a large range in light, turbidity, water temperature and sedimentation across time (between seasons) and space (between sites) indicating a highly variable and extreme environment within the study area.

In general, the majority of light, turbidity, water temperature and sedimentation data were weather dependent and showed a strong seasonal transition from the dry to the wet season. The tidal regime appeared to be an influential factor determining variations in the light climate, turbidity and water temperature at all sites on a fortnightly basis. On a seasonal basis, these water quality variables appeared to be influenced by climate (air temperature), storms and cyclone events.

Turbidity fluctuations and sedimentation rates were greatest at the inshore site Weerdee Reef followed by the mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island. The offshore sites Cornelisse Shoal and Coxon Shoal showed the least variability in turbidity. Within a sampling period (two weeks), turbidity varied considerably among those sites separated by only a few kilometres, this was thought to be due to differences in exposure, amount of sediment on the substrata, depth and other physical characteristics of the site location.

The light climate was the most variable at the inshore site Weerdee Reef while at the mid-shore and offshore sites the light climate fluctuated in a regular pattern coinciding with the tidal regime.

The most constant water quality environment occurred at the deeper, offshore sites Coxon and Cornelisse Shoals which appeared to be less susceptible to changes in light, turbidity, water temperature and sedimentation as a result of winds and tides.

There was a distinct seasonal transition in light, turbidity and sedimentation rates from the dry to the wet season. The turbidity at all six sites increased at the onset of the wet season and the light climate decreased. The sedimentation rates at all six sites increased during the wet season. This was to be expected since the highest levels of sedimentation appeared to follow acute periods of strong winds and waves as a result of storms and cyclones.

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 in conjunction with weather conditions and seasonal trends.

Contents

List of Figures

List of Tables

List of Acronyms

ANZECC & ARMCANZ	*Australian and New Zealand Guidelines for Fresh and Marine Water Quality.*, Australian and New Zealand Environment Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand
BoM	Bureau of Meteorology
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
DWT	Dead weight tonnes
EIS	Environmental Impact Statement
EPA	Environmental Protection Authority
LAC	Light Attenuation Coefficient
LTI	Little Turtle Island
MAFRL	Marine and Freshwater Research Laboratory
MIB	Minilya Bank
NTU	Nephelometric Turbidity Units
PAR	Photosynthetically Active Radiation (µmoles/m^2/s)
PER	Public Environmental Review
PHPA	Port Hedland Port Authority
PSD	Particle Size Distribution
QA/QC	Quality Assurance and Quality Control
SKM	Sinclair Knight Merz
TSS	Total Suspended Solids
WIS	Weerdee Reef

Document history and status

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1. Introduction

1.1. Background

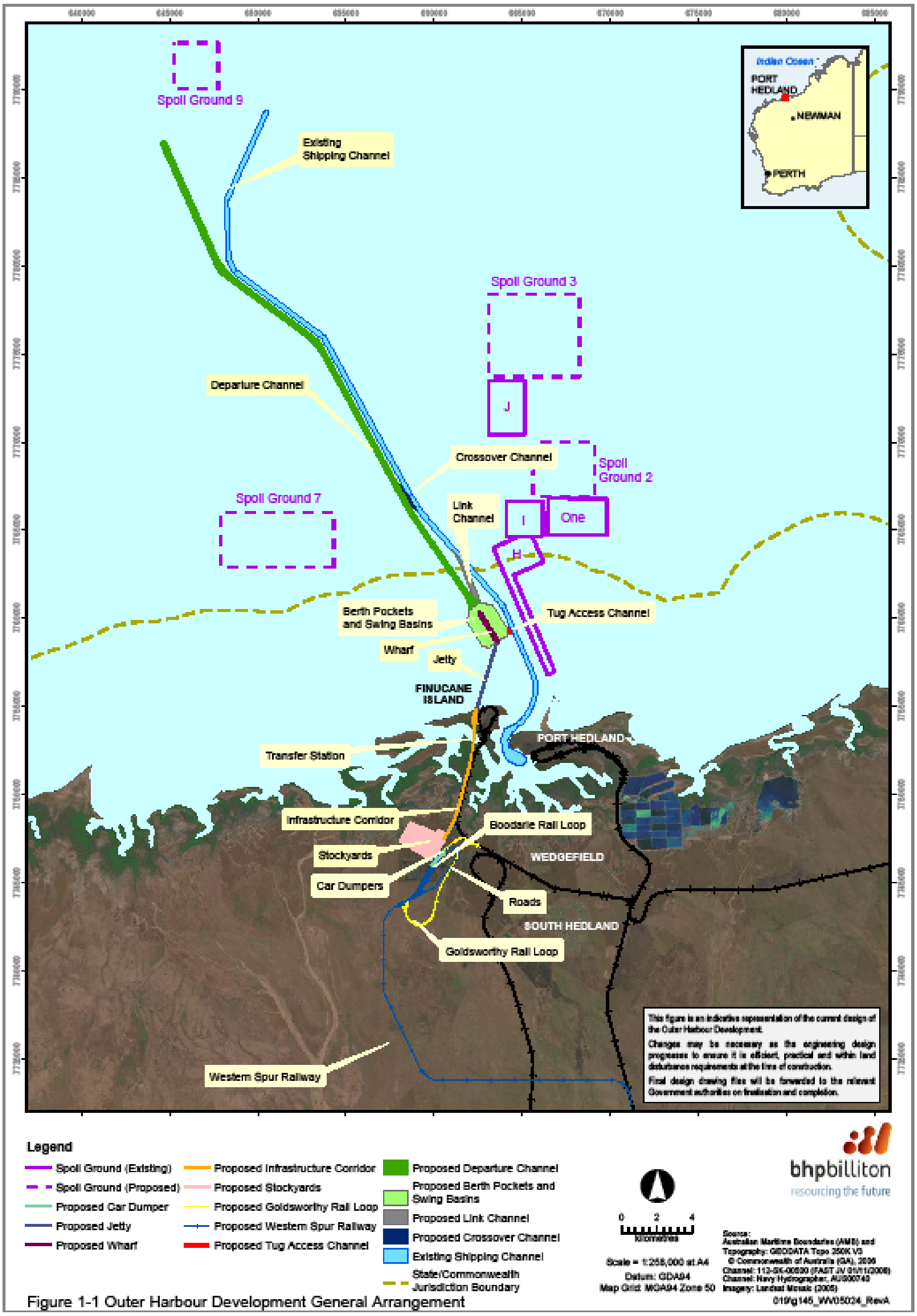
A key component in the environmental approval process for the BHP Billiton Iron Ore Port Hedland Outer Harbour Development is to demonstrate to regulatory authorities that potential impacts on the marine environment have been adequately investigated. Marine dredging programs, such as the Outer Harbour Development, 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 out and potentially smother marine organisms. Smothering can lead to the disruption of the organisms’ photosynthetic rates, feeding and respiratory processes. These effects can cause immediate stress, and reduce productivity and increase mortality if sustained (Turner *et al*. 2006).

In order to predict the effects of increased total suspended solids (TSS) produced by dredging, it is necessary to first determine the baseline conditions that benthic primary producers (BPPs) are exposed to prior to dredging. Therefore, for the proposed Outer Harbour Development (**Figure 1-1**), baseline water quality monitoring was carried out at six sites offshore of Port Hedland for the duration of 22 months, prior to dredging activities, to capture natural systematic changes such as tides and seasonal cycles as well as non-periodic events such as storms.

1.2. Purpose and Objectives

The objectives of the baseline water quality monitoring programme were to:

- determine existing water quality conditions to gain an understanding of
    i. natural seasonal variation within the proposed development area; and
    ii. existing tolerances of BPPs, both theoretical and observed, to changes in water quality (a requirement of Environmental Protection Authority (EPA) Guidance Statement No. 29) (EPA 2004).
- provide site specific information from which it can then be demonstrated to regulatory authorities/agencies that the basis for predicting potential impacts on the marine environment is robust and based upon site measured data; and
- allow for comparisons of water quality conditions and BPPs health within the Port Hedland region with other locations where similar data have been collected.



▪ **Figure 1-1 Outer Harbour Development General Arrangement**

The objectives of this report are to provide details of the methods used to collect, analyse and interpret the baseline data collected so far from June 2008 to March 2010 and provide a summary of the data.

1.3. Other Related Studies

A coral monitoring programme was also conducted at the six water quality monitoring sites to allow for correlation between turbidity, light conditions, TSS, sedimentation and BPP health. This will be an essential tool for investigating the potential impact of dredging activity on coral health. Baseline monitoring will be undertaken for the same duration as for water quality monitoring to allow for seasonal change and natural variability.

At each of the water quality monitoring sites, the health of 60 scleractinian corals (hard corals) was monitored. Hard corals are the dominant subtidal BPP group in the region. 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, if not the most, sensitive BPPs in terms of the potential impacts from dredging (Stoddart & Stoddart 2005; Brown *et al*. 1990). It is therefore assumed that these are the most sensitive marine receptors and will act as sentinels for potential impacts on all the BPPs that are present within the region. A separate report describing coral health observed to date has been prepared (SKM 2009a).

The range of water quality and light climate data collected during the first nine months of monitoring for the Outer Harbour Development provided the basis for the development of water quality thresholds. A threshold report has been written based on the effect of TSS on light, to allow predictions of the spatial and temporal impacts to corals BPP based on interrogations of the dredge plume modelling output (SKM 2009b). The theoretical thresholds presented in the report 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.

2. Materials and Methods

2.1. Site Selection

Six water quality monitoring sites were selected based on the existing information provided by preliminary plume modelling results, pilot field surveys of BPPH and field observations of environmental characteristics. The sites were selected based on the following process.

A zone of increased TSS, such as an increase of 1 mg/L, was predicted based on preliminary plume modelling to identify the spatial extent of increased TSS from proposed dredge and spoil disposal activities. The preliminary plume model was based on conceptual project information and limited environmental data such as sediment characteristics, hydrodynamic and wave models previously supplied for similar projects in the Port Hedland region. The selected zone of influence was a preliminary prediction and used only as a guide to approximately define the boundaries of the study area.

Following this, areas with suitable BPPs were identified using observations from field surveys undertaken within the broad study area (**Figure 2-1**). For example, the presence of corals and the suitability of substrate for the installation of site markers. The base of the site markers requires a minimum separation distance of 15 m from sensitive BPPs to avoid any inadvertent damage to the benthic habitat. A summary of the field survey methods and observations used to select monitoring sites are provided in SKM (2008a).

Finally, three environments were identified within the study area based on their physical characteristics. For example, depth, distance from the mainland, exposure and susceptibility to sediment re-suspension. These factors were known to have an effect on the water quality environment based on previous studies (see Gilmour *et al*. 2006; Wolanski *et al*. 2005; Forde 1985). The three environments were defined as inshore, mid-shore and offshore and are detailed in **Table 2.1** and **Figure 2-2**. The six water quality sites were assigned to one of these three environments based on *a priori* knowledge.

The six sites were reassessed once sufficient field measurements of light climate, turbidity, sedimentation and water temperature were available from each monitoring site. These data further indicated there were three distinct water quality environments based on water depth and distance from shore; inshore (< 5 m datum), mid-shore (5–10 m datum) and offshore (> 10 m datum). Based on preliminary results the inshore environment was characterised by variable turbidity and high sedimentation rates, highly variable light and sea temperatures. The mid-shore environment had fewer extremes of water quality variables, but still experienced occasional high levels of sedimentation and turbidity, low light and variable temperatures. The offshore environment was more stable in terms of all water quality variables. These three environments provided a basis for the plume modellers to model the areas of impact and influence with meaningful thresholds based on spatially broad categories rather than site specific categories that are difficult to model. Therefore using the information available at the time, the six water quality monitoring sites were selected to adequately represent the full range of environmental characteristics and BPPs within the study area. The details of each site are listed in **Table 2.1** and illustrated in **Figure 2-2**.

- **Table 2.1 Water quality monitoring sites offshore from Port Hedland**

Site Name	Code	Environment	Approx. distance from the mainland (km)	Approx. mid tidal water depth (m)	Susceptibility to sediment re-suspension	Latitude	Longitude
Weerdee Reef	WIS	Inshore	3	4.6	HIGH	20° 17.414' S	118° 28.893' E
Cape Thouin	CTH	Mid-shore	10	7.9	MEDIUM	20° 14.995' S	118° 17.194' E
Minilya Bank	MIB	Mid-shore	16	10.2	MEDIUM	20° 09.002' S	118° 38.157' E
Little Turtle Island	LTI	Mid-shore	19	10.2	MEDIUM	20° 01.081' S	118° 47.991' E
Cornelisse Shoal	COR	Offshore	33	12.5	LOW	20° 02.040' S	118° 22.560' E
Coxon Shoal	COX	Offshore	28	13.5	LOW	20° 03.998' S	118° 27.485' E

Note: Datum is GDA94

It is intended that the location, number and relevancy of all sites be reviewed as the project is further defined in detailed engineering phases and as additional site specific data becomes available during ongoing monitoring.

2.2. Site Description

A general description of each site is given below, including the relevant percentage contributions of BPPs and abiotic substrate assessed using video transects during baseline surveys in early 2008, as summarised in SKM (2008a).

2.2.1. Inshore Site: Weerdee Reef

Weerdee Reef (WIS) is located approximately 10 km west of the entrance to Port Hedland Harbour and 3 km offshore of the mainland. The site is 2 km to the north of Weerdee Island and located at a depth of approximately 4.6 m mid-tidal (**Figure 2-2**). The site is susceptible to sediment re-suspension due to the shallow depth, proximity to the mainland and thus strong tidal currents. The site is predominantly abiotic (69%) with a moderate percentage cover of sponges (12%), hard corals (11%) and soft corals (7%). Upon examination of the data collected during all initial baseline habitat surveys (SKM 2008a), it was concluded that there were very little BPPs growing in this environment. Only at WIS and on hard ridges in the vicinity of this site were sufficient BPPs found to set up a monitoring site. Hence, only one inshore monitoring site was initially selected. Further investigation will be undertaken to identify additional site(s) representative of the inshore environment.

2.2.2. Mid-shore sites: Cape Thouin, Minilya Bank and Little Turtle Island

Cape Thouin (CTH) is approximately 35 km west of the entrance to Port Hedland Harbour, 14 km to the north-east of Cape Thouin and 10 km from the mainland. The site is located on an extensive reef platform at a depth of 7.9 m mid-tidal. The predominant cover is abiotic (78%), hard corals (8%) and sponges (8%) with small patches of macroalgae (5%) and soft corals (1%).

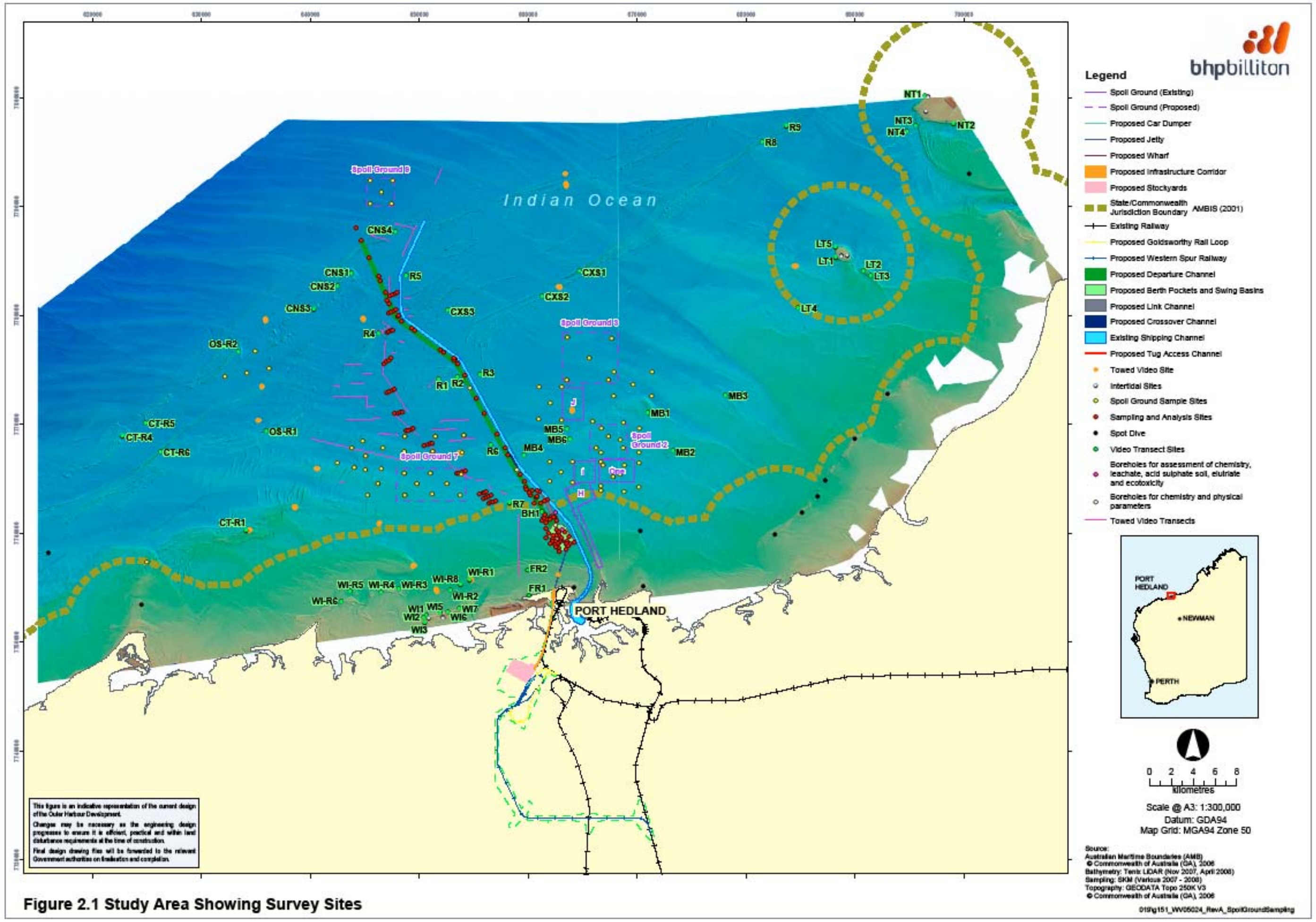
Minilya Bank (MIB) is approximately 19 km north north-east of the entrance to Port Hedland Harbour (16 km from the mainland) and consists of a low mound rising from a depth of 11 m at the mooring to 9 m. The mid-tidal depth is approximately 10.2 m. The site is predominantly abiotic (88%), with small patches of hard coral (6%), macroalgae (5%) and sponges (2%).

Little Turtle Island (LTI) is approximately 40 km north-east of the entrance to Port Hedland Harbour and 19 km offshore of the mainland at Spit Point. The site has low topographic complexity substratum rising from a depth of 9 m at the mooring to 7 m at the highest point of the site with an approximate mid-tidal depth of 10.2 m. The substrate mainly consists of sand, rubble and rock with occasional corals. The site was predominantly abiotic (76%) with a moderate cover of hard corals (18%) and lesser quantities of sponge (3%), macroalgae (3%), and soft corals (0.2%).

2.2.3. Offshore Sites: Cornelisse Shoal and Coxon Shoal

Cornelisse Shoal (COR) is part of a reef complex approximately 37 km north-west of the entrance to Port Hedland Harbour and 33 km offshore from the mainland. The site mooring is located on the top of the shoal at a depth of 9 m and begins at the crest of the shoal and follows the reef slope down to a maximum mid-tidal depth of 12.2 m. The site is in close proximity to the Port Hedland Harbour entrance channel and the water quality is therefore occasionally affected by shipping activity. Coral colonies are sparsely distributed. The site is predominantly abiotic (61%), with areas of hard corals (21%) and varying quantities of sponges (9%), macroalgae (5%) and soft corals (1%).

Coxon Shoal (COX) is part of a reef system approximately 24 km north-west of the entrance to Port Hedland Harbour and 28 km offshore from the mainland. The shoal is a low mound rising from a depth of 14 m at the mooring to 12 m with a mid-tidal depth of 13.5 m. The site is predominantly abiotic (73%), with patches of hard corals (22%) sponges (4%), soft corals (1%) and macroalgae (0.2%). Results from baseline coral monitoring indicated that the dominant hard coral taxa at five of the six sites were *Turbinaria* spp. However, at COR the most dominant hard coral taxa were *Acropora* spp. (**Figure 2-3**). The relative proportions of *Turbinaria* spp. at each site, where this genus dominated, ranged from 19% at WIS to 12% at MIB. The highest hard coral cover was recorded at CTH (32%) and the lowest at COR (14%). For a detailed summary of the baseline coral monitoring programme and all results to date see SKM (2009a).



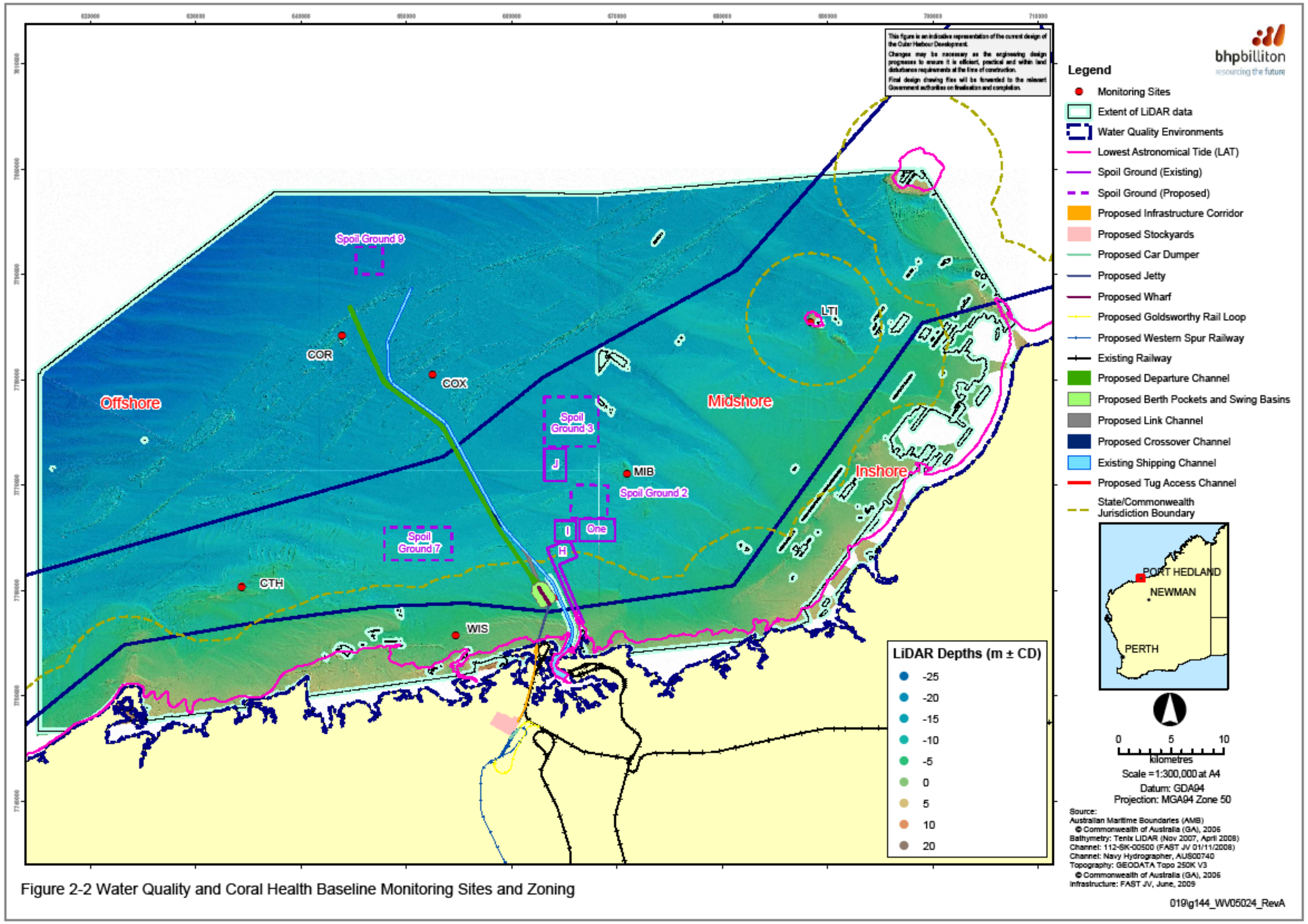
This figure is an indicative representation of the current design of the Outer Harbour Development.

Changes may be necessary as the engineering design progresses to ensure it is efficient, practical and within land disturbance requirements at the time of construction.

Final design drawing files will be forwarded to the relevant Government authorities on finalisation and completion.

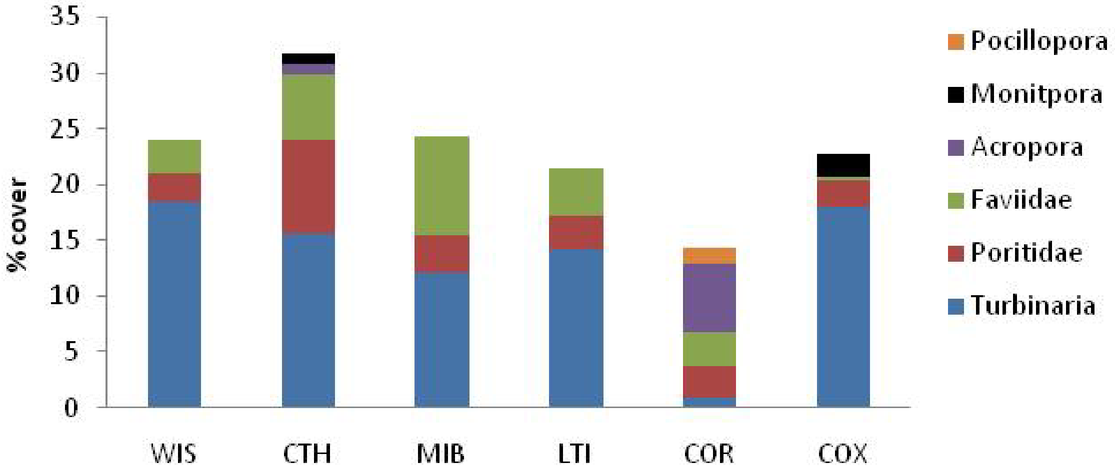
Source:
Australian Maritime Boundaries (AMB)
© Commonwealth of Australia (GA), 2006
Bathymetry: Tenix LIDAR (Nov 2007, April 2008)
Sampling: SKM (Various 2007 - 2008)
Topography: GEODATA Topo 250K V3
© Commonwealth of Australia (GA), 2006

- **Figure 2-1 Study area showing survey sites**



Source:
Australian Maritime Boundaries (AMB)
© Commonwealth of Australia (GA), 2006
Bathymetry: Tenix LIDAR (Nov 2007, April 2008)
Channel: 112-SK-00500 (FAST JV 01/11/2008)
Channel: Navy Hydrographer, AUS00740
Topography: GEODATA Topo 250K V3
© Commonwealth of Australia (GA), 2006
Infrastructure: FAST JV, June, 2009

- **Figure 2-2 Water Quality and Coral Health Baseline Monitoring Sites and Zoning**



Source: SKM 2009a

- **Figure 2-3 The percentage cover of the dominant coral taxa at the six monitoring sites determined via baseline coral monitoring**

2.3. Sampling Techniques and Equipment

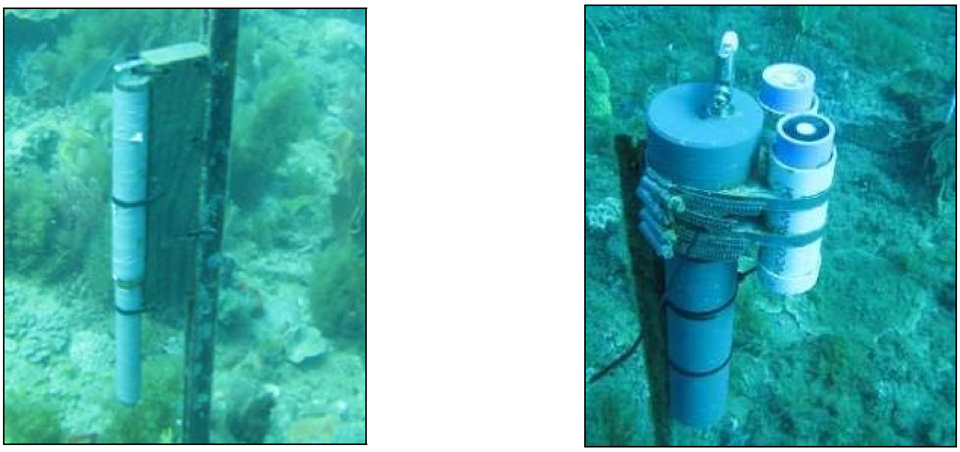
2.3.1. Light

Light was measured *in situ* every 30 minutes, 24 hours a day in units of photosynthetically active radiation, (PAR) µmoles/m^2/s, using an Odyssey Integrating Light Sensor, calibrated by In situ Marine Optics Pty Ltd (**Figure 2-4**). Eighteen Odyssey units were acquired. Three units were assigned to each site, with two deployed at any one time and one reserve unit for each site. A wiper unit cleaned the top of the light sensor every 30 minutes, offset from sensor measurement times, to remove any biofouling that may have otherwise obscured the sensor, such as algal and barnacle growth on the sensors. The wiper unit and loggers were mounted at the top of a star picket approximately 50 cm above the sea bed (at coral level). Logger calibration checks were undertaken periodically by In situ Marine Optics Pty Ltd. In early February 2009, additional loggers were added to each site to measure light attenuation. Light attenuation coefficients (LAC) were 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.

2.3.2. Turbidity and Temperature

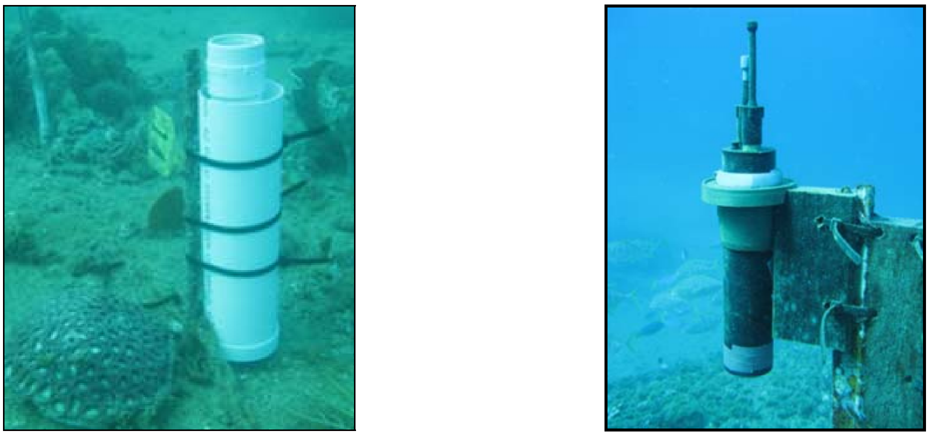
Turbidity, measured in nephelometric turbidity units (NTU), and temperature in degrees Celsius (°C) were recorded *in situ* every 30 minutes, 24 hours a day, using an ANALITE NEP 495 turbidity and temperature logger from June 2008 to June 2009. These devices were calibrated by the supplier, McVan Instruments, prior to deployment. They were set to log NTU on a range from 0 to

400 to prevent the loggers from becoming stuck on values just below 100 NTU and logging inaccurate values for continuous periods (hours). When required, further calibration checks are undertaken by the Marine and Freshwater Research Laboratory (MAFRL). From July 2009 to March 2010, WETLABS turbidity loggers were installed at each site and measured turbidity in NTU *in situ* every 30 minutes, 24 hours a day. The WETLABS loggers were intended to eventually replace the existing ANALITE loggers whilst also initially providing a data redundancy and comparison between the two loggers. All instruments were fixed by cable ties to a star picket embedded in the sea bed (**Figure 2-4**). The frequency of turbidity and temperature measurements was set to detect rapid changes and determine the duration of short term, non-periodic changes.



(a) ANALITE turbidity and temperature

(b) Odyssey light loggers



(c) Sediment trap

(d) WETLABS turbidity

- Figure 2-4 Water quality measurement instruments *in situ*

2.3.3. Sedimentation

Three replicate sediment traps were deployed at each site to measure gross sedimentation rates (mg/cm^2/day) and percentage of organic versus inorganic material (**Figure 2-4**). Gross sedimentation rate does not incorporate the removal of sediment by re-suspension. If re-suspension is regular, 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.

The sediment traps consisted of a piece of PVC tubing approximately 11.5 cm high with a diameter of 4.95 cm, sealed at the bottom and with a wire mesh covering over the top to prevent habitation by fish or invertebrates. The traps were placed inside larger PVC tubes that were cable tied to a star picket at ground level. This allowed for easy removal and deployment of the traps during water quality monitoring. Every fortnight the sediment traps were capped underwater and replaced with new traps. The capped traps were brought to the surface and emptied into sample containers. Sample containers were then transported to MAFRL for analysis.

Particle size distribution (PSD) data were collected from each site and from inside the sediment traps installed at each site. During April 2009, sediment samples from each site (taken from a depth of 2 cm) along with the sediment collected inside the traps from each site were sent to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for sediment particle sizing by laser diffraction. The sediment traps prevent the re-suspension of material once it has been collected inside the trap and therefore provides a direct example of the size of material that is initial deposited as a result of suspended material in the water column. The size of sediment particles collected in the traps were compared to sediment samples collected at each site in order to determine if the particles being deposited in the traps are similar or different from the particles in the immediate vicinity. This provides insight into the origin and fate of fine sediment susceptible to re-suspension.

2.4. Sampling Regime

The first water quality monitoring field trip was conducted on 28th May to 1st June 2008. Following this, subsequent water quality monitoring field trips were conducted on a fortnightly basis, coinciding with neap tides to ensure the safety of the dive team. During each fortnightly water quality field trip, instruments were exchanged, cleaned and maintained. This maintenance frequency prevented the loss of data due to unknown equipment failure and/or accumulated biofouling on the logger sensors and provided regular checks of the data.

During each field trip:

- one predetermined Odyssey light logger, a single ANALITE turbidity and temperature logger and three sediment traps were retrieved from each site;

- as of July 2009, one predetermined WETLABS turbidity logger was also retrieved from each site;
- retrieved loggers were cleaned and maintained to prevent biofouling of sensors and ensure accurate function;
- data were downloaded from the retrieved loggers and saved as text files;
- a different predetermined Odyssey light logger, ANALITE turbidity and temperature logger and WETLABS turbidity logger were deployed to replace the retrieved loggers and three new sediment traps were deployed; and
- the contents of retrieved sediment traps were sent to MAFRL for analysis.

2.5. Reporting

This report is a summary of all the baseline data collected to date from June 2008 to March 2010 and provides details of the methods used to collect, analyse and interpret the data for inclusion in the Public Environmental Review (PER)/ Environmental Impact Statement (EIS).

2.6. Data Analysis

Data analysis and interpretation were carried out as per the guidance provided by ANZECC & ARMCANZ (2000) on the procedures for water quality monitoring analysis and reporting. Prior to any analysis a preliminary check of the turbidity data integrity was undertaken. Marine data loggers, particularly turbidity, are susceptible to environmental influences which can result in unexplainable measurements, such as a fish or pieces of macroalgae floating past the sensor as it is making a measurement; or objects in the water column knocking the logger and disrupting internal components causing recording errors. To remove this surrounding ‘noise’ a function was applied to the data set that takes the average of two adjacent readings when the value in question is greater than two times either of the adjacent values. For details on techniques such as these see ANZECC & ARMCANZ (2000); Section 6.3.7. Following this the data set was treated for remaining outliers by scanning for any anomalous recordings outside the detectable range, prolonged identical and elevated readings or unexplained outliers that did not reflect neighbouring sites or meteorological data. When there were no rational explanations for specific outliers the decision was made to remove them based on the argument that these values were not likely representative of actual biological conditions. All omitted data were retained for quality assurance and quality control (QA/QC) measures. A description of the final percentage of data used in analyses can be inferred from **Section 3.1**.

Analyses were then performed on the 22 months of data for light, turbidity, temperature, sedimentation and PSD to investigated inter-annual and seasonal trends within the data sets. The processes described below provide an inspection of all results and help to identify trends, anomalies, periodicities and other phenomena. Results were interpreted in conjunction with tidal height, wind speed, air temperature, rainfall and cloud cover data from the Port Hedland Port Authority (PHPA) and Bureau of Meteorology (BoM).

2.6.1. Light

Raw light data (counts) were converted to PAR (µmoles/m^2/sec) by first dividing the raw counts by the scan time of the logger in seconds (30 x 60 = 1800) and then multiplying the result by the in water calibration coefficient for that particular logger. This result was then multiplied by 30 x 60 to provide an estimate of PAR for each 30 minute block (µmoles/m^2/30 min). The accumulated total amount of light per day (µmoles/m^2/day) was then calculated by summing the 48 PAR values from each half hour block in a day. Attenuation coefficients were calculated as the difference between the logarithm$_{10}$ of irradiance (I) values (or the PAR values of each the upper and lower loggers) and then divided by the distance between the two loggers (depth) according to the equation (adapted from Kirk 1977):

$$Attenuation\,coefficient = \frac{Log_{10} I(upper) - Log_{10} I(lower)}{Depth}$$

Sites with a similar water quality environment (inshore, mid-shore and offshore) were graphed together. Sample size, median, minimum, maximum, 20th percentile and 80th percentile were calculated for light (moles/m^2/day) and light attenuation (m^{-1}) at each site in each season of each year (dry 2008, wet 2008/2009, dry 2009 and wet 2009/2010).

The median is defined as the ‘middle’ value in a set of data such that half of the observations have values numerically greater than the median and half have values numerically less than the median. It is considered a robust estimator of central tendency because it is relatively unaffected by extremes in the data. The maximum, minimum, 20th percentile and 80th percentile values were calculated to summarise the spread of data. The 80th percentile represents the value at which 80% of all values are numerically less than or equal to and the 20th percentile represents the value at which 20% of all values are numerically less than or equal to.

2.6.2. Turbidity and Temperature

A daily median was calculated for turbidity and temperature from the 48 data points obtained during each day. Sites with a similar water quality environment (inshore, mid-shore and offshore) were graphed together.

Descriptive statistics (sample size, median, minimum, maximum, 20th percentile and 80th percentile) were calculated for turbidity (NTU) and water temperature (ºC) at each site in each season of each year, using the pre-treated data.

2.6.3. Sedimentation and PSD

Sedimentation data were analysed for total solids and per cent total loss on ignition at 550°C, representing the organic content, for each of the three sediment traps at each site. Following this, the mean sedimentation rate and standard deviation was calculated for each site using the sediment dry weight from each of the three traps and the trap diameter of 4.95 cm ($r = 2.475$ cm) and expressed as $mg/cm^2/day$ using the formulae:

$$Sediment\ Rate = \frac{\dfrac{\text{Sediment dry weight (mg)}}{\text{Area of trap } (\pi r^2)(\text{cm}^2)}}{\text{Duration of trap deployment (days)}}$$

As there were only three data points per fortnightly occasion per site, the mean was used in this case to take into account all the data available. If the median was used, only the central data point would be taken into account and in effect, data would be lost or not used. Thus, the sample size, mean and standard deviation were calculated for each site in each season of each year. The mean and standard deviation for each month were graphed for each site. Sites with a similar water quality environment (inshore, mid-shore and offshore) were graphed together.

In early May 2009 the material collected in the sediment traps was sent to CSIRO for PSD by laser diffraction. Three additional sediment samples were collected *in situ* from the substrate adjacent to the sediment traps at each site and were also sent to the laboratory for PSD. The particle sizes were grouped according to categories based on sediment size classifications and defined by settling behaviour (Graeme Hubbert pers. comm.; **Table 2.2**).

- **Table 2.2 Particle size distribution groupings based on sediment size classifications and defined by settling behaviour**

Category	Settling Behaviour	Size Fraction
Clay	Will not settle out of the water column until they are well offshore in very deep water, where the hydrodynamic conditions do not continually resuspend the particles	0–5 µm
Silt to very fine sand	Will drop out of suspension over distances ranging from 10 km to 100 m respectively	6–149 µm
Fine to medium sand	Will drop out of suspension over distances ranging from 100 m to 10 m respectively	150–499 µm
Coarse sand to gravel	Will drop out immediately at the point of release	> 500 µm

Source: Graeme Hubbert, pers comm.

3. Results and Interpretations

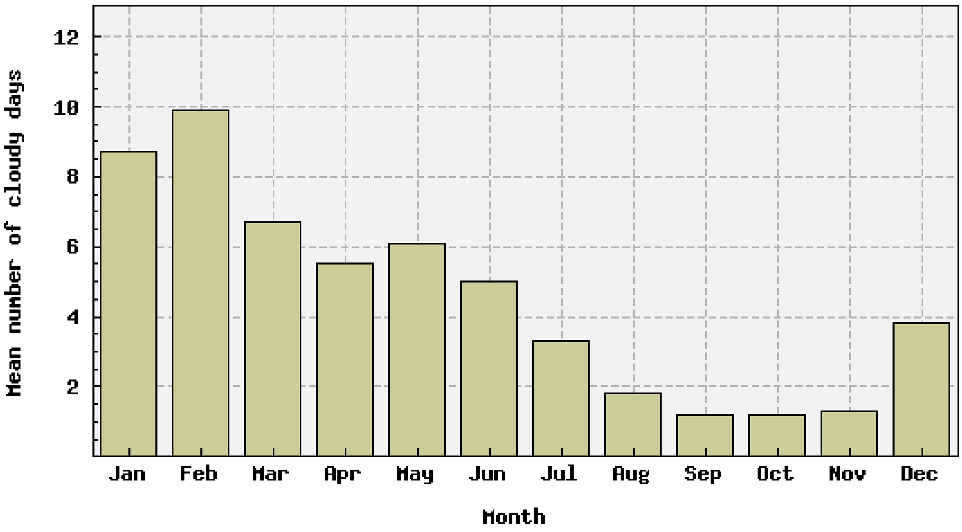
3.1. Limitations

Limitations on field work, such as equipment reliability, biofouling of the sensors, weather conditions and access can potentially have an effect on the quality of data obtained. In particular, marine data loggers are susceptible to environmental influences which can result in unexplainable measurements, such as fish and macroalgae floating past the sensor and/or objects in the water column knocking the logger and disrupting internal components can lead to potentially erroneous data and data being omitted. Those limitations experienced so far during baseline monitoring are listed below.

- Sediment traps during the survey (21st January to 7th February 2009) at Weerdee Reef were found to be completely full, thus, it cannot be assumed that this value represented the maximum rate of sedimentation but rather it was relative compared with the other five sites.
- There was a 3.5% total loss of turbidity data among all sites throughout this study to date. Specifically, there was a 3.9% loss of data from the inshore site, a 2.1% loss from the mid-shore sites, and a 5.6% loss from the offshore sites. These data were lost due to equipment failure or unexplained high readings. Readings greater than 100 NTU were removed.
- There was a 4.3% total loss of temperature data among sites due to logger malfunctions. Specifically, there was a 3% loss of data from the inshore site, a 3.4% loss from the mid-shore sites, and a 6.2% loss from the offshore sites.
- A total of 6.5% of the light data was lost in this study due to flooded loggers and logger malfunctions. There was a 14.3% loss of data from the inshore site, a 6.6% loss from the mid-shore sites, and a 2.5% loss from the offshore sites.

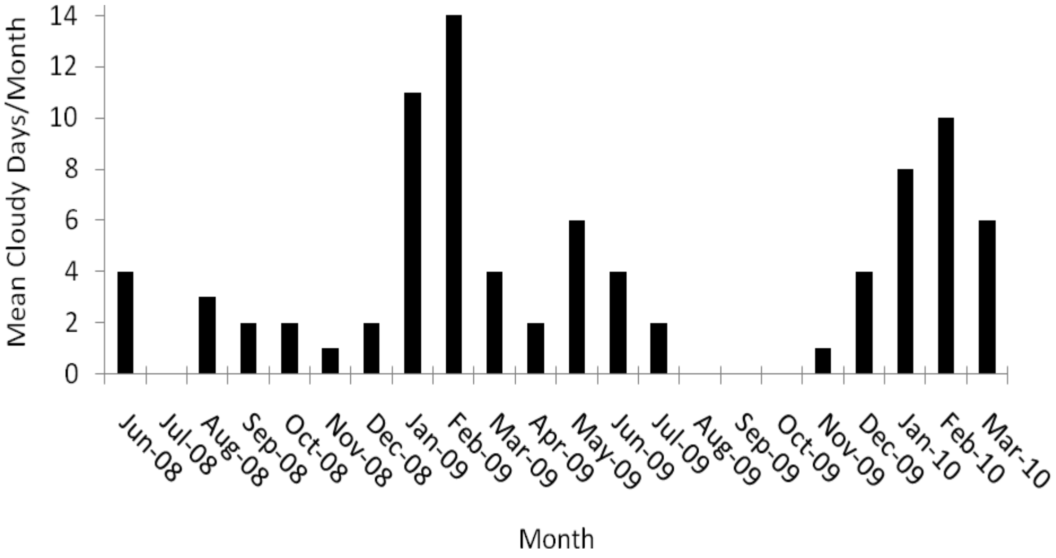
3.2. Meteorological and Tide Data

Port Hedland is in a tropical area and the seasons are more appropriately viewed as a “wet” season and a “dry” season. The dry seasons are characterised by lower sedimentation rates, lower turbidity events, lower water temperatures and high light levels due to lack of clouds, despite less light hours (**Figure 3-1** and **Figure 3-2**). The wet seasons are characterised by high water temperatures and sequential high sedimentation and turbidity events due to the passage of periodic storms and cyclones producing increased wind speeds (**Figure 3-3**). In years where these events are relatively frequent (inter-annual variation in rainfall is high) there may be a lower overall light climate. For the purposes of this report the dry season was defined from May to October and the wet season was defined from November to April.



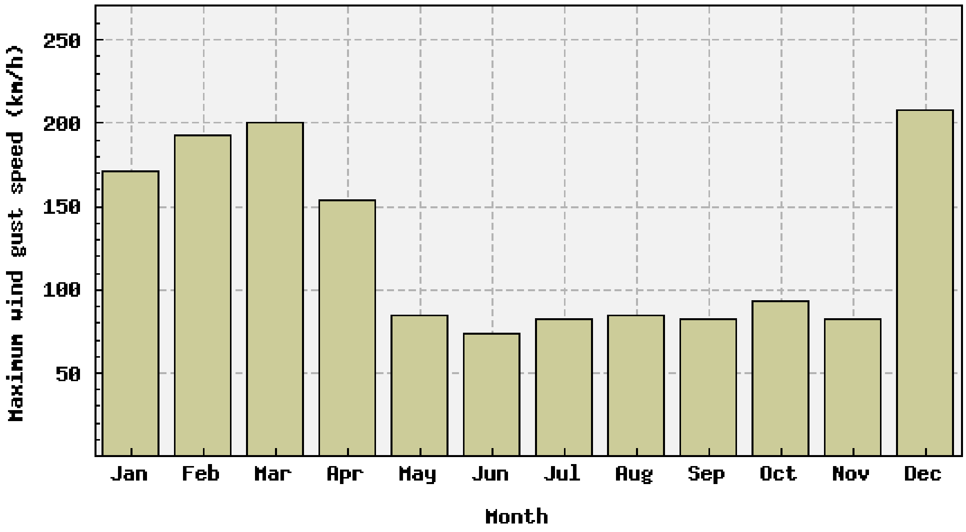
(Source: BoM 2011, Port Hedland Airport)

- **Figure 3-1 Monthly mean number of cloudy days at Port Hedland averaged from 1942 to 2010**



- **Figure 3-2 Mean number of cloudy days per month at Port Hedland from June 2008 to March 2010**

(Source: Mean data determined from okta recordings taken by BoM)



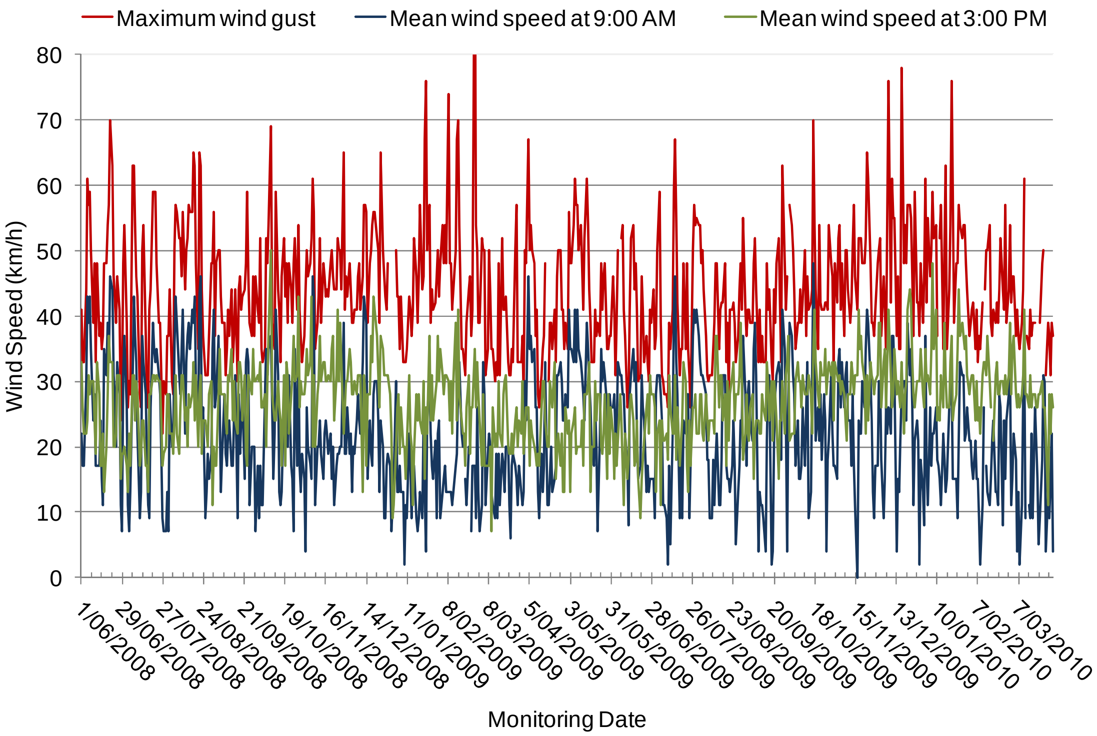
(Source: BoM 2011, Port Hedland Airport)

- **Figure 3-3 Monthly maximum wind gusts (km/h) at Port Hedland averaged from 1954 to 2010**

The greatest cloud cover in Port Hedland recorded during baseline monitoring was in January and February during the passing of tropical cyclones associated with the wet season (**Figure 3-2**). This statistic is derived from cloud cover observations, which are measured in oktas (eighths). The sky is visually inspected to produce an estimate of the number of eighths of the dome of the sky covered by cloud. A completely clear sky is recorded as zero okta, while a totally overcast sky is 8 oktas. The presence of any trace of cloud in an otherwise blue sky is recorded as 1 okta, and similarly any trace of blue on an otherwise cloudy sky is recorded as 7 oktas. A cloudy day is recorded when the mean of the 9 am and 3 pm cloud observations is greater than or equal to 6 oktas.

The windiest conditions in the Port Hedland region were generally experienced in the wet season. During this time, west and north-westerly winds dominate (**Appendix A**). In general, westerly winds were dominant in the morning, shifting to north-westerly in the afternoon, with an increase in speed from morning to afternoon (**Figure 3-4**).

During baseline monitoring five significant tropical cyclones occurred within the Port Hedland region, they are summarised in **Summary** of tropical cyclones which occurred within the Port Hedland region .

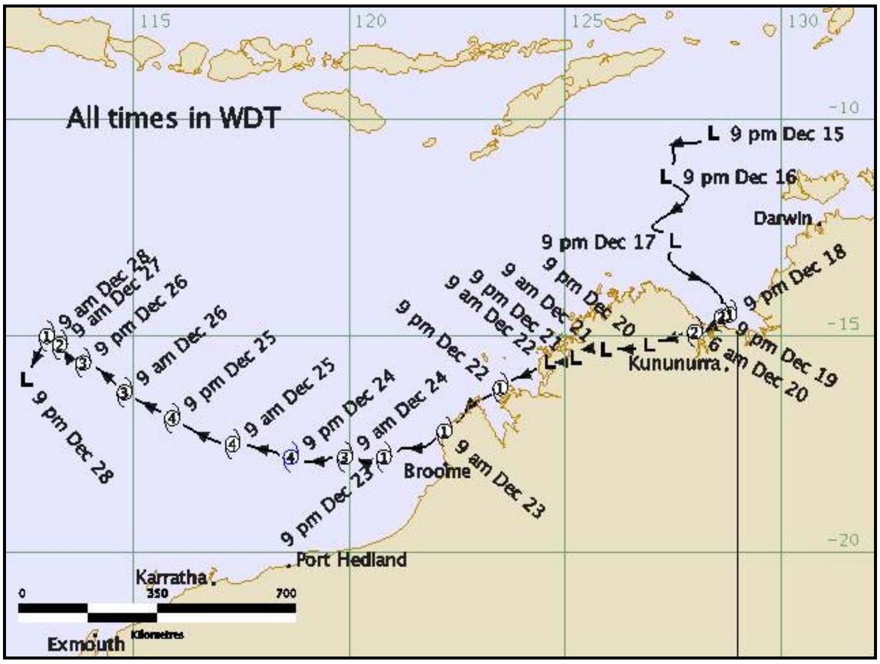


- **Figure 3-4 Maximum wind gusts, mean wind speed at 9:00 am and mean wind speed at 3:00 pm (km/h), from June 2008 to March 2010**

(Source:BoM, Observations were drawn from Port Hedland Airport)

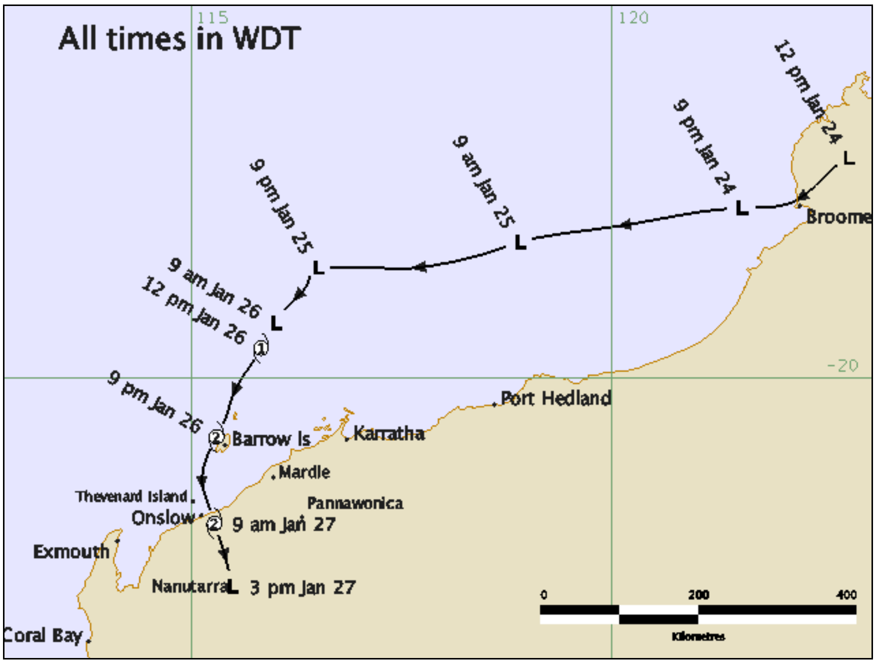
- **Table 3.1 Summary of tropical cyclones which occurred within the Port Hedland region**

Cyclone	Figure	Date when closest to Port Hedland	Location when closest to Port Hedland	Category	Maximum recorded wind gusts	Maximum wind gusts at Port Hedland
Billy	**Figure 3-5**	23rd–24th December 2008	280 km north of Port Hedland	Four	250 km/h	65 km/h
Dominic	**Figure 3-6**	24th–25th January 2009	300 km west-north-west of Port Hedland	Two	140 km/h	55 km/h
Freddy	**Figure 3-7**	5th–7th February 2009	1000 km west-north-west of Port Hedland	Two	130 km/h	50 km/h
Laurence	**Figure 3-8**	21st-22nd December 2009	230 km north east of Port Hedland	Four	285 km/h	50 km/h
Magda	**Figure 3-9**	19th-24th January 2010	700 km north east of Port Hedland	Three	185	50 km/hr



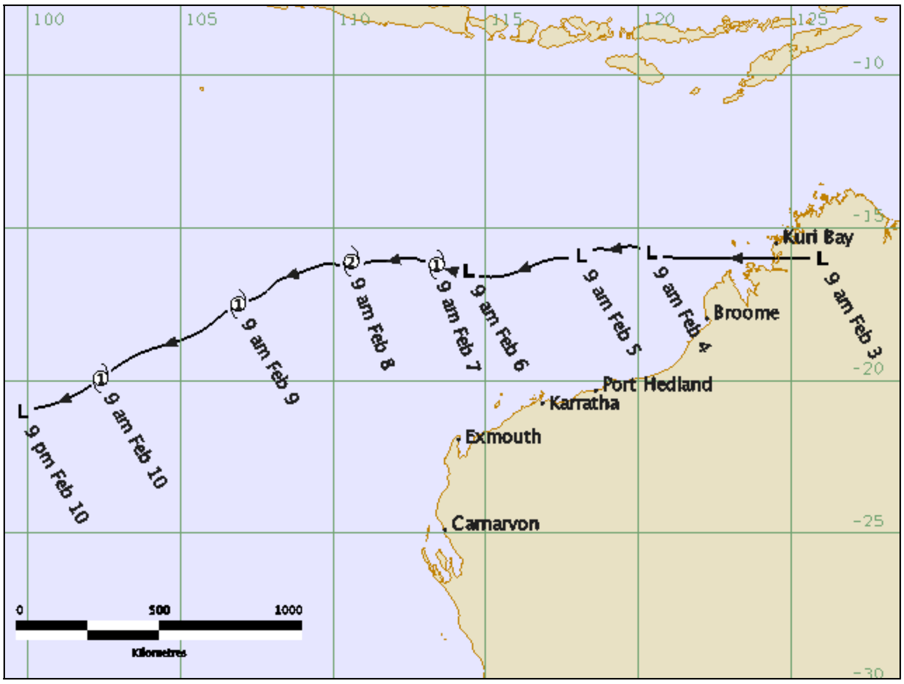
■ **Figure 3-5 Tropical cyclone Billy, December 2008**

(Source: BoM 2009)



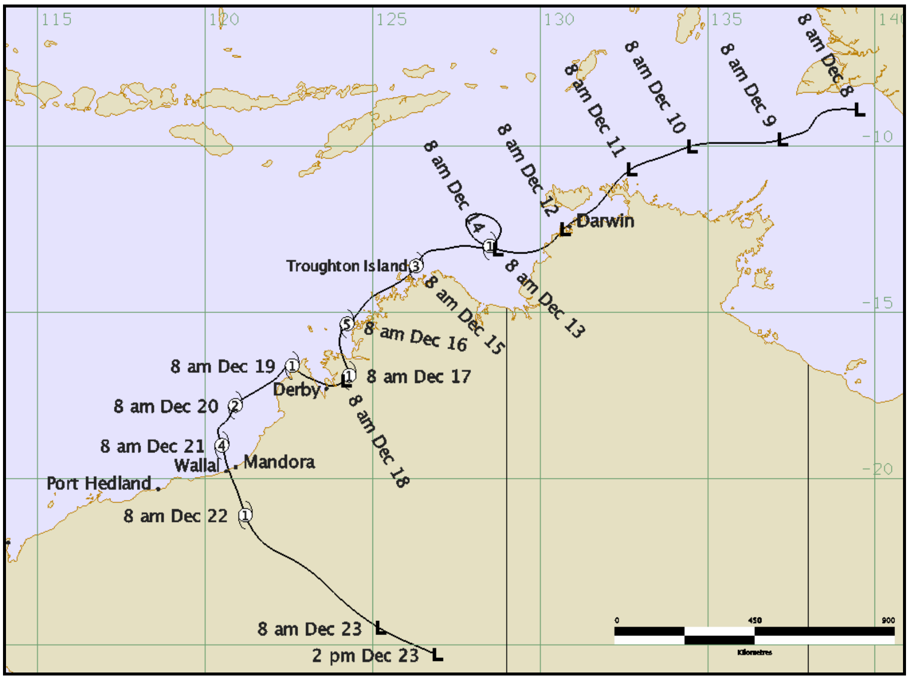
■ **Figure 3-6 Tropical cyclone Dominic, January 2009**

(Source: BoM 2009)



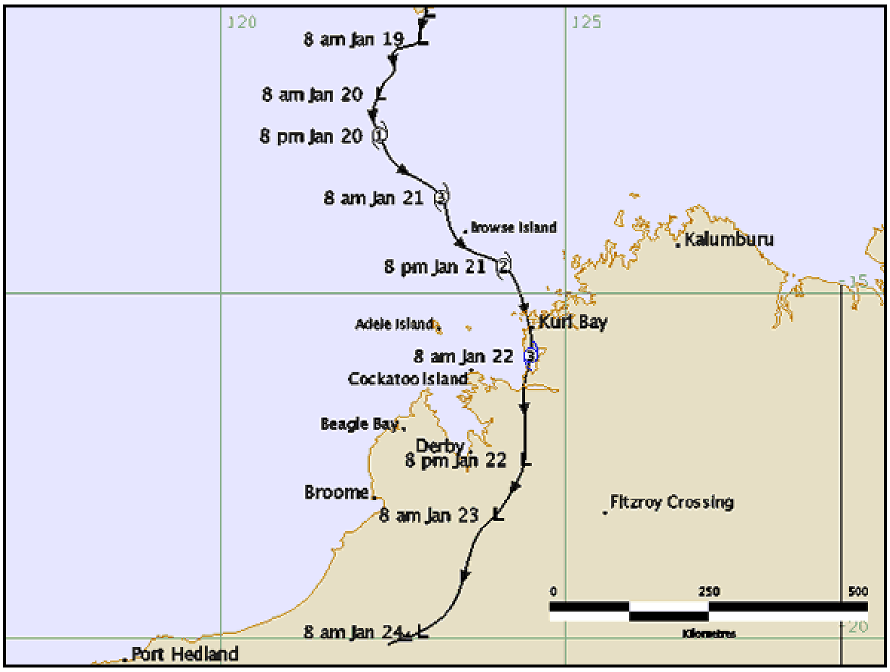
- **Figure 3-7 Tropical cyclone Freddy, February 2009**

(Source: BoM 2009)



- **Figure 3-8 Tropical cyclone Laurence, December 2009**

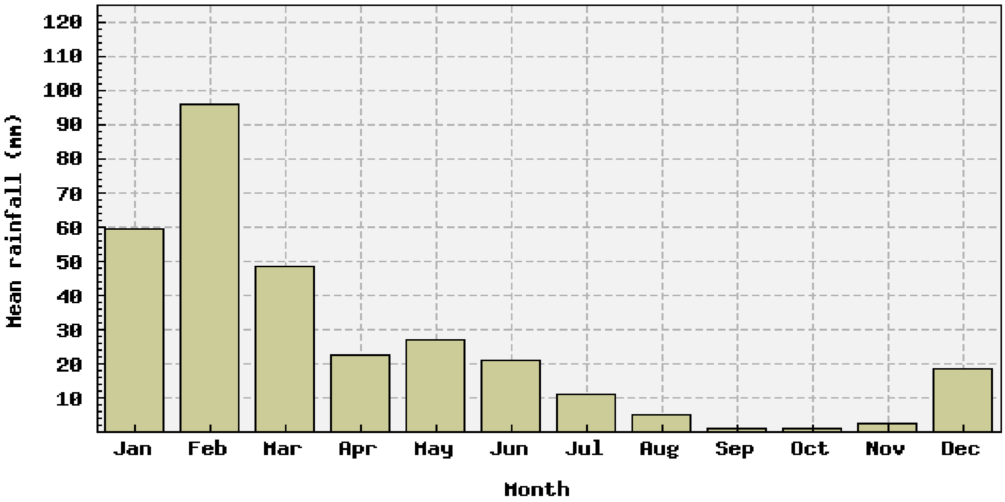
(Source: BoM 2011)



- **Figure 3-9 Tropical cyclone Magda, January 2010**

(Source: BoM 2011)

The majority of rainfall in the Port Hedland region occurs during the wet season (**Figure 3-10**) and is generally associated with scattered thunderstorms and tropical cyclones (BoM 2011). The total amount of rainfall which occurred during baseline monitoring was 431.6 mm.



- **Figure 3-10 Monthly mean rainfall (mm) at Port Hedland averaged from 1942 to 2010**

(Source: BoM 2011, Port Hedland Airport)

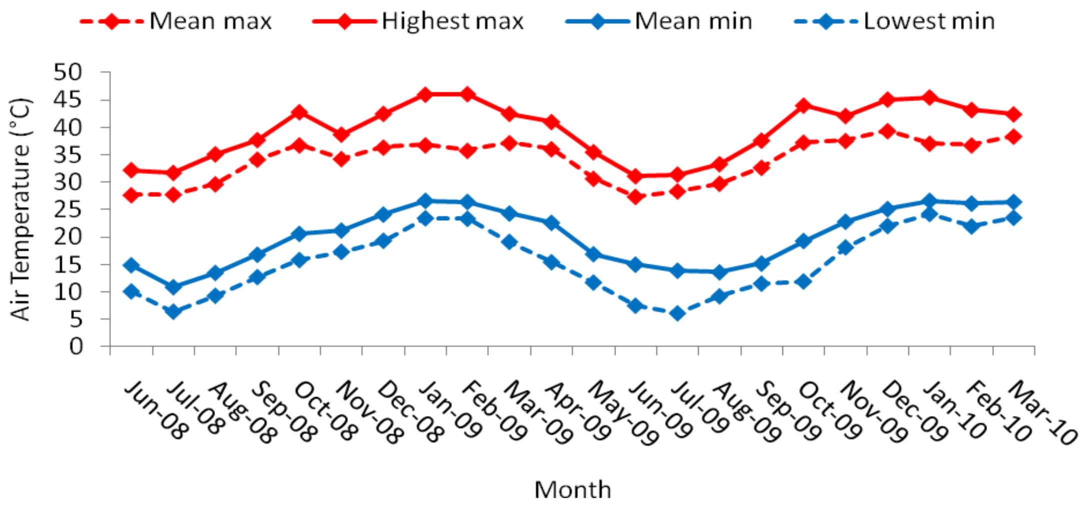
- **Table 3.2 Recorded rainfall at Port Hedland from June 2008 to March 2010**

Date	Rainfall (mm)
June – December 2008	82
January –December 2009	317
January – March 2010	32.6

(Source: BoM 2011, Port Hedland Airport)

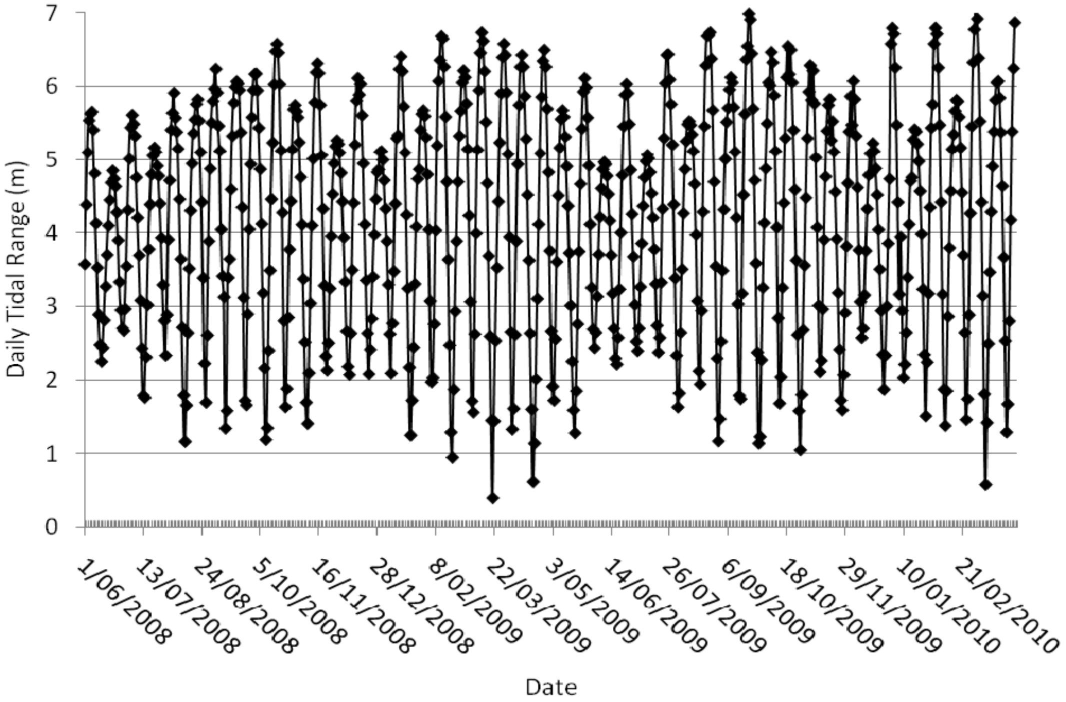
The average monthly maximum and minimum as well as the highest and lowest air temperature recorded for the wet and dry seasons are shown in (**Figure 3-11**). Seasonal air temperature was highest during the first half of the wet season and lowest during the first half of the dry season. The average maximum and highest maximum air temperatures decreased in November before increasing again to January (**Figure 3-11**).

The Port Hedland region is characterised as a macro-tidal environment as the tidal range can exceed four metres, with the potential to reach a maximum of eight metres during cyclone events (PHPA 2008). During baseline monitoring daily tides ranged from 0.4 m during neap tides to 6.7m during spring tides (**Figure 3-12**).



- **Figure 3-11 Seasonal air temperature from June 2008 to March 2010 for the Port Hedland Region**

(Source: BoM 2011)



- **Figure 3-12 Daily tidal range during at Port Hedland from June 2008 to March 2010**

(Source: Port Hedland Port Authority and BoM)

3.3. Light

3.3.1. Total Daily Light

The light climate of the six sites varied spatially between sites and temporally between and within sites during baseline monitoring. Light was the most variable at the inshore site Weerdee Reef (**Table 3.3**).

Median light was greatest in the dry season 2008 and lowest during the wet season 2009/2010 (**Table 3.3**). Median light also differed between the years with 2008 having generally higher light conditions than 2009, although for both years the dry season had a greater light climate than the subsequent wet season. Factors controlling the total amount of light available during a day include cloud cover, the angle of the sun, sea state and light scattering caused by material dissolved and suspended in the water column. During the wet season there is generally more cloud cover associated with storms and cyclones (**Figure 3-2**) and greater wind speeds which increase wave height. These factors combined can potentially reduce the light climate.

- **Table 3.3 Descriptive statistics for light (moles/m^2/day) at each of the six monitoring sites for each season in each year**

Site Name	Dry Season 2008						Wet Season 2008/2009					
	n	Median	Min	Max	20%ile	80%ile	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	153	7.64	1.14	20.85	4.64	12.51	180	5.54	0.02	16.13	1.90	9.47
Cape Thouin	147	7.23	1.15	13.68	4.34	10.13	155	6.74	0.02	13.62	4.18	10.54
Minilya Bank	141	4.21	0.34	9.40	2.28	5.71	180	2.85	0.00	9.63	1.22	5.60
Little Turtle Island	153	2.52	0.06	8.23	0.80	4.93	180	2.31	0.00	10.07	0.92	4.66
Cornelisse Shoal	153	6.44	1.48	11.26	4.31	7.97	181	4.13	0.39	9.51	2.53	5.93
Coxon Shoal	153	4.99	1.31	8.47	3.59	6.38	170	3.01	0.24	8.77	1.19	5.70
	Dry Season 2009						Wet Season 2009/2010					
	n	Median	Min	Max	20%ile	80%ile	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	131	4.72	0.00	12.76	2.38	6.63	104	3.20	0.01	15.07	1.37	6.97
Cape Thouin	168	4.74	0.22	8.09	3.17	5.96	128	3.33	0.04	9.32	1.27	5.17
Minilya Bank	142	3.88	0.85	8.38	2.36	4.92	129	2.14	0.06	8.09	1.23	3.41
Little Turtle Island	172	1.53	0.05	4.80	0.44	2.87	146	1.31	0.01	8.24	0.48	2.69
Cornelisse Shoal	175	4.35	0.63	7.99	3.37	6.14	146	3.10	0.20	5.73	1.73	4.43
Coxon Shoal	166	2.92	0.09	9.01	1.81	4.72	130	2.11	0.13	9.48	0.94	3.28

3.3.1.1. Inshore Environment

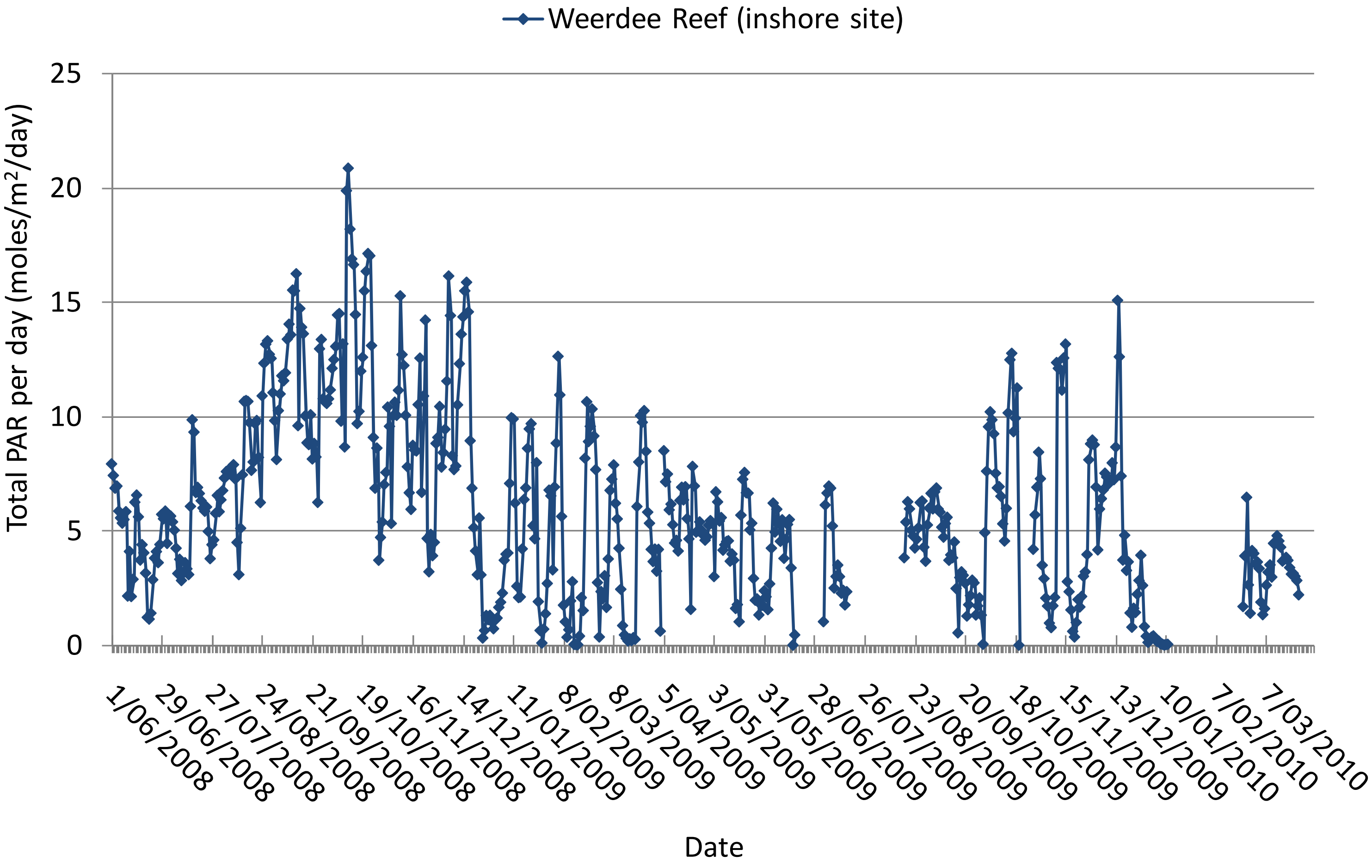
The light climate at Weerdee Reef fluctuated on a daily basis and had the greatest range compared to the remaining five sites (**Figure 3-13).** There appeared to be no regular pattern that coincided with the tidal phase (**Figure 3-12**). Light decreased from the dry season to the wet season when there was high cloud cover and increased storm surge and winds associated with the tropical cyclone events (**Figure 3-2** and **Table 3.1**).

3.3.1.2. Mid-shore Environment

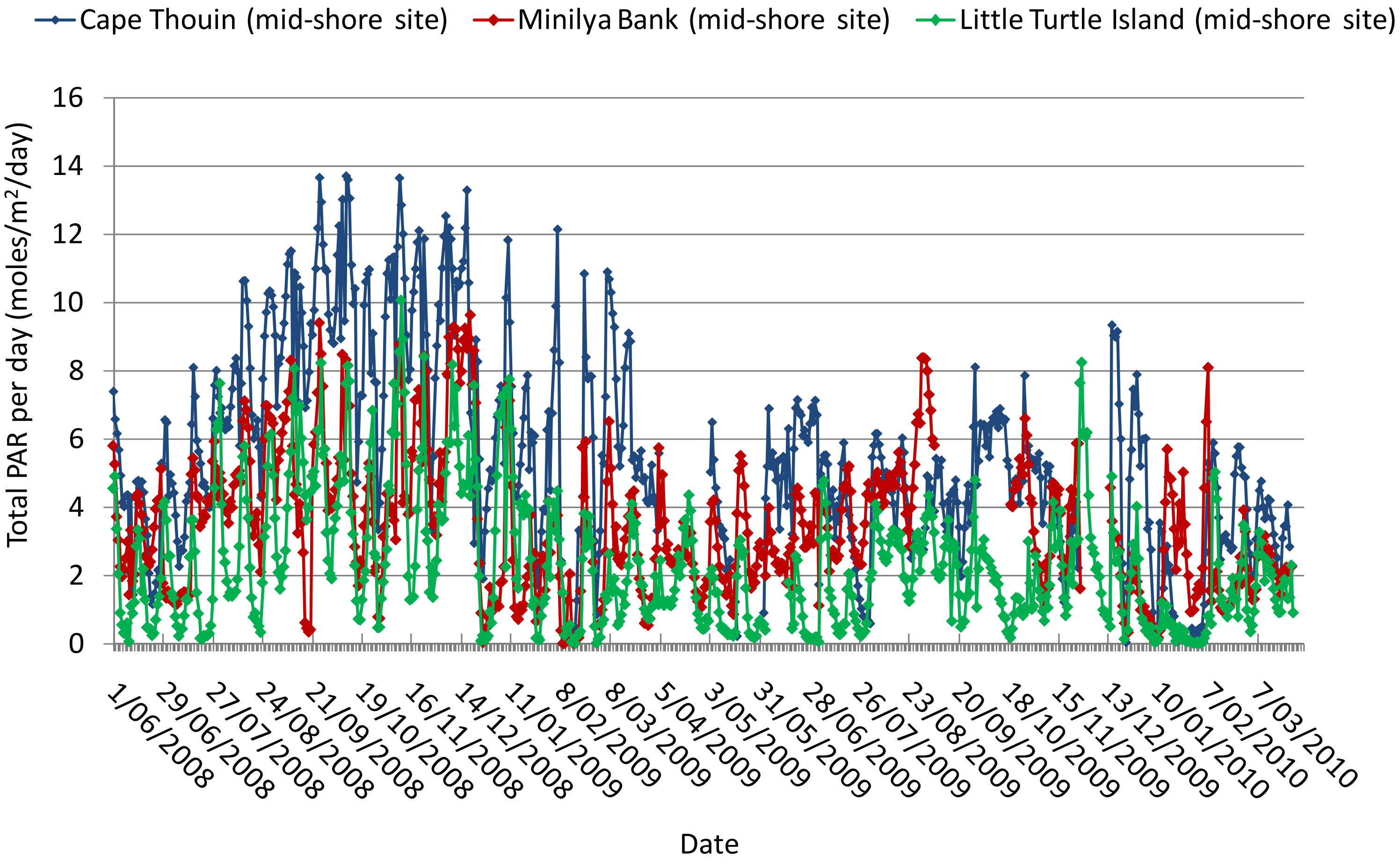
Daily light at the mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island followed a regular oscillating pattern that coincided with the tidal regime (**Figure 3-12** and **Figure 3-14**). Low light levels occurred during spring tides and high light during neap tides. During neap tides light levels frequently fell below 1.0 moles/m^2/day at Little Turtle Island and occasionally at Minilya Bank. Light levels were lowest during wet season when there was high cloud cover and increased storm surge and winds associated with the tropical cyclone events (**Figure 3-2** and **Table** 3.1).

3.3.1.3. Offshore Environment

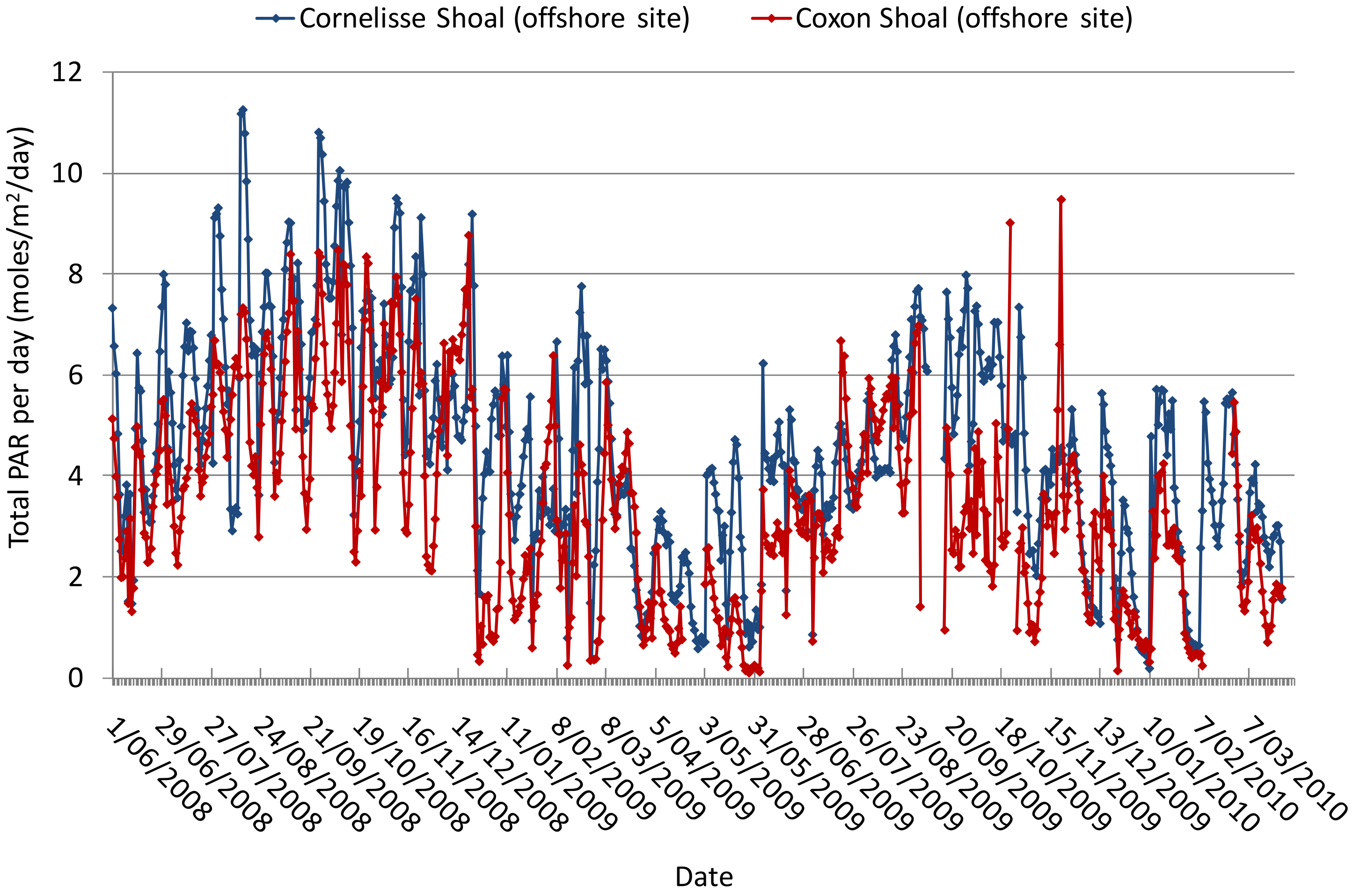
Daily light at the offshore sites Cornelisse Shoal and Coxon Shoal was relatively constant and had the lowest range compared to the remaining four sites (**Figure 3-15**). There was a regular oscillating pattern at both sites that coincided with the tidal regime (**Figure 3-12**). Low light levels occurred during spring tides and high light during neap tides. The lowest light levels at both sites occurred during the wet season, as seen at the remaining four sites when there was high cloud cover and increased storm surge and winds associated with the tropical cyclone events (**Figure 3-2** and **Table 3.1**).



- **Figure 3-13 Daily light at the inshore monitoring site Weerdee Reef**



- **Figure 3-14 Daily light at the mid-shore monitoring sites Cape Thouin, Minilya Bank and Little Turtle Island**



- **Figure 3-15 Daily light at the offshore monitoring sites Cornelisse Shoal and Coxon Shoal**

3.3.2. Light Attenuation Coefficient

Light attenuation coefficient (LAC) is a measure of water clarity, where the higher the LAC the lower the water clarity or for the marine environment, the greater number of particles suspended in the water column. Measurement of LAC was introduced later in the programme therefore there were no dry season 2008 data. Generally for all seasons where LAC was measured, Weerdee Reef had the most suspended particles while Cornelisse Shoal had the clearest water with the least suspended particles (**Table 3.4**).

- **Table 3.4 Descriptive statistics for light attenuation at each of the six monitoring sites for each season in each year**

Site Name	Wet Season 2008/2009					
	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	71	0.2	0.1	1.0	0.16	0.61
Cape Thouin	52	0.07	0.02	0.49	0.05	0.13
Minilya Bank	71	0.11	0.0006	1.17	0.06	0.21
Little Turtle Island	79	0.11	0.0008	0.71	0.05	0.20
Cornelisse Shoal	67	0.08	0.0007	0.64	0.03	0.13
Coxon Shoal	71	0.12	0.03	0.49	0.07	0.28
	Dry Season 2009					
	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	50	0.2	0.1	1.2	0.16	0.38
Cape Thouin	138	0.09	0.02	0.52	0.06	0.12
Minilya Bank	102	0.05	0.001	0.2111	0.04	0.07
Little Turtle Island	136	0.11	0.008	0.52	0.05	0.20
Cornelisse Shoal	132	0.04	0.003	0.11	0.02	0.07
Coxon Shoal	108	0.05	0.002	0.32	0.02	0.17
	Wet Season 2009/2010					
	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	88	0.3	0.1	0.6	0.19	0.39
Cape Thouin	75	0.07	0.0003	0.34	0.03	0.14
Minilya Bank	118	0.13	0.04	0.52	0.08	0.24
Little Turtle Island	95	0.14	0.008	0.89	0.06	0.38
Cornelisse Shoal	75	0.05	0.0002	0.27	0.03	0.10
Coxon Shoal	70	0.15	0.03	0.34	0.09	0.2

Data collected from the 8th February 2009

3.3.2.1. Inshore Environment

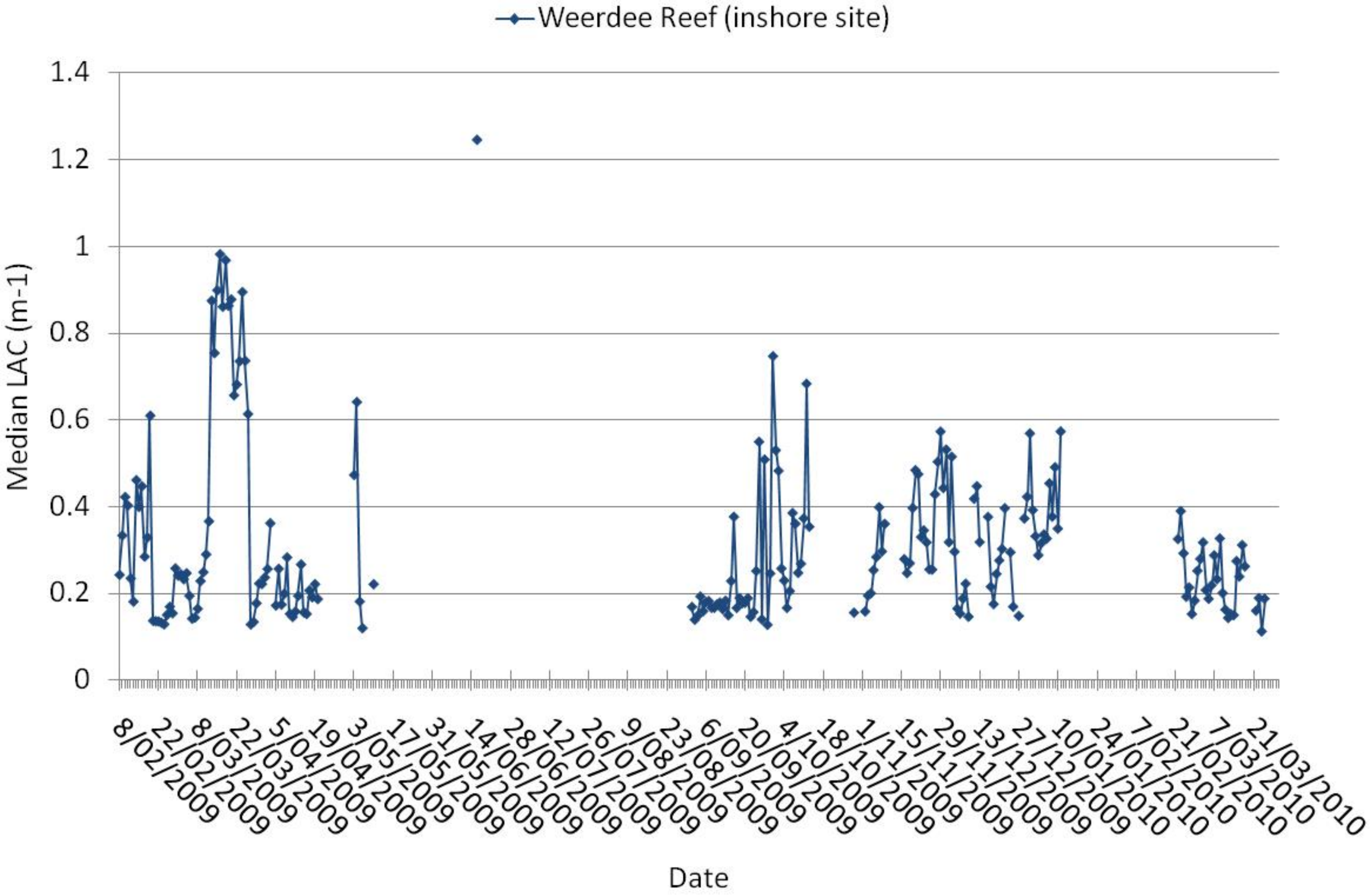
The inshore site of Weerdee Reef had the greatest range of light attenuation data over the monitoring period, compared with the other five sites (**Figure 3-16**) and the most variable. The highest light attenuations generally occurred during the wet season and coincided to strong winds and high turbidity events (**Figure 3-19**).

3.3.2.2. Mid-Shore Environment

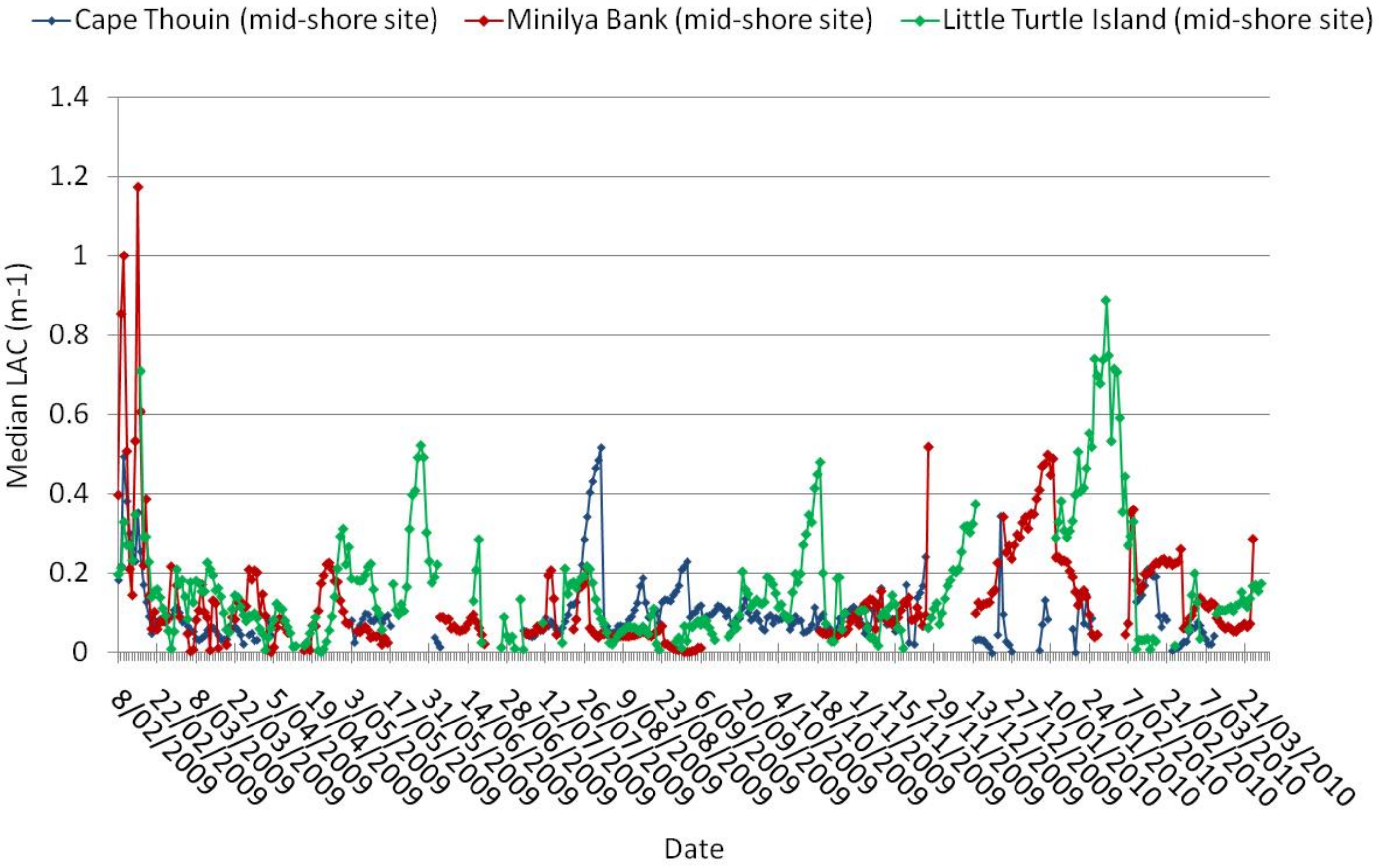
Of the mid-shore sites, the greatest range of light attenuation data occurred at Minilya Bank while the light attenuation at Little Turtle Island was the most variable (**Figure 3-17**). The highest light attenuation at each site appeared to correspond to the passing of tropical cyclone Freddie in early February 2009 (**Figure 3-7**). During this time mean wind speeds increased to over 40 km/h (**Figure 3-4**) and there was an increase in turbidity (**Figure 3-16**). The light attenuation at Little Turtle Island was also high in January 2010 when there were strong predominantly north westerly winds.

3.3.2.3. Offshore Environment

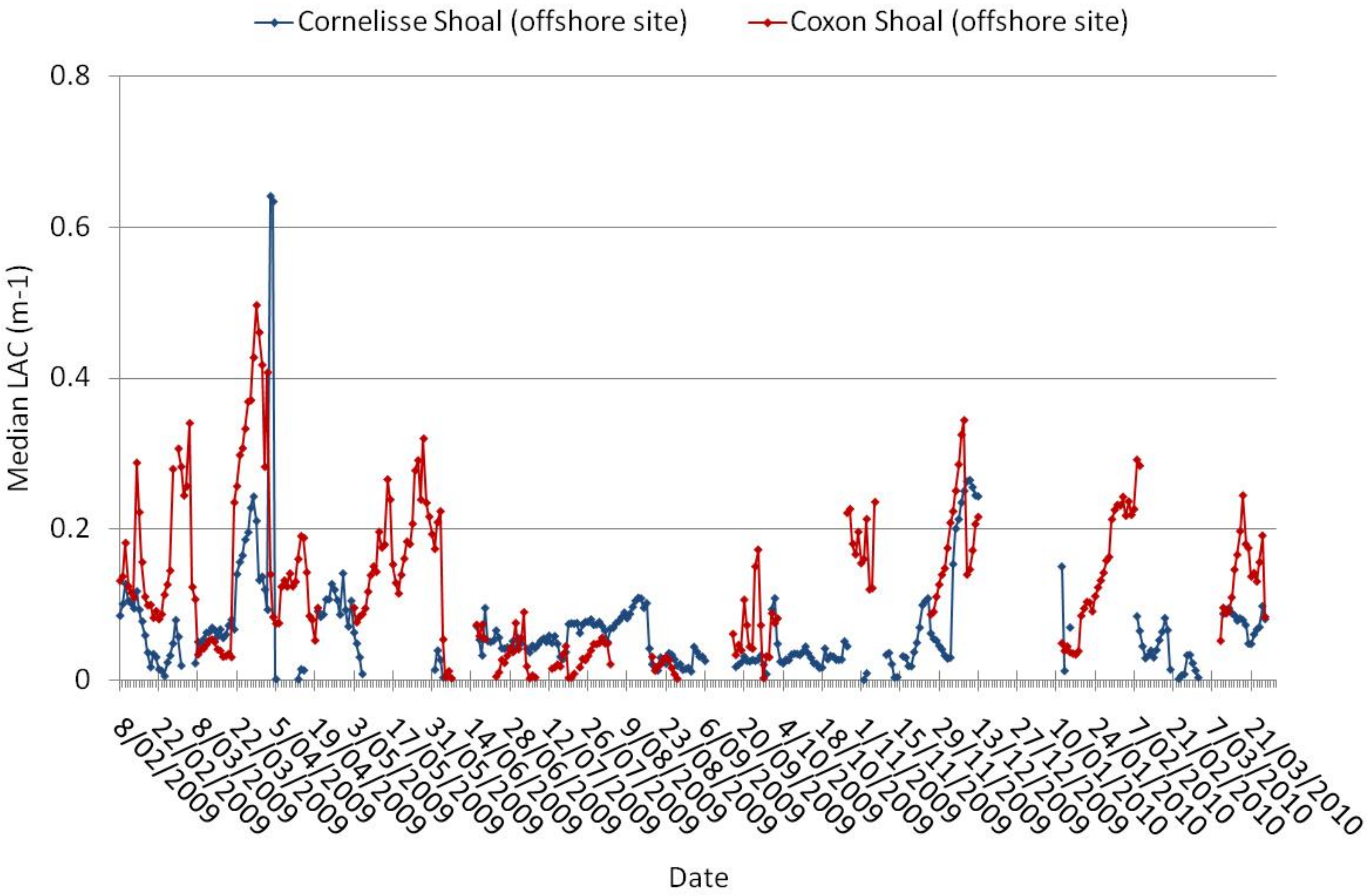
The light attenuation coefficients from Cornelisse Shoal had the smallest range and the least variability (**Figure 3-18**) compared with the other five sites. High wind events did not appear to affect the offshore sites to the same extent as the inshore and mid-shore sites.



- **Figure 3-16 Median light attenuation coefficients for the inshore site Weerdee Reef**



- **Figure 3-17 Median light attenuation coefficients for the mid-shore sites Little Turtle Island, Cape Thouin and Minilya Bank**



- **Figure 3-18 Median light attenuation coefficients for the offshore sites Coxon Shoal and Cornelisse Shoal**

3.4. Turbidity

Turbidity data varied spatially between sites and temporally between and within sites during baseline monitoring. Median turbidity (NTU) was low at all sites over the baseline monitoring period (less than 2 NTU) and for all seasonal periods (except the wet season 2008/2009) 80% of data from the offshore sites were still less than 1 NTU, while the mid-shore sites 80% of data was less than 2 NTU and at the inshore site less than 4.6 NTU (**Table 3.5**). During the wet season 2008/2008 the range of turbidity data was much higher at all sites.

Generally the range of data was higher during the wet season than the dry season for each site (**Table 3.5**). This was to be expected since background levels of turbidity within the Pilbara are generally higher during the summer months (wet season) due to storms and cyclones (Gilmour *et al*. 2006).

- **Table 3.5 Descriptive statistics for turbidity (NTU) at each of the six monitoring sites for each season in each year**

Site Name	Dry Season 2008						Wet Season 2008/2009					
	n	Median	Min	Max	20%ile	80%ile	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	6912	1.2	0	105	0.5	4.6	7247	1.8	0	124	0.4	9.8
Cape Thouin	7341	0.6	0	64	0.3	1.4	7460	1.3	0	114	0.4	11.0
Minilya Bank	7306	0.8	0	294	0.5	1.3	8315	1.8	0	154	0.8	9.9
Little Turtle Island	7335	1.9	0	99	0.9	4	7668	1.8	0.1	100	0.8	4.7
Cornelisse Shoal	5934	0.4	0	83	0.2	0.9	7615	0.6	0	123	0.3	1.4
Coxon Shoal	7043	0.4	0	81	0.2	0.6	7191	0.8	0	204	0.3	5.7
	Dry Season 2009						Wet Season 2009/2010					
	n	Median	Min	Max	20%ile	80%ile	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	7968	0.7	0	59.5	0.4	1.4	6659	1.1	0.04	119.9	0.5	4.5
Cape Thouin	8818	0.4	0	11.0	0.2	0.7	6820	0.6	0.01	16.8	0.3	1.6
Minilya Bank	8771	0.6	0	225.0	0.4	0.9	6988	0.7	0.01	54.3	0.5	1.4
Little Turtle Island	8003	1.0	0	99.2	0.6	2.1	6713	0.9	0.1	157.2	0.5	1.8
Cornelisse Shoal	6312	0.2	0	69.7	0.2	0.3	6985	0.3	0.1	4.9	0.2	0.5
Coxon Shoal	8822	0.3	0	78.0	0.2	0.4	6935	0.4	0.1	7.3	0.3	0.6

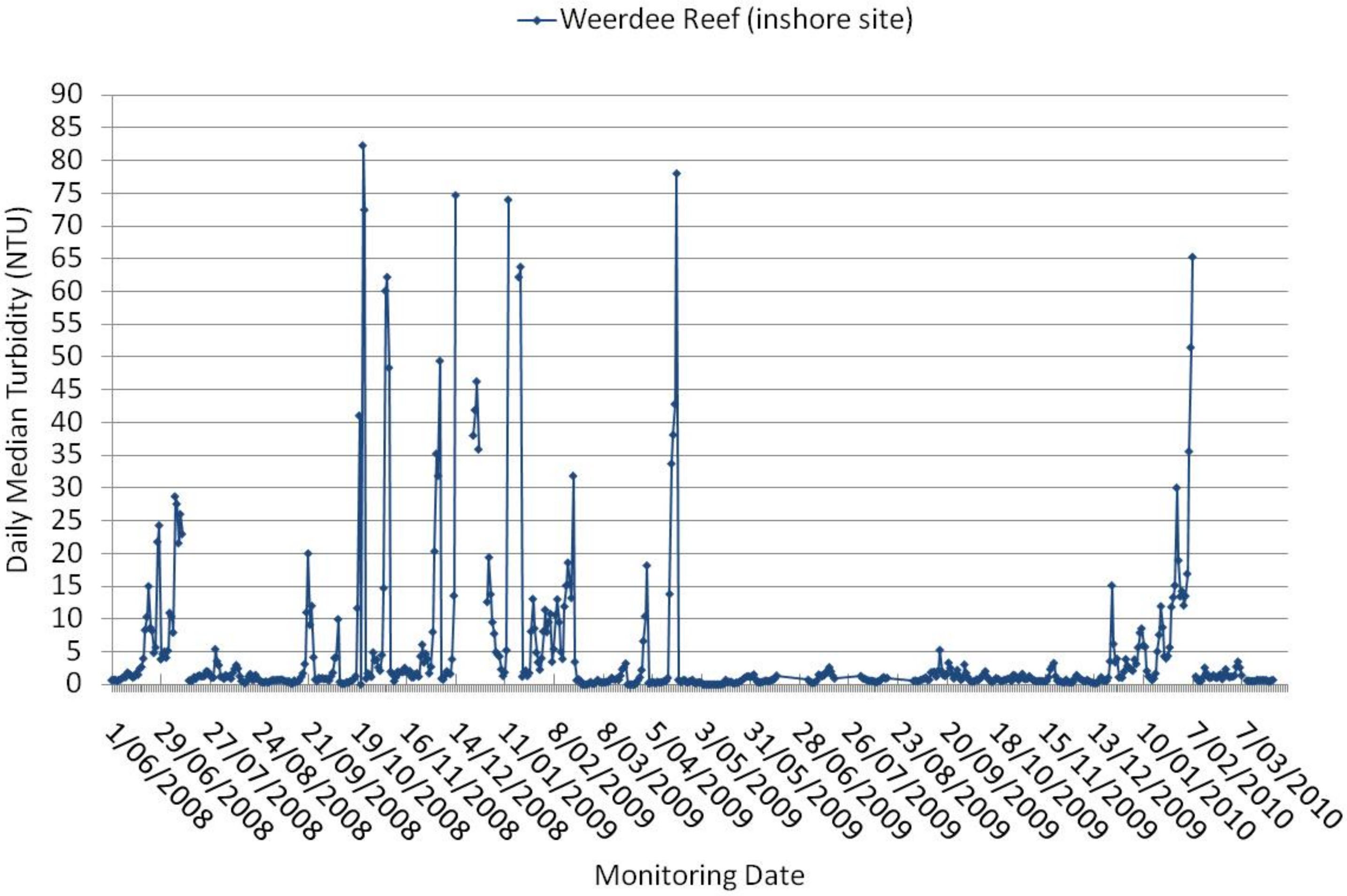
3.4.1. Inshore Environment

Daily median turbidity at the inshore site Weerdee Reef fluctuated regularly on a daily basis. There were regular peaks in turbidity greater than 10 NTU that consistently coincided with large daily tidal ranges greater than 5 m and wind speeds greater than 50 km/h (**Figure 3-4** and **Figure** 3-19). Strong tidal currents can cause sediment re-suspension leading to high turbidity. However, tides within the Pilbara region are semi-diurnal and although there may be high turbidity during rising and falling tides, particularly spring tides when the daily tidal range is at its greatest, localised turbidity may be reduced during slack water when the direction of the tidal current is changing. Thus during a day, turbidity can vary temporally. Weerdee Reef is the shallowest (4.6 m) of the six monitoring sites. Tidal currents and thereby re-suspension of solids in shallow water tend to increase in magnitude with tidal range (Allen 1997). There were greater peaks in turbidity during the wet season.

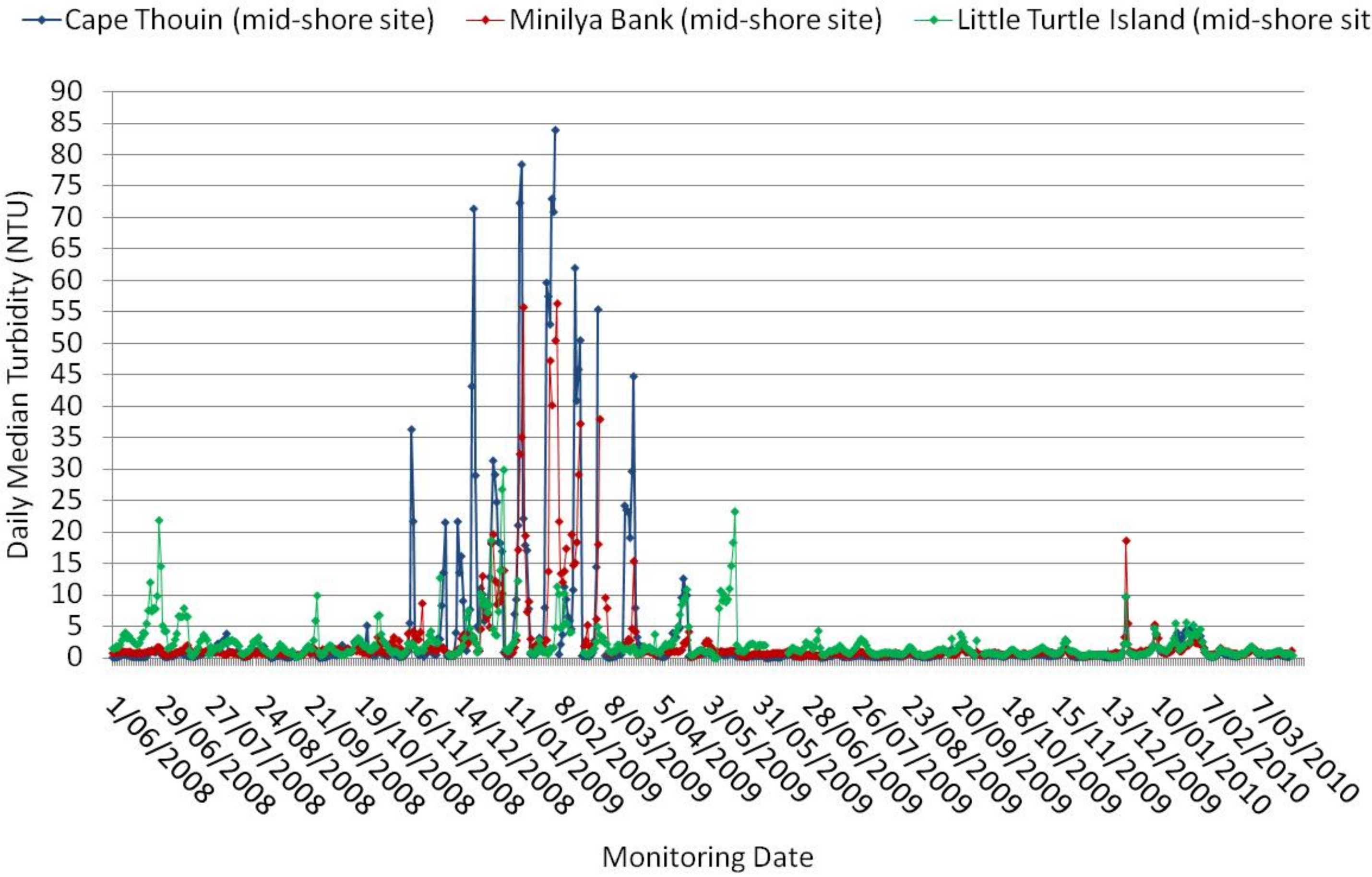
3.4.2. Mid-shore Environment

Daily median turbidity at the mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island ranged from 0.1 to 83.9 NTU (**Figure 3-20**), with higher turbidity occurring during the wet season. During the dry season 2008 median turbidity was relatively low and constant with only four peaks greater than 10 NTU. These peaks in turbidity occurred during a combined spring tide event (daily tidal range reached 4.8 m) and increased wind speeds of greater than 55 km/h from 22nd to 28th June 2008 (**Figure 3-4**). During the dry season 2009 no median turbidity was above 5 NTU. Turbidity at Little Turtle Island regularly fluctuated with higher turbidity during spring tides and lower turbidity during neap tides, whilst at Cape Thouin and Minilya Bank turbidity appeared to be less affected by the tidal regime.

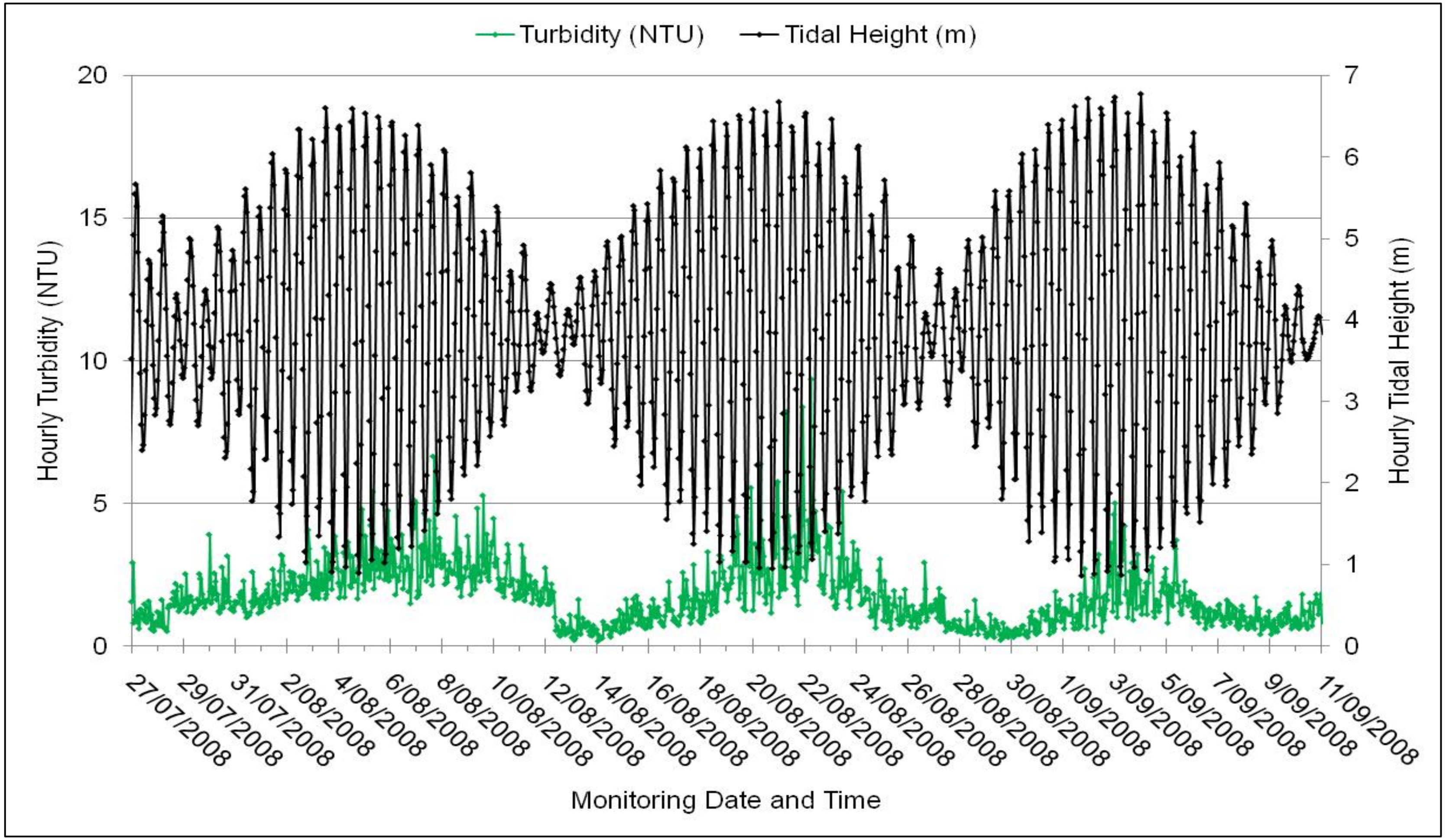
The relationship between the tidal regime and turbidity at Little Turtle Island is more evident when the data are compared on a smaller temporal scale. For example, using data from the 27th July to 11th September at Little Turtle Island, the hourly turbidity readings follow a trend of increased turbidity during spring tides and reduced turbidity during neaps tides (**Figure 3-21**). The trend between turbidity and the tidal regime becomes less obvious when multiple factors are involved, such as wind and tides, since these each influence the turbidity whilst also interacting with each other such that it is difficult to distinguish the individual affect over the combined effect. As seen at the inshore site Weerdee Reef, turbidity increased from the dry season to the wet season. The greatest peak in daily median turbidity at Cape Thouin was 83.9 NTU, at Minilya Bank 56.4 NTU and at Little Turtle Island 29.9 NTU.



- **Figure 3-19 Daily median turbidity at the inshore monitoring site Weerdee Reef**



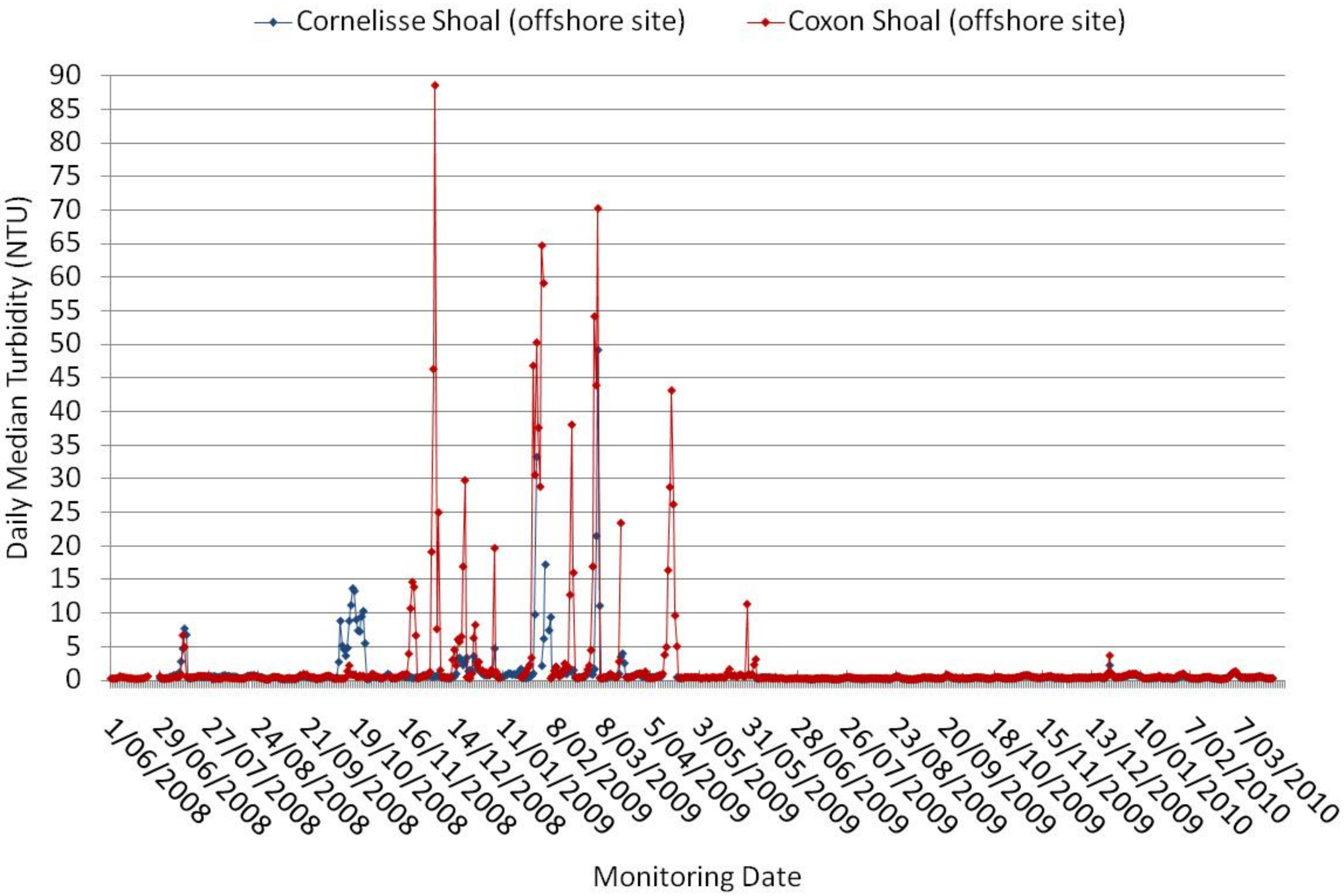
- **Figure 3-20 Daily median turbidity at the mid-shore monitoring sites Cape Thouin, Minilya Bank and Little Turtle Island**



- **Figure 3-21 Turbidity (hourly) and recorded tidal height at the mid-shore monitoring site Little Turtle Island**

3.4.3. Offshore Environment

Daily median turbidity at the offshore sites Cornelisse Shoal and Coxon Shoal ranged from 0.1 to 88.6 NTU (**Figure 3-22**). During the dry season turbidity was consistently less than 5 NTU compared to the remaining four sites. During the 2008 dry period there were two peaks in daily median turbidity from 11th to 14th July 2008 at Cornelisse Shoal and Coxon Shoal and again from 9th to 24th October 2008 at Cornelisse Shoal. These peaks were likely due to increased winds since during both these occasions there were maximum wind gusts greater than 60 km/h (**Figure 3-4**). Turbidity at the offshore sites appeared to be less affected by the tidal regime compared to the inshore and mid-shore sites. This was most likely due to the greater depth at the offshore sites and their distance further from the mainland. There were regular peaks in turbidity during the wet season, particularly at Coxon Shoal. However, some peaks in turbidity at Coxon Shoal did not coincide with spring tides or increased winds and were possibly due to shipping activity. Coxon Shoal is in close proximity to the Port Hedland Harbour entrance channel and field observations have indicated that ships frequently pass by the site. Large vessels can create bottom eddies and lift sediments into the water column. The greatest peak in the daily median turbidity at Coxon Shoal was 88.6 NTU and at Cornelisse Shoal was 49.2 NTU.



- **Figure 3-22 Daily median turbidity at the offshore monitoring sites Cornelisse Shoal and Coxon Shoal**

3.5. Water Temperature

The water temperature was relatively similar at all six sites throughout baseline monitoring. All six sites followed the same general trends of increasing and decreasing water temperature which reflected the seasonal trends in air temperature. The inshore site Weerdee Reef had the greatest range in water temperature, followed by the mid-shore sites Little Turtle Island, Minilya Bank and Cape Thouin and lastly the offshore sites Cornelisse Shoal and Coxon Shoal (**Table 3.6**).

The median water temperature at each of the six monitoring sites increased from the dry to the wet season in both years (**Table 3.6**). This was most likely due to seasonal factors such as climate (air temperature) (**Figure 3-11**). Higher air temperatures during December to February were coincided with an increase in water temperature. The median water temperature in the wet and dry seasons did not change substantially between years.

- **Table 3.6 Descriptive statistics for water temperature (°C) at the six monitoring sites for each season in each year**

Site Name	Dry Season 2008						Wet Season 2008/2009					
	n	Median	Min	Max	20%ile	80%ile	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	7340	21.4	17.3	29.5	20	25.7	8581	30.2	23.2	33.7	27.9	31.8
Cape Thouin	7343	22.6	18.5	29.1	20.8	26.1	8685	30.5	26.5	32.9	27.9	31.5
Minilya Bank	7343	21.5	19.1	28.7	20.1	25.4	8688	30.2	23.5	32.8	27.9	31.4
Little Turtle Island	7343	22.4	18.5	29.3	20.8	26	7991	29.9	25.3	32.6	28.2	31.3
Cornelisse Shoal	5973	22.5	19.9	27.8	21	25.1	7958	30.1	26.3	31.3	27.3	30.7
Coxon Shoal	7341	22.7	20.1	28.3	21	25.7	7981	29.7	27.0	31.7	27.9	31
	Dry Season 2009						Wet Season 2009/2010					
	n	Median	Min	Max	20%ile	80%ile	n	Median	Min	Max	20%ile	80%ile
Weerdee Reef	6663	23.2	18.9	30.1	21.2	25.3	6480	30.6	25.0	32.5	29.3	31.204
Cape Thouin	8033	22.8	19.6	28.6	21.2	24.2	6934	30.1	27.7	33.2	29.3	30.849
Minilya Bank	8669	22.7	18.9	28.1	21	24.5	6403	30.3	28.1	31.3	29.665	30.849
Little Turtle Island	6067	23.3	19.8	27.8	22.2	24.6	6510	30.5	27.7	31.8	29.8	31.077
Cornelisse Shoal	6316	23.4	20.4	26.9	22.4	24.3	6635	29.2	26.7	30.8	28.5	29.765
Coxon Shoal	8124	23.4	20.2	28.0	21.9	24.6	6218	29.5	27.0	30.7	28.841	29.966

3.5.1. Inshore Environment

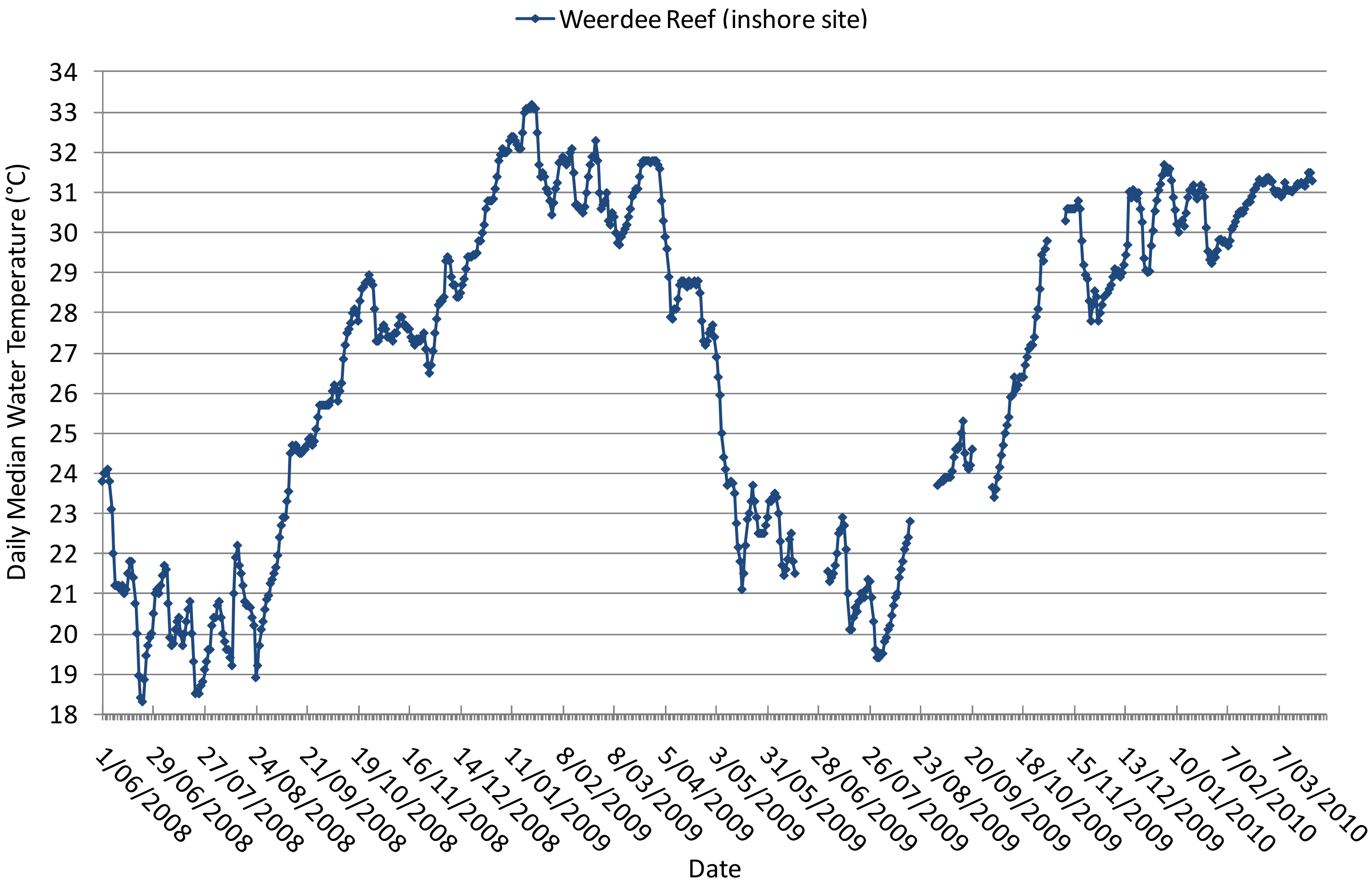
Daily median water temperature at the inshore site Weerdee Reef fluctuated regularly on a daily and fortnightly basis. In general, there was a decrease in water temperature during spring tide events. This was particularly evident from June to August 2008 (**Figure 3-23**). After this time water temperature increased steadily with only small decreases during spring tides. As to be expected, temperature at all sites was strongly influenced by seasonal trends, being colder in the dry season and warmer in the wet season.

3.5.2. Mid-shore Environment

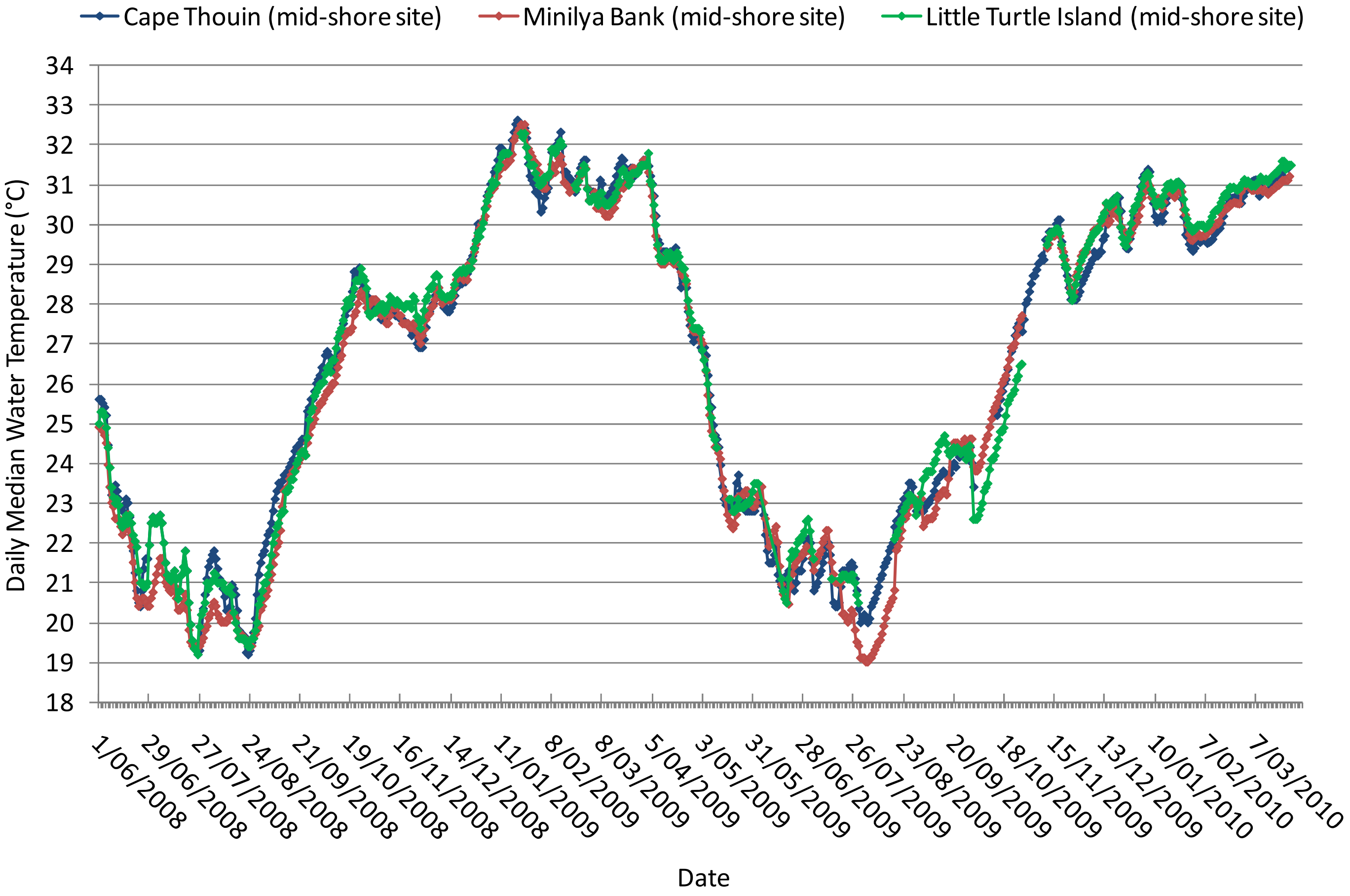
Daily median water temperature at the mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island followed the same general trends seen at the inshore site Weerdee Reef with the exception that peaks and troughs were less extreme and subsequently the range was lower (**Figure** 3-24). Decreases in water temperature appeared to coincided with spring tide events, as seen at Weerdee Reef.

3.5.3. Offshore Environment

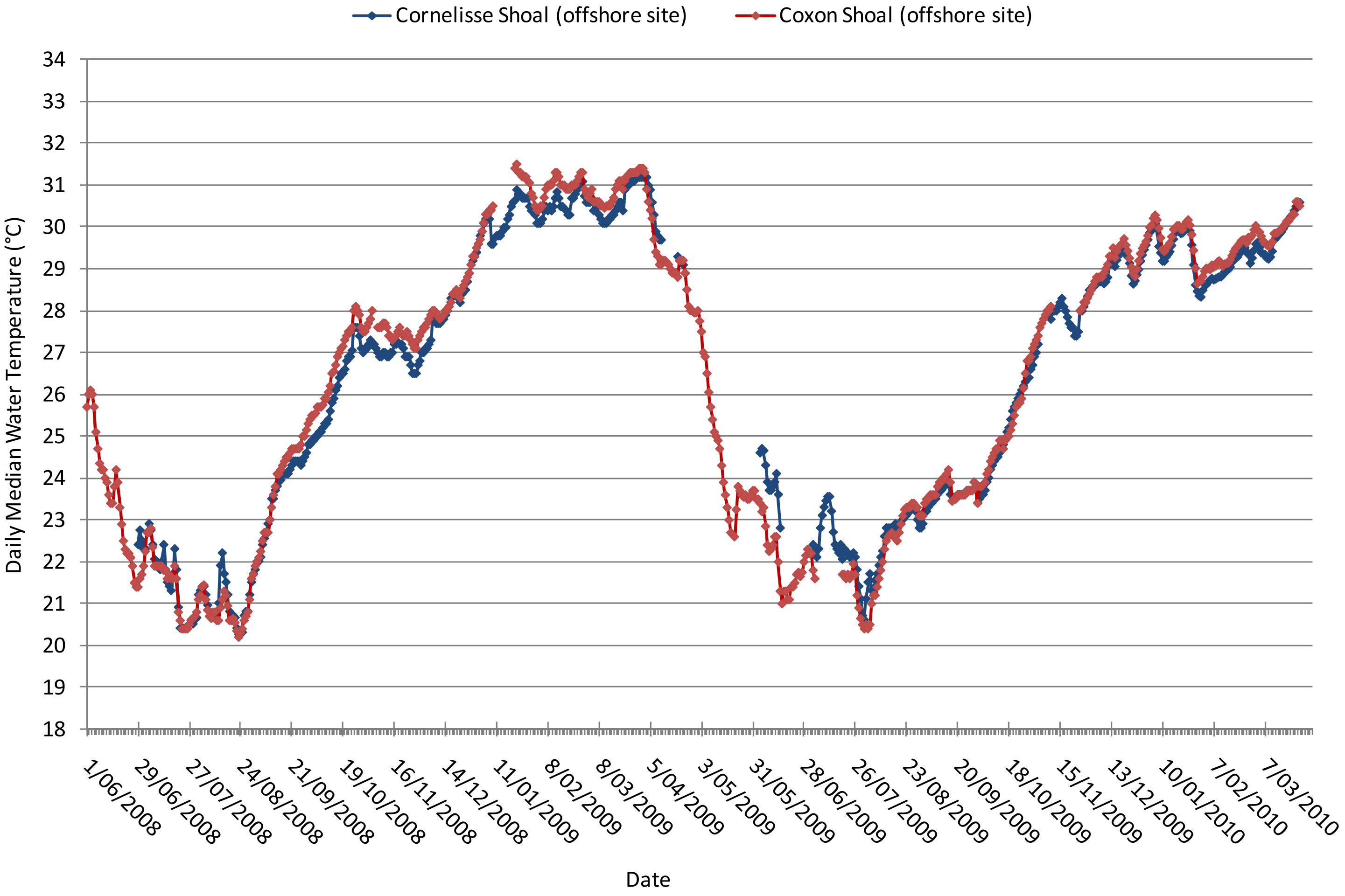
Daily median water temperature at the offshore sites Cornelisse Shoal and Coxon Shoal was the most constant throughout baseline monitoring and had the lowest range compared to the remaining four sites (**Figure 3-25**). Small decreases in water temperature appeared to coincide with spring tides, as seen at the remaining four sites, yet these were less extreme.



- **Figure 3-23 Daily median water temperature at the inshore monitoring site Weerdee Reef**



- **Figure 3-24 Daily median water temperature at the mid-shore monitoring sites Cape Thouin, Minilya Bank and Little Turtle Island**



- **Figure 3-25 Daily median water temperature at the offshore monitoring sites Cornelisse Shoal and Coxon Shoal**

3.6. Sedimentation

The gross daily sedimentation rates (calculated over a two week time period) were higher at all sites in the wet seasons compared to the dry seasons. The wet season mean gross daily sedimentation rates were typically two to three times higher than those in the dry season (**Table 3.7**). The greatest increase in gross daily sedimentation rates between the dry and wet season occurred at Weerdee Reef and Cape Thouin. As with turbidity and light, these sites experienced the greatest seasonal shift in their water quality characteristics from the dry to the wet season.

- **Table 3.7 Descriptive statistics for gross daily sedimentation rate (mg/cm^2/day) at the six monitoring sites for each season in each year**

Site Name	Dry Season 2008			Wet Season 2008/2009		
	n	Mean	S.D	n	Mean	S.D
Weerdee Reef (inshore)	18.0	79.6	38.6	35.0	313.9	452.7
Cape Thouin (mid-shore)	18.0	9.1	3.1	35.0	120.4	203.18
Minilya Bank (mid-shore)	18.0	5.6	1.4	36.0	37.3	52.0
Little Turtle Island (mid-shore)	18.0	13.9	4.0	36.0	33.1	20.1
Cornelisse Shoal (offshore)	18.0	5.6	1.7	36.0	17.1	13.0
Coxon Shoal (offshore)	18.0	4.2	1.0	36.0	25.5	33.4
	Dry Season 2009			**Wet Season 2009/2010**		
	n	**Mean**	**S.D**	**n**	**Mean**	**S.D**
Weerdee Reef (inshore)	30.0	174.6	122.3	20.0	337.1	312.1
Cape Thouin (mid-shore)	30.0	11.5	6.3	20.0	43.5	50.1
Minilya Bank (mid-shore)	27.0	9.1	6.6	19.0	28.7	28.9
Little Turtle Island (mid-shore)	27.0	19.4	11.9	20.0	47.4	66.3
Cornelisse Shoal (offshore)	30.0	7.0	2.9	20.0	15.5	12.2
Coxon Shoal (offshore)	29.0	16.4	20.0	20.0	56.6	76.6

3.6.1. Inshore Environment

The mean sedimentation rate (mg/cm^2/day) was the greatest at the inshore site Weerdee Reef compared with the remaining five sites. Sedimentation is usually highest at inshore reefs and decreases with distance from the shore (Gilmour *et al*. 2006). The highest sedimentation rate was at Weerdee Reef in February 2009 with 1,559 mg/cm^2/day (**Figure 3-26**). The mean sedimentation rate increased during the wet season when the speed and frequency of wind events increased. In particular, the high sedimentation rate during December 2008 was most likely due to the combined effect of large tidal ranges (**Figure 3-12**) and increased wind speeds (greater than 40 km/h). The high sedimentation rate during February 2009 may have been due to residual sediment deposited following cyclone Dominic (**Table 3.1**). Considerable amounts of sediment are often deposited weeks after a cyclone (Gilmour *et al*. 2006).

3.6.2. Mid-shore Environment

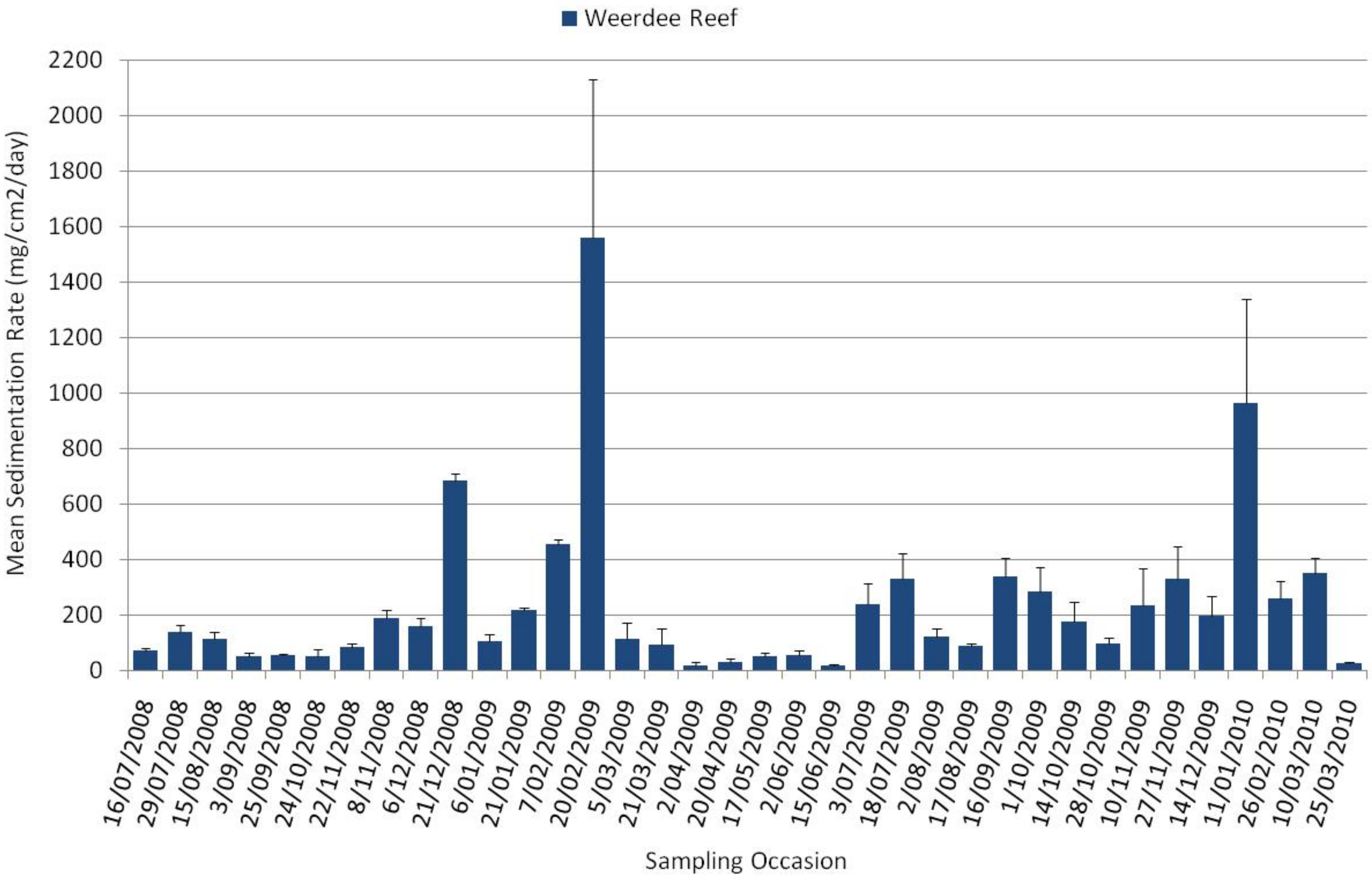
The mean sedimentation rates at the mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island were much less compared with the inshore site Weerdee Reef. The range in sedimentation rates at the mid-shore sites was 4.4–712 mg/cm^2/day (**Figure 3-27**). The mean sedimentation rate at the mid-shore sites increased from the dry season to the wet season. The strength of winds, waves, tides and currents determine both the amount and duration of sediment deposition (Gilmour *et al*. 2006).

3.6.3. Offshore Environment

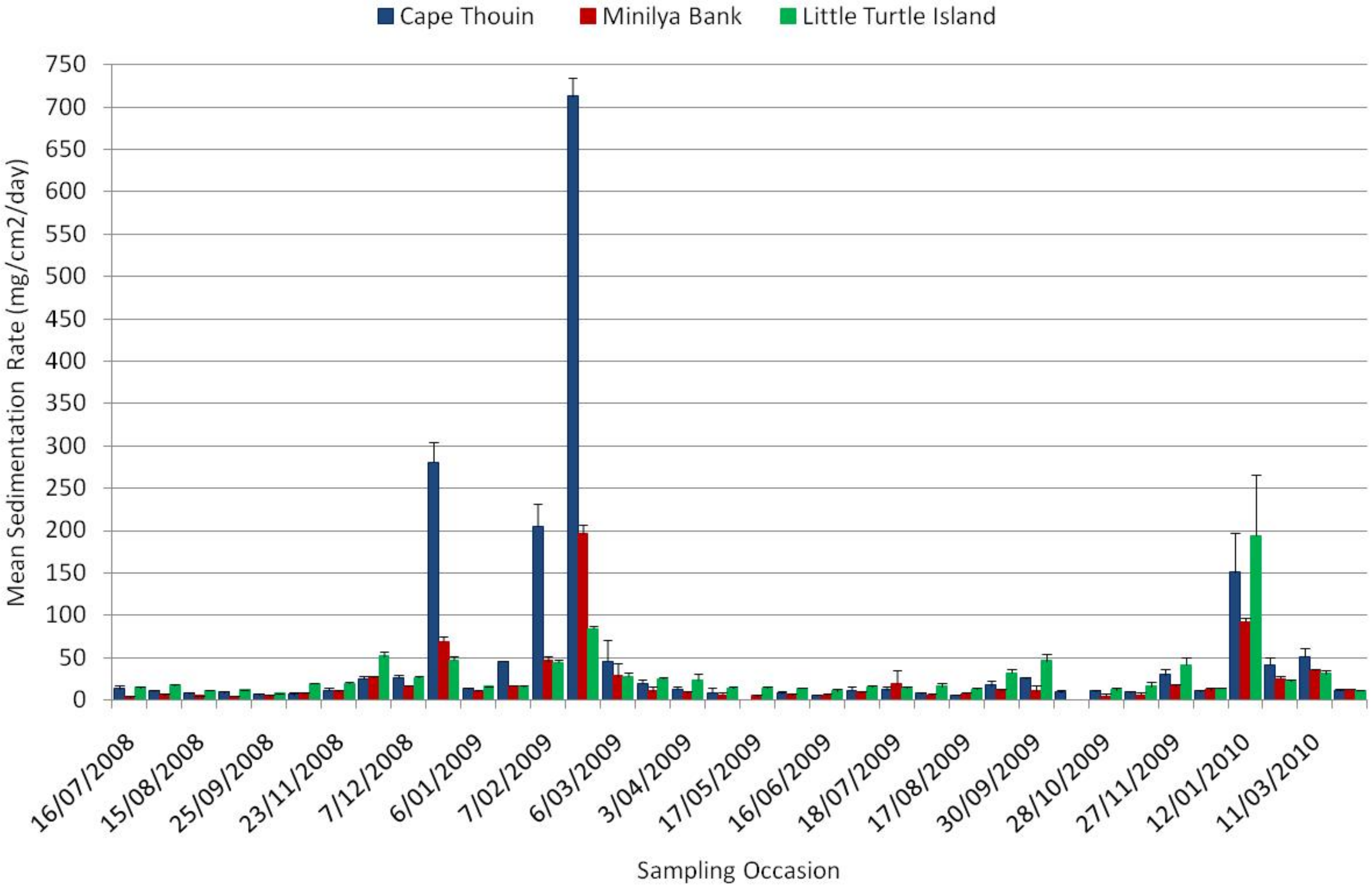
Mean sedimentation rates were the lowest at the offshore sites Cornelisse Shoal and Coxon Shoal compared with the remaining four sites. They ranged from 3.4–196 mg/cm^2/day and were generally less than 20 mg/cm^2/day (**Figure 3-28**). The mean sedimentation rates increased during the wet season, as seen at the other monitoring sites and were possibly due to the combined effect of large tidal ranges (**Figure 3-12**) and increased wind speeds (greater than 40 km/h) (**Figure 3-4**).

3.7. Particle Size Distribution

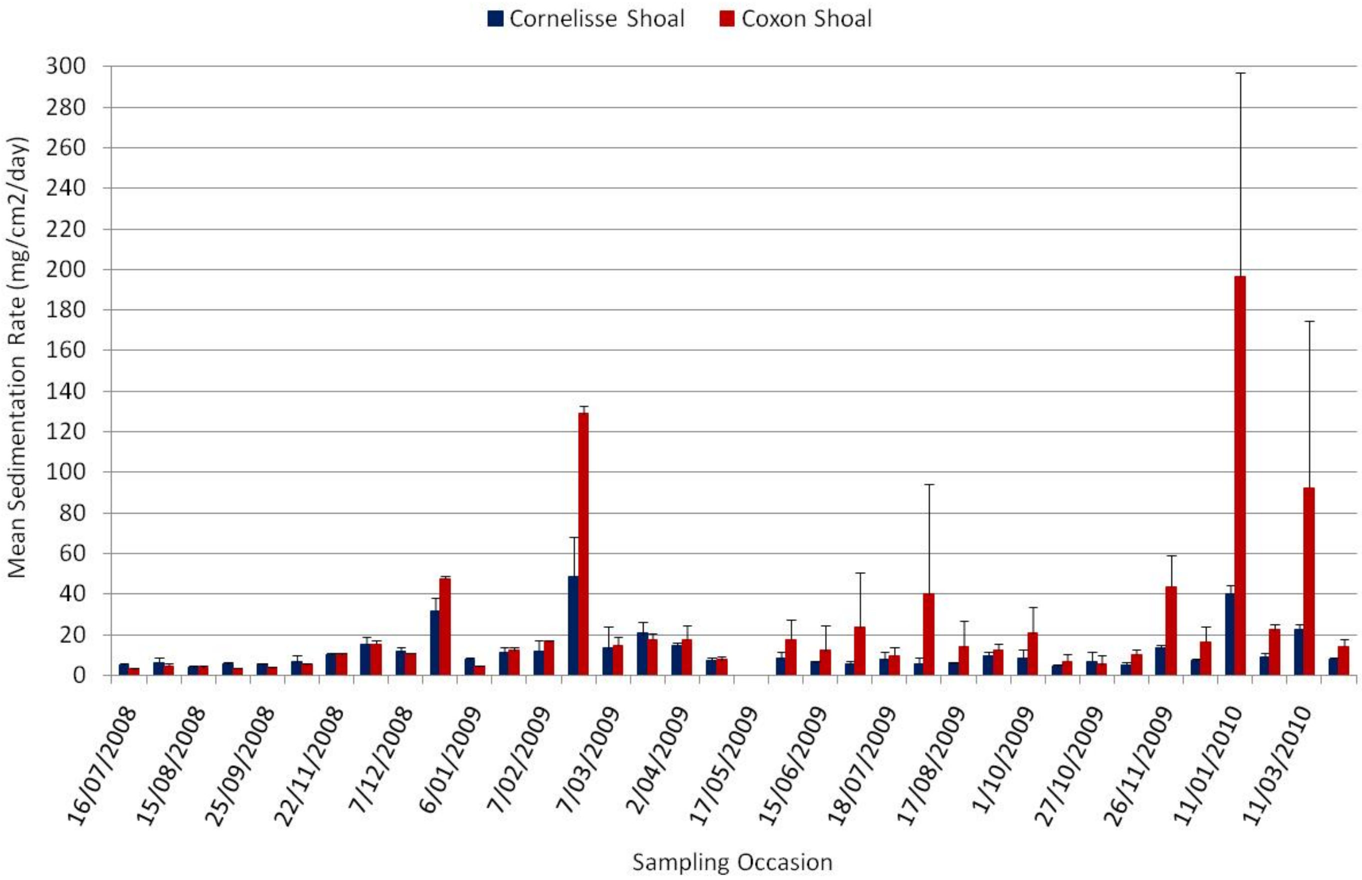
Particle size distribution analysis indicated the material in the sediment traps was mostly fine (< 150 µm) (**Figure 3-29**); whereas, the material adjacent to the sediment traps was mostly coarse (150 µm to > 500 µm) (**Figure 3-30**). This suggests that once the fine material settles it is re-suspended again and does not remain at any of the sites. Since the material existing naturally at each site is relatively course, it can be suggested that the majority of fine sediment collected inside the sediment traps is a result of re-suspension and the fine sediment has been transported from elsewhere. The sediment particle distribution inside the traps was relatively similar between sites. However, the traps at the inshore and mid-shore sites had slightly greater amounts of finer material and less material > 500 µm compared with the offshore traps. The sediment particle distributions in the samples adjacent to the traps were all relatively similar between sites and there were no distinct trends. However, there was much less material in the category 150–500 µm at Minilya Bank and Little Turtle Island compared with the remaining four sites.



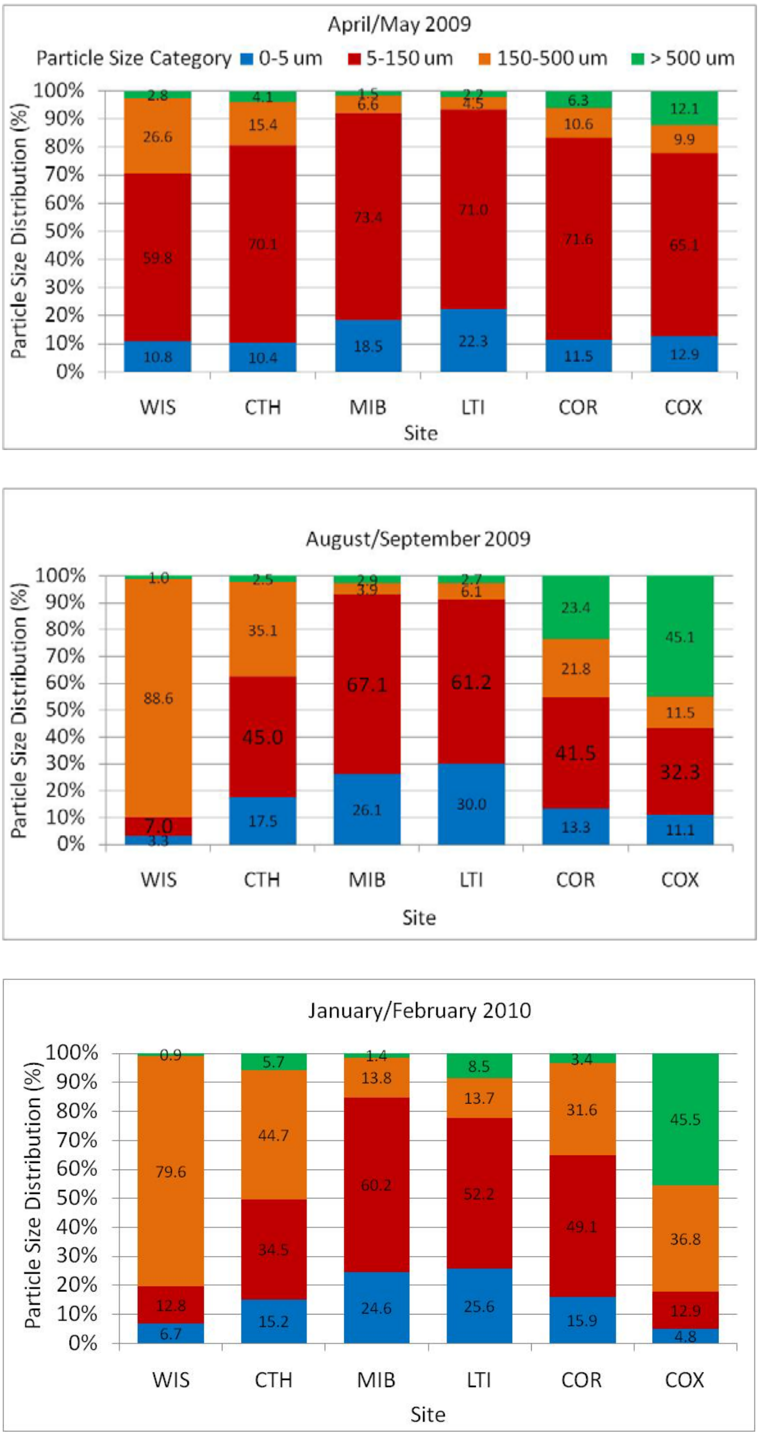
- **Figure 3-26 Mean sedimentation rate ± standard deviation at the inshore monitoring site Weerdee Reef**



- **Figure 3-27 Mean sedimentation rate ± standard deviation at the mid-shore monitoring sites Cape Thouin, Minilya Bank and Little Turtle Island**

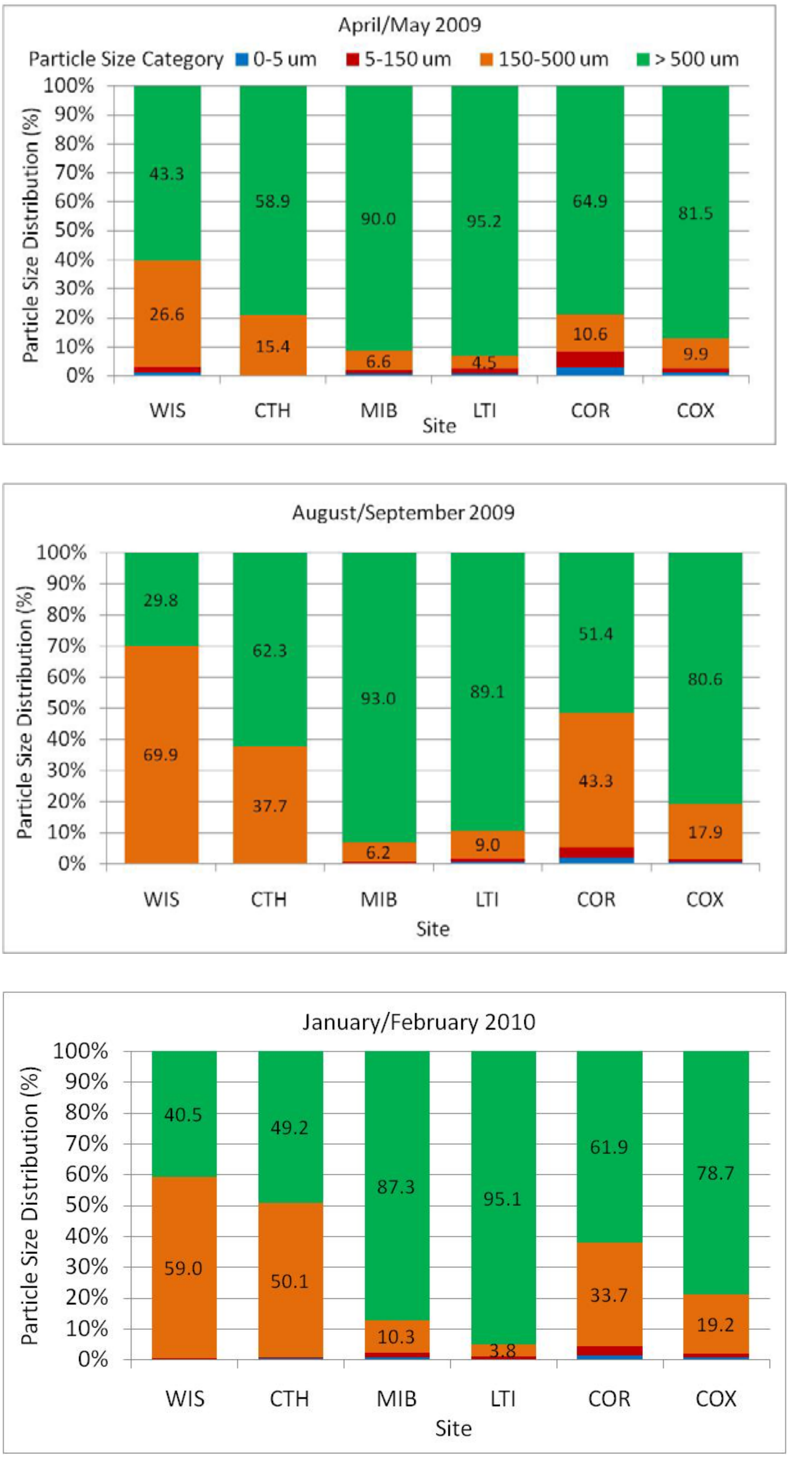


- **Figure 3-28 Mean sedimentation rate ± standard deviation at the offshore monitoring sites Cornelisse Shoal and Coxon Shoal**



Note: Grouped according to categories based on settling behaviour (refer to ***Table 2.3****).*

- **Figure 3-29 Particle size distribution (%) of sediment collected by sediment traps at each of the monitoring sites**



Note: Grouped according to categories based on settling behaviour (refer to ***Table 2.3****).*

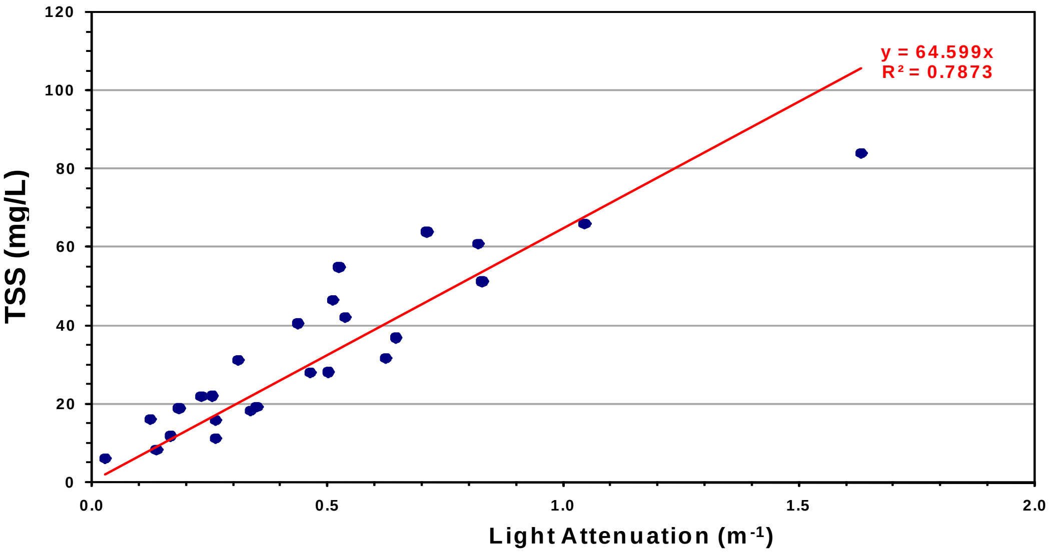
- **Figure 3-30 Particle size distribution (%) of sediment collected outside sediment traps from surrounding substrate at each of the monitoring sites**

4. Relationships between Water Quality Variables

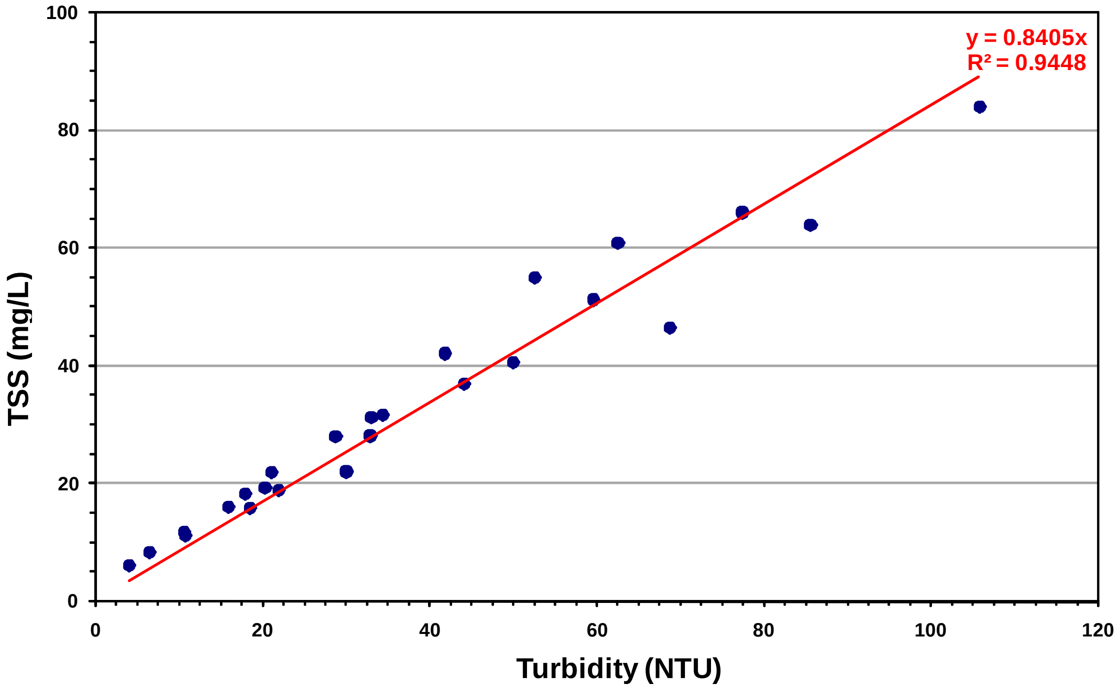
In 2007, SKM contracted the services of In situ Marine Optics Pty Ltd to estimate the relationships between turbidity (NTU), TSS (mg/L) and light attenuation (m^{-1}) using laboratory experiments on cored sediments from the proposed Port Hedland Outer Harbour Project dredging footprint (**Figure** 4-1; **Figure 4-2** and **Figure 4-3**; see SKM 2007b). The observed relationships all had a strong linear association (R^2 values >0.70).

A total suspended solid is the variable used to characterise the behaviour of particles in modelling of dredge plume behaviour. The use of water quality thresholds based on turbidity (NTU) or light requires an understanding of the locally relevant relationship/s between TSS, NTU and light in order to use the baseline and reactive monitoring datasets 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 reliable relationship/s between TSS, turbidity and light.

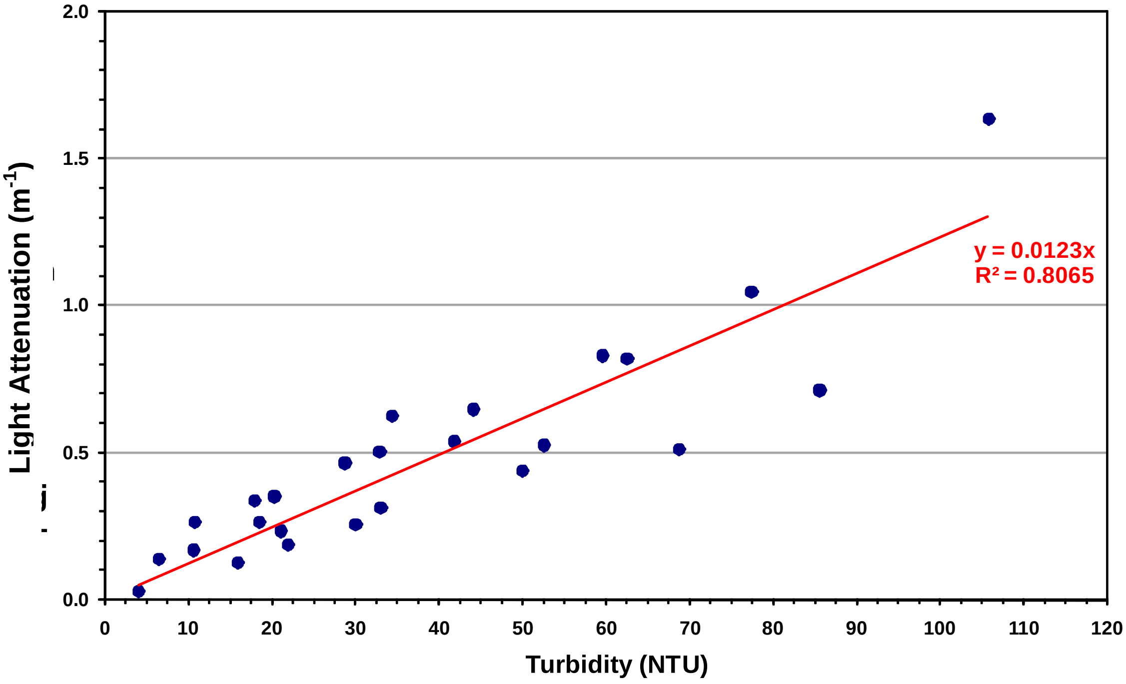
These relationships have been used in the current threshold development process. Based on the comparatively strong R^2 values, any potential transformation of calculated turbidity thresholds into TSS values and subsequent TSS thresholds for interrogations of the dredge plume modelling output is considered robust. It follows that any transformations of light attenuation to TSS to develop thresholds based on light climate are also considered robust.



- **Figure 4-1 Overall relationship between light attenuation and total suspended solids**



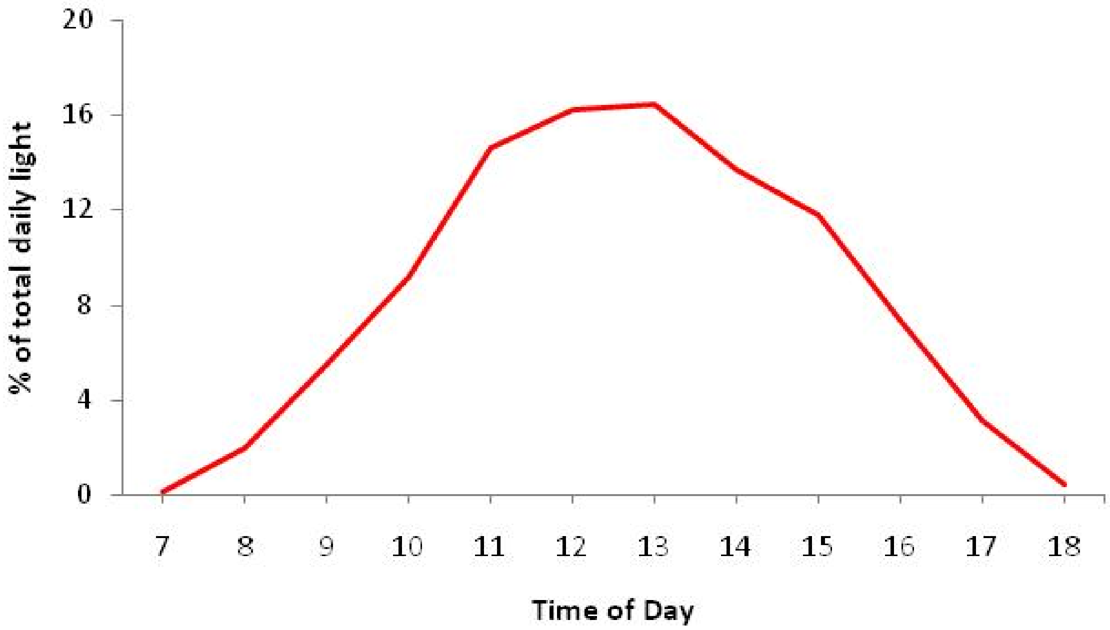
- Figure 4-2 Overall relationship between turbidity and total suspended solids



- Figure 4-3 Overall relationship between turbidity and light attenuation

Future work has been planned to collect background TSS samples six times during spring tides and six times during neap tides at all sites. These data will enable site specific relationships to be developed between background TSS, turbidity and light. As the measurement of turbidity (NTU) can be influenced by changes in particle size, the relationships between turbidity and TSS can vary widely among sites.

Relationship/s between turbidity (NTU) and light are currently being developed using the baseline dataset. At present the relationship between turbidity (NTU) and light at the point during the day when the maximum amount of light is reaching the substrate (BPPs) is being explored. Analysis of the baseline light climate data indicates that over 95% of all light falls on the corals in the 9 hours between 8 am and 5 pm (**Figure 4-4**), and 50% of all light falls in the 4 hours between 10 am and 2 pm. The single greatest amount of light available to BPPs at any one time occurs between 12 and 1 pm. To ensure a robust and accurate assessment, these relationships will be finalised now that the full 12 month baseline dataset is available.



- **Figure 4-4 The percentage of daily light reaching BPPs (coral colonies) during daylight hours**

5. Conclusions

The plume modelling (APASA 2009) predicted a much larger plume than the initial plume used to locate the six water quality sites. These sites adequately characterise the large study area however additional sites may be required for monitoring during dredging activities, these will be identified in the Dredge Spoil and Disposal Management Plan.

5.1. Baseline Water Quality Results

5.1.1. Turbidity

- The median turbidity at the three environments (inshore, mid-shore and offshore) was low over the course of the baseline monitoring (less than 2 NTU).
- The turbidity observed at the inshore site Weerdee Reef followed the trend of shallow tidal areas where local conditions are influenced by the macro-tidal environment which produces mixing and re-suspension of sediments.
- The mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island were typically less susceptible to sediment re-suspension possibly due to their greater depth and increased distance from the mainland reducing the amount of fine sediment material available for re-suspension. The turbidity at these sites appeared to be influenced to a greater extent by increased wind speeds and associated mixing of the water column. The turbidity at Little Turtle Island was observed to increase during spring tides and decrease during neap tides.
- Turbidity at the offshore sites Cornelisse Shoal and Coxon Shoal was comparatively low and constant. This appeared to follow the trend of conditions further offshore, in deeper water, less prone to sediment re-suspension since the sediments are generally courser and have higher calcium carbonate content. The large peaks in turbidity at the offshore site Coxon Shoal that did not correspond with environmental factors such as winds or tides but could be due to shipping activity.
- At all six monitoring sites median turbidity increased from the dry to the wet season, possibly due to the onset of regular cyclone events that resulted in increased winds, increased tidal height and storm surge causing sediment re-suspension.

5.1.2. Light

- Light levels at the mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island and the offshore sites Cornelisse Shoal and Coxon Shoal oscillated in a regular pattern that appeared to coincide with the tidal regime. High light levels appeared to occur during neap tides and low light levels during spring tides.
- Light levels at the inshore site Weerdee Reef fluctuated irregularly and did not always oscillate in a regular pattern consistent with the tidal regime. Light levels were influenced by the shallow water depth which meant high light penetration.

- The light climate was lower during the wet season at all six monitoring sites.
- Lower light levels during the wet season were possibly due to increased cloud cover and increased turbidity.

5.1.3. Water Temperature

- In general, water temperature at all six sites followed the same trends throughout baseline monitoring.
- Water temperature increased at all sites during the wet seasons, likely resulting from increasing ambient air temperatures.
- There were daily fluctuations in water temperature at all six sites possibly due to local scale events such as tides, mixing due to winds and changes in depth and irradiance.

5.1.4. Sedimentation

- The mean sedimentation rate was greatest at the inshore site Weerdee Reef followed by the mid-shore sites Cape Thouin, Minilya Bank and Little Turtle Island and least at the offshore sites Cornelisse Shoal and Coxon Shoal.
- The mean sedimentation rate increased at all six sites during the wet seasons.
- The sediment size distributions found within sediment traps indicate there is re-suspension of finer sediments occurring at all sites, however more distinctly at the inshore and mid-shore sites.

All of the results observed to date were within the range of previous water quality observations made during other studies within the Pilbara region (SKM 2007a; MScience 2008).

6. References

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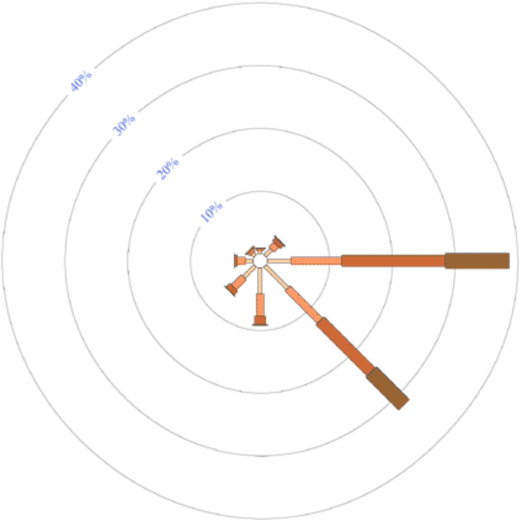
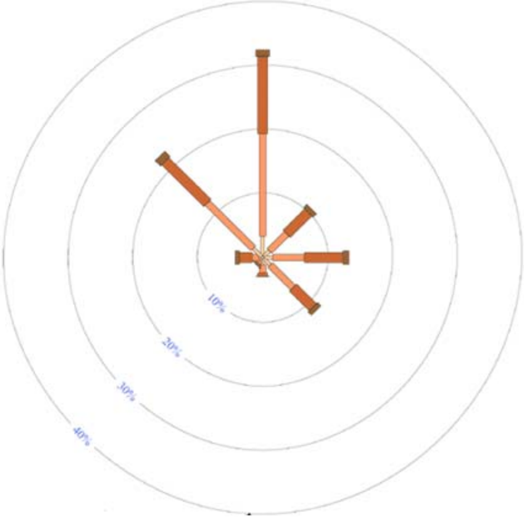
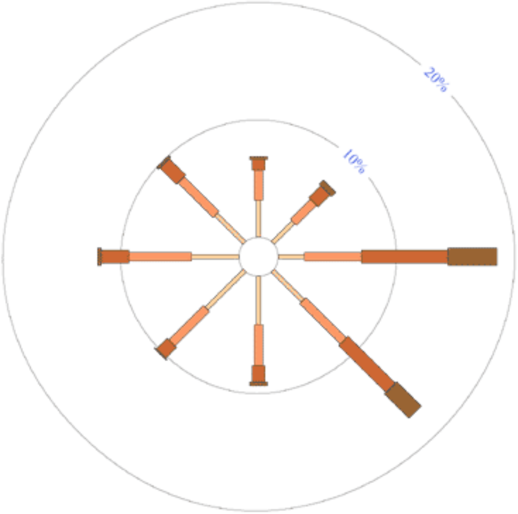
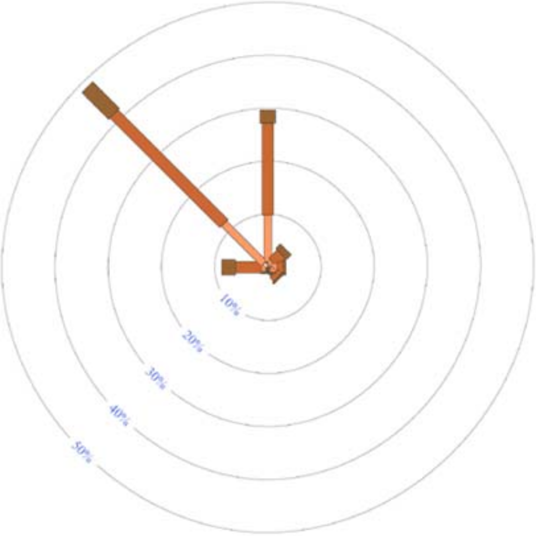
Appendix A Wind Roses for the Port Hedland Region

	
▪ **Dry Season 9 am**	▪ **Dry Season 3 pm**
	
▪ **Wet Season 9 am**	▪ **Wet Season 3 pm**

(Source: BoM, seasonal wind rose for Port Hedland from 1942 to 2004)