PORT OF **WEIPA**

REPORT

Environmental thresholds report

PORT & COASTAL SOLUTIONS

Port of Weipa: Sustainable Sediment Management Assessment

Environmental Thresholds

Report No. P022_R03F1

North Queensland Bulk Ports Corporation

Technical Report

April 2020

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Executive Summary

North Queensland Bulk Ports Corporation (NQBP) commissioned Port and Coastal Solutions (PCS) to undertake an assessment into ambient water quality conditions and environmental thresholds at the Port of Weipa. The aim of this assessment is to better understand the natural water quality conditions at the Port of Weipa and to relate these to published environmental thresholds to define relevant, site specific thresholds at the Port of Weipa long-term ambient water quality monitoring sites.

The most sensitive receptor in and around the Port of Weipa is seagrass. There are also some coral species present in the Weipa region, although based on dredge plume modelling undertaken as part of the Sustainable Sediment Management (SSM) Project they are expected to be beyond the area where increased turbidity occurs as a result of maintenance dredging programs at the Port of Weipa.

Statistical analysis of measured water quality and deposition data was undertaken using an intensity, duration and frequency (IDF) approach to understand the natural variability in the environment in terms of turbidity, benthic light availability (benthic PAR) and sediment deposition. The analysis undertaken was based on approximately nineteen months of data collected at three sites in the Weipa region by James Cook University (JCU). To understand the seasonal variability, separate IDF analyses were undertaken for the wet and dry seasons. The results have focused on the conditions during the dry season as any future maintenance dredging is likely to occur during dry season conditions.

Published information on thresholds for seagrasses are typically defined in terms of benthic PAR rather than turbidity. The measured data were used to determine relationships between benthic PAR and turbidity at the monitoring sites and based on these approximately equivalent thresholds in terms of turbidity intensity were derived. Based on the seagrass species present around the Port of Weipa and the benthic PAR thresholds noted in the literature, the analysis suggests that a turbidity threshold in the order of 15-20 NTUe (equivalent to approximately 30 mg/l) is representative of the lower threshold for light availability at the monitoring sites during the dry season (i.e. when the turbidity is above this there is insufficient benthic light).

Published information suggests light-based intensity thresholds are between 1.5 mol/m^2/day over 7 days and 3.5 mol/m^2/day over 14 days for the seagrass species present at and around the Port of Weipa. At the water quality monitoring sites, light levels were regularly naturally below the upper threshold value. The lower threshold value is more representative of the natural light environment, however light levels still drop below this level for durations which are longer than both the 7 day duration noted in the literature and the duration of a typical maintenance dredge program. While it could be possible to develop more applicable thresholds based on the local data, in view of practical limitations associated with obtaining accurate benthic PAR readings in real time during dredging operations, we do not recommend the adoption of benthic PAR as a trigger for adaptive management of maintenance dredging at the Port of Weipa.

Published information on the tolerance of seagrass species to sedimentation suggests that thresholds rates of between 1.6 mg/cm^2/day and 8.0 mg/cm^2/day would be applicable to the seagrass species present at and around the Port of Weipa. Measured deposition was much higher than these published thresholds with median values above even the upper limit at most sites. This may in part be due to the inability to accurately measure net deposition/erosion as opposed to gross deposition and the associated limited accuracy of measured deposition rates. This limitation in sedimentation data, coupled with the lack of suitable adaptive management responses available if deposition thresholds are exceeded led to the conclusion that deposition data is of limited use for adaptive monitoring purposes.

The IDF results indicate that turbidity data is the most appropriate parameter for monitoring during dredging operations when real-time monitoring is required to inform adaptive management. Further analysis of the measured turbidity data indicated that a single threshold value across all sites and both seasons would not be applicable as this would not take into account the large variations that occur. Instead, the adoption of a percentile was considered to be the best approach, enabling a comparable interpretation of natural SSC/NTUe and dredge related changes in intensity and duration between sites. Based on the results of the percentile analysis and the derived turbidity thresholds based on the published benthic PAR thresholds, the 90th percentile turbidity was adopted as a turbidity intensity threshold. As the proposed 90th percentile turbidity/SSC threshold is on average only naturally exceeded for 10% of the time, it can be considered to be representative of a threshold for short duration acute impacts due to high turbidity/SSC, as opposed to longer duration chronic impacts due to prolonged periods of lower SSC.

The IDF analysis was applied for periods of 20 days and 40 days to allow them to potentially be applied for a range of maintenance dredge program durations. The results from the analysis (presented in Table E1 and Table E2) define the natural conditions in terms of both the intensity and duration, thus providing the basis for potential trigger limits if adaptive monitoring is required during future maintenance dredging programs.

Table E1. Suggested SSC/NTUe intensity and duration triggers at the three water quality monitoring sites around the Port of Weipa, based on a 20 day period

Site	Intensity (mg/l)	Intensity (NTUe)	Average Duration (hours)	90th Percentile Duration (hours)	Maximum Duration (hours)
Wet Season (90th percentile data)					
WQ1	43	33	48	116	251
WQ2	273	204	48	176	359
WQ4	168	95	48	115	225
Dry Season (90th percentile data)					
WQ1	22	17	48	97	133
WQ2	20	15	48	123	238
WQ4	31	18	48	109	173

Table E2. Suggested SSC/NTUe intensity and duration triggers at the three water quality monitoring sites around the Port of Weipa, based on a 40 day period

Site	Intensity (mg/l)	Intensity (NTUe)	Average Duration (hours)	90th Percentile Duration (hours)	Maximum Duration (hours)
Wet Season (90th percentile data)					
WQ1	43	33	96	271	324
WQ2	273	204	96	366	396
WQ4	168	95	96	237	252
Dry Season (90th percentile data)					
WQ1	22	17	96	142	155
WQ2	20	15	96	239	273
WQ4	31	18	96	194	248

The proposed thresholds were tested against measured data collected during the 2019 maintenance dredging program (a worst case sedimentation year which involved two dredgers working concurrently to relocate 2.4 Mm^3 of sediment) by quantifying the cumulative duration that the near bed turbidity was above the defined thresholds during the dredge program. The duration of time the turbidity was above the threshold (17 NTUe) at WQ1 was more than what would be expected to occur naturally. At WQ2 and WQ4, while the duration of time the thresholds were exceeded appear high, the duration of time the turbidity was above the thresholds was within the range of what naturally occurs.

Results from numerical modelling undertaken as part of the Port of Weipa SSM Project were analysed to identify whether periods of enhanced turbidity associated with maintenance dredging of a range of different volumes of sediment would also increase the period of enhanced turbidity above what would occur naturally. The results indicated that the increase in duration above the intensity threshold for typical (400,000 m^3) and cyclonic (800,000 m^3) dredge volumes is unlikely to be detectable in the context of the natural variations which occur. On this basis, monitoring during maintenance dredging is not considered necessary during years when the dredge volume is within its normal range (400,000 to 800,000 m^3) and can be removed by a single dredger. However, it is recommended that real-time monitoring be undertaken for years when the maintenance dredging requirement is comparable to the 2019 maintenance dredge program (2.4 Mm^3), and requires two dredgers to be working concurrently, so that threshold exceedances can be monitored and adaptive management measures implemented if required. The intensity and duration thresholds for the dry season, calculated over the 40 day period, are considered most applicable for adaptive management of this type of dredging program due to the likely duration of the program (Table E2).

1. Introduction

North Queensland Bulk Ports Corporation (NQBP) and Rio Tinto Alcan (RTA) commissioned Port and Coastal Solutions (PCS) to undertake a series of studies as part of NQBP/RTA's long-term Sustainable Sediment Management (SSM) assessments at the Port of Weipa (and Amrun Port). The scope of work for the studies being undertaken by PCS are as follows:

- Onshore pond and reclamation assessment: the aim of the study is to assess a single onshore pond option at the Port of Weipa and Amrun Port and a land reclamation option at the Port of Weipa. As part of the assessment, preliminary concept designs will be developed to allow a comparative analysis between the options and other options being considered as part of the SSM assessments to be undertaken;
- Sediment transport and dredge plume modelling: the aim of the study is to model the transport of suspended sediment released into the marine environment by maintenance dredging at the Port of Weipa and Amrun Port. The modelling will include a number of offshore and onshore placement sites as well as a range of possible metocean conditions and maintenance dredging volumes;
- Thresholds analysis: the turbidity, deposition and benthic PAR data collected as part of the ambient water quality monitoring at the Port of Weipa and Amrun Port will be analysed to understand the natural variability of these parameters in the environment. Based on this and information available from the literature, relevant thresholds (using an intensity, duration and frequency approach) will be defined for the long-term monitoring sites at the Ports; and
- CO_2 emission calculations: the aim of this study is to undertake calculations to provide an estimate of Greenhouse Gas (GHG) CO_2 equivalent emissions for a number of placement options for the Port of Weipa and Amrun Port.

This report details the thresholds analysis for the Port of Weipa. The thresholds analysis for Amrun Port is reported separately in PCS (2019b). The overall aims of this assessment are to:

- review and summarise knowledge on relevant environmental thresholds at the Port of Weipa based on published literature;
- undertake statistical analysis of observational data using the intensity, duration and frequency (IDF) approach to define the water quality conditions at the Port of Weipa; and
- recommend appropriate water quality triggers that can be considered for use in adaptive monitoring and management plans.

1.1. Project Background

Annual maintenance dredging is required at the Port of Weipa to ensure there is sufficient depth for vessels to safely travel to and from the berths. The sediment that has historically been removed by maintenance dredging, has been relocated to an offshore dredge material placement area (DMPA) located in Albatross Bay (Figure 2).

In 2016, a Maintenance Dredging Strategy (MDS) was developed for the ports that are situated within the Great Barrier Reef World Heritage Area (GBRWHA) (DTMR, 2016). This MDS (which supports the wider *Reef 2015 Plan*) provides a framework for the sustainable, leading practise management of maintenance dredging in the GBR (Figure 1). Although the Port of Weipa is not located within the GBRWHA, NQBP has decided to adopt the MDS to ensure the same high standard is adopted at all of their Ports. It is a requirement of the MDS that each Port within the GBRWHA develops Long-term Maintenance Dredging Management Plans (LMDMPs). Such LMDMPs are aimed at creating a framework for continual improvement in environmental performance. DTMR have provided guidelines to assist in the development of the LMDMPs (DTMR, 2018). The guidelines note that they should include, among other aspects, the following:

- an understanding of port-specific sedimentation conditions and processes;
- management approaches (including dredge avoidance and reduction); and
- long-term dredging requirements based on sedimentation rates, port safety and port efficiency needs.

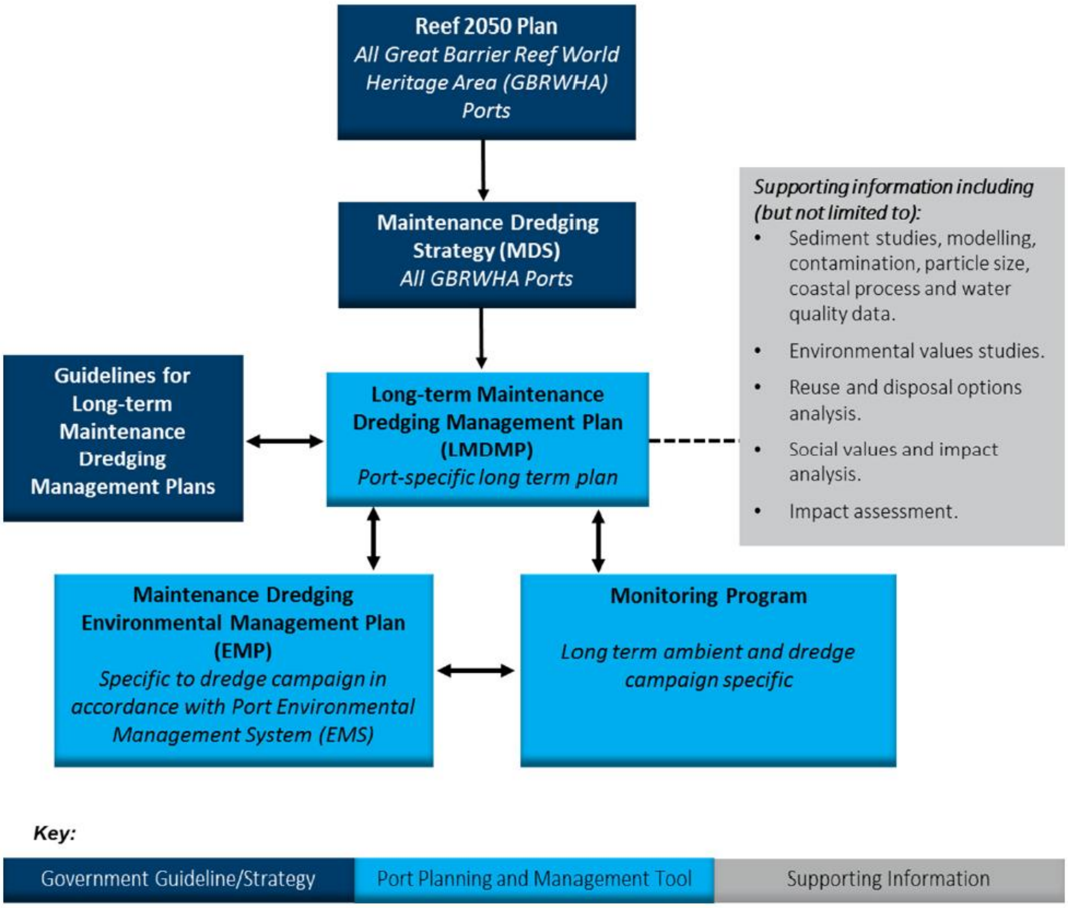

Figure 1. Planning and implementation mechanisms for maintenance dredging of Queensland Ports (DTMR, 2018).

The requirement to investigate whether sedimentation at ports can be managed to avoid or reduce the need for maintenance dredging is derived from the London Protocol, which forms the basis for Australia's Sea Dumping Act 1981. Based on this, the environmental regulators are particularly focused on the following questions:

1. Can sedimentation be managed at the Port to avoid or reduce the need for maintenance dredging?
   - Where do sediments accumulate in the Port and at what volumes and rates?
   - What causes sedimentation in the Port?
   - Does sedimentation at the Port pose a risk to port operations and safety?
   - Why does the Port need to undertake maintenance dredging?
2. If maintenance dredging must occur, has there been a comprehensive assessment of whether the material can be beneficially reused?
3. If no beneficial reuse options are available, what would be the most suitable and feasible disposal or placement options?

4. Has a comparative analysis of options been undertaken, that considers human health, social values, environmental impacts and disproportionate costs?

To answer these questions, NQBP developed a framework as part of the SSM assessment at the Port of Hay Point. This framework was subsequently used to inform the framework that has been adopted at the Port of Weipa well as the framework developed for the MDS, demonstrating that NQBP have been proactive at developing sound long-term maintenance dredging strategies. The findings from all the SSM studies being undertaken will feed into the development of a new LMDMP at the Port of Weipa.

1.2. Port of Weipa

The Port of Weipa is located in the Gulf of Carpentaria, on the north-west coast of the Cape York Peninsula in Northern Queensland. The Port is located within Albatross Bay, a large embayment, with the wharves and berths located in the Embley River (Figure 2 and Figure 3). The Port of Weipa consists of:

- a main shipping channel in Albatross Bay called South Channel; and
- an Inner Harbour which is within the Embley River and consists of four shipping berths (Lorim Point East and West, Humbug Wharf and Evans Landing) and the Approach and Departure Channels.

The Port has approximately 622 hectares of channels, swing basins and berths where depths are maintained by maintenance dredging. Since 2002 maintenance dredging at the Port has been undertaken annually by the Trailing Suction Hopper Dredger (TSHD) Brisbane, with volumes ranging from approximately 300,000 m^3 to 2,400,000 m^3. The majority of the maintenance dredging requirement at the Port of Weipa is within the mid to outer sections of the South Channel where the sediment is predominantly fine-grained silt and clay. There is also some requirement for annual maintenance dredging within the Inner Harbour and inner area of the South Channel where the sediment has a higher proportion of sand.

The fact that the Port has required annual maintenance dredging indicates that regular natural sediment transport and sedimentation occurs in the region. In addition to the regular sedimentation, it has also been observed that extreme events such as tropical cyclones (TCs) can result in significant increases in the sedimentation and therefore increased maintenance dredging requirements at the Port. TCs influence the Gulf of Carpentaria almost annually, with some of these also influencing the Weipa region. Based on analysis of historical TCs, the region has been found to be influenced by tropical cyclones on average every other year, although the magnitude of this influence can vary significantly. To reduce the risk of increased sedimentation from a TC resulting in operational or safety issues at the Port, maintenance dredging at the Port has typically been scheduled immediately after the wet season (when TCs occur).

1.3. Report Structure

The report herein is set out as follows:

- an introduction to the study is provided in **Section 1**;
- an overview of the measured water quality data and the data processing and analysis methods are provided in **Section 2**;
- the literature review on environmental thresholds and the results of the IDF analysis are presented in **Section 3**; and
- a summary of the key components of the report are given in **Section 4**, including recommendations.

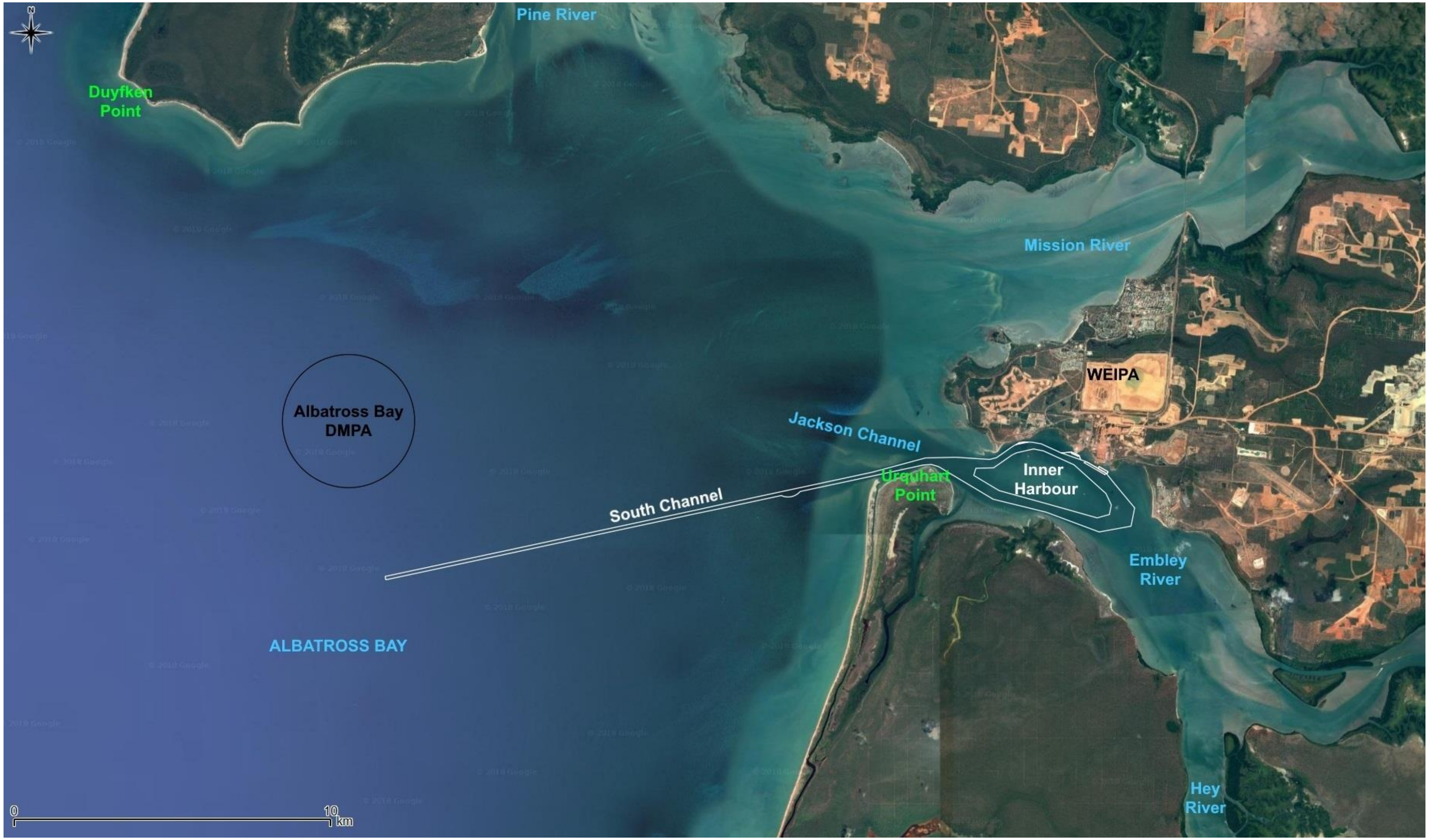

Figure 2. Location of the Port of Weipa.

Figure 3. Close up of the Port of Weipa Inner Harbour area and berths

2. Water Quality Data

2.1. Introduction

To develop suitable water quality triggers, high quality site-specific baseline data are required. Data collected between January 2018 and August 2019 by James Cook University (JCU) were available at multiple sites (although not all sites collected data for the full duration) around the Port of Weipa (Figure 4). The ambient marine water quality monitoring program collected baseline water quality measurements using multiparameter instrumentation manufactured by JCU.

The following parameters were measured and have been analysed as part of this assessment:

- near bed turbidity;
- benthic light availability/ Photosynthetically Active Radiation (PAR); and
- deposition rates.

Additional information on the instrumentation and the measurements obtained are provided in Waltham *et al.* (2016).

2.2. Data Sources

JCU has been carrying out NQBP's ongoing ambient marine water quality monitoring around the coastal waters of the Port of Weipa since January 2018. As part of the program, water quality sensors were deployed at five locations (see Figure 4 and Table 1), with each sensor returning data on turbidity, benthic light and deposition at a ten-minute temporal resolution. Four of these measurement locations provide data to characterise the water quality local to the Port of Weipa, while the fifth location (WQ3) provides data to characterise the water quality around Amrun Port. No further consideration to the data from WQ3 is provided in this report as these data are considered separately as part of the Amrun Port environmental thresholds assessment.

Details on data availability at each site is given in Table 1. The longest datasets were at WQ1 and WQ4, where, at the time of analysis, data were available for a nineteen month period from late January 2018 to late August 2019. The instrument at WQ5 was recovered in July 2018 and the deployment period (six month) was therefore considered too short to be considered as part of this analysis.

PCS (2019a) noted that the instrument at WQ4 recorded very high peaks from May 2019 onwards. These high peaks do not generally correlate with peaks in turbidity at other sites or the metocean conditions. Further, the near bed turbidity readings did not correlate well with surface turbidity readings taken at WQ4 during the 2019 maintenance dredge program. Data collected at WQ4 after the start of May 2019 were therefore considered to either be erroneous, or representative of a very localised process influencing the near bed turbidity (the location of WQ4 was moved approximately 350 m to the south-east at the start of May 2019). Data at WQ4 obtained after the start of May 2019 were therefore not included in the analysis (for turbidity, PAR and deposition rates).

The data return for each instrument (except for WQ5 which was only deployed for a short period) has been calculated and the results are presented in Table 2 and the periods of data return for turbidity are also shown as a time series in Figure 5. The data return for turbidity at individual locations was between 65% and 70% during the wet season and more than 90% during the dry season, except at WQ4 where data post 1st May 2019 were removed (giving a data return of 53%). The data return for PAR was slightly higher than the turbidity data return, while the data return for deposition rates was slightly lower.

Table 1. Summary of water quality data used in this study

Site Name	Latitude	Longitude	Period
WQ1	-12.6709° S	141.8475° E	19/01/2018 to 27/08/2019 (ongoing)
WQ2	-12.6736° S	141.7765° E	16/03/2018 to 28/08/2019 (ongoing)
WQ4	-12.6918° S	141.8693° E	19/01/2018 to 28/08/2019 (ongoing)*
WQ5	-12.6798° S	141.7494° E	19/01/2018 to 13/07/2018

** data from 01 May 2019 were removed from the dataset*

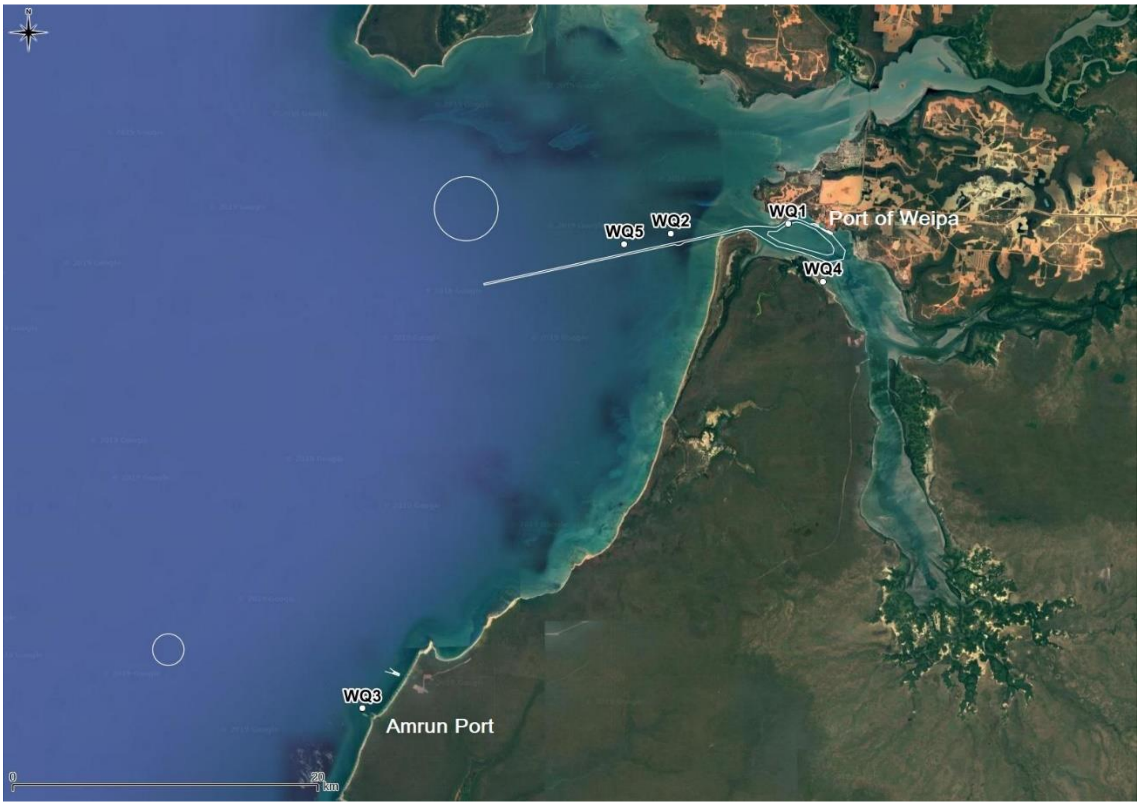

Figure 4. Location map of the water quality monitoring sites.

Table 2. Summary of data return at water quality monitoring stations

Site Name	Turbidity				PAR		Deposition Rates	
	Hours of data		Percentage return*		Percentage return		Percentage return	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
WQ1	4,726	6,803	70	94	91	96	67	87
WQ2	4,543	6,714	67	93	78	88	59	92
WQ4	4,380	4,066	65	56	87	46	54	36

** Percentage return quantified as the percentage of time readings were obtained between 19 Jan 2018 to 28 August 2019*

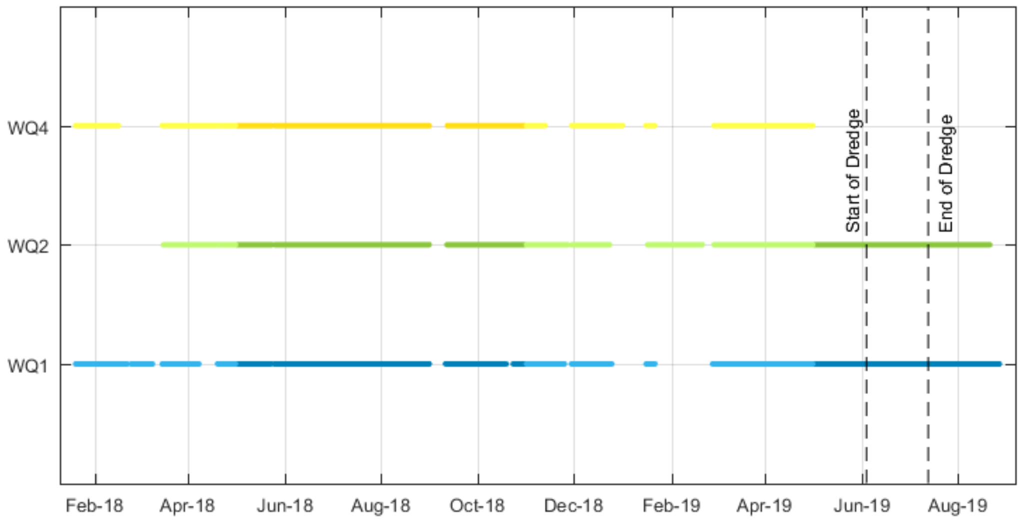

Figure 5. Periods of data return for Turbidity (wet season shown as lighter colour, dry season as darker colour)

2.3. Data Processing

The JCU turbidity loggers use 180 degree backscatter to measure turbidity. The international turbidity standard ISO7027 defines turbidity readings in Nephelometric Turbidity Unit (NTU) only for 90 degree scatter. However, the JCU instrumentation uses 180 degree backscatter as it allows for much more effective cleaning (critical to avoid issues with bio-fouling during long deployment periods). Because particle size influences the angular scattering functions of incident light (Ludwig and Hanes 1990; Conner and De Visser 1992; Wolanski *et al*., 1994; Bunt *et al*., 1999) instruments using different scattering angles can give different measurements of turbidity (in NTU). In acknowledgement of this fact, the readings obtained in this study are referred to in units of NTU equivalent (NTUe).

Instrumentation used for real-time monitoring during dredging activity may differ from the instrumentation deployed by JCU (for example, during the 2019 maintenance dredge program Vision Environment used telemetered surface turbidity loggers for monitoring which measured NTU). It is important that differences in data analysed to develop thresholds and triggers and real-time monitoring data are understood and accounted for (including any differences over the angle that backscatter is measured).

The IDF analysis has been performed directly on the turbidity data measured in NTUe so that thresholds and management triggers can be defined which can be applied as part of any adaptive management required during future dredging programs.

The turbidity data were processed using an hourly rolling average to smooth the data and remove any spikes/noise which can occur when measuring turbidity. To ensure that the management triggers are representative of the natural conditions that sensitive receptors can tolerate, the following periods were removed from the data and excluded from the analysis:

- periods when natural conditions resulted in impacts to sensitive receptors (no periods identified); and
- periods when conditions were modified by anthropogenic activities such as dredging. The duration of the 2019 maintenance dredging program was removed from the data (4 June 2019 to 13 July 2019) as the dredging was observed to result in some increases in turbidity (PCS, 2019a). Data were also removed for the seven day period following the completion of the dredge, to allow turbidity to return to natural levels. The period of the 2018 maintenance dredging program was not removed from the data as the program only

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involved the TSHD Brisbane (the 2019 program also included the much larger TSHD Oranje) and is not expected to have noticeably increased turbidity at any of the sites.

To enable comparison of management triggers relative to published thresholds which are given in Suspended Sediment Concentrations (SSC), conversion factors can be applied. The conversion factors vary between sites/instruments and were calculated based on concurrent in-situ water sampling and turbidity measurements by JCU at each monitoring site. The conversions applicable at each site are provided in Table 3.

Table 3. Conversion factors at each site

Site Name	Conversion Factor (NTUe to mg/l)
WQ1	1.295
WQ2	1.337
WQ4	1.770

The relationship between NTUe and SSC can vary and change during dredging operations due to the different sediment properties of the suspended sediment resulting from the dredging activities (Thackston and Palermo, 2000). In the case of maintenance dredging, when the sediment to be removed is natural sediment which has been recently deposited in the dredged areas, the properties of the sediment in suspension due to dredging compared to the sediment naturally in suspension is not expected to differ significantly. As such, the NTUe to SSC relationship is not expected to change significantly during periods of maintenance dredging.

Light intensity was measured at the monitoring stations at ten minute intervals using a PAR sensor, which was positioned on the horizontal surface of the water quality logging instrument. The instantaneous values recorded at each ten minute interval are multiplied by 600 and summed for each day to provide total daily PAR in mol photons/m^2/day. The IDF analysis was performed on these derived daily PAR readings. As with turbidity, PAR data collected during the 2019 maintenance dredge program (and a seven day period following completion of the dredge) were removed prior to analysis.

Sediment deposition was measured using optical backscatter sensors which determine deposition based on the backscatter of light detected by the sensor (Waltham *et al*., 2018). During deployment, the sensor is wiped clean every 2 hours to prevent the deposition from becoming too thick for the sensor to measure. The instruments can therefore accurately measure deposition over time, but they can only measure erosion of any sediment which has been deposited over the previous 2 hours. For example, a period of consistent erosion would only be shown as zero deposition by the sensor. As such, the instruments are not able to define the net deposition/erosion which has occurred, but the gross deposition over time.

Deposition data are provided as a measurement of deposited sediment in mg/cm^2. The deposition rate is calculated over the two hour interval between sensor wipes and averaged over the day to derive daily deposition rates in mg/cm^2/day. Data collected during the 2019 maintenance dredge program and for a seven day period following completion of the dredging were removed and the IDF analysis was applied to the average daily deposition rates.

2.4. IDF Analysis Method

The IDF analysis has the following aims:

- to describe the water quality of the natural environment and its temporal and spatial variability in and around the Port of Weipa;

- to assist in defining relevant thresholds which could be used for adaptive management of future maintenance dredging activities at the Port of Weipa; and
- to assist in defining thresholds that can be adopted for processing plume modelling results for the maintenance dredging activities.

The results from the site-specific IDF analysis can be used to inform the magnitude (intensity) and associated duration of naturally occurring water quality changes and to provide site specific context to the discussion around intensity threshold values from the literature.

Measured data obtained as part of the ambient water quality monitoring program at the Port of Weipa were analysed to calculate intensity (percentiles) of turbidity, daily light and daily deposition rates and the associated duration and frequency of exceedances for the calculated intensities (i.e. IDF analysis).

The IDF analysis calculated the following, using the Fox (2016) approach:

- Calculation of **intensity** percentiles (1st to 99th percentile) for turbidity, daily light and daily deposition;
- Calculation of average **duration** and **frequency** for a range of intensity percentile exceedances;
- Presentation of a range of percentiles to show natural variability of conditions.

To try and capture the seasonal variability in the metocean and water quality conditions, the IDF analysis was undertaken for two separate periods:

- the wet season (taken to be November to April inclusive); and
- the dry season (taken to be May to October inclusive).

This allowed the water quality conditions resulting from the differing metocean conditions which occur during these two periods to be considered.

During the survey period, multiple cyclones and tropical lows occurred during the wet season, particularly in the 2018/19 wet season. However, quarterly monitoring of the seagrass habitats at Weipa in May 2019 indicated that there was no negative impact on the seagrass following these events (McKenna and Rasheed, 2019) and as such all available data collected during these periods were included in the IDF analysis. At some of the sites, the instruments continued to collect data during the periods of cyclone activity, while at other sites no data were returned. Data gaps during the 2018/2019 wet season (and for some of the dry season period of erroneous data at WQ4) were filled using results from numerical modelling. The numerical model was calibrated at the sites where data were available during the extreme conditions and was shown to provide a good representation of the turbidity. For further details on the numerical modelling see PCS (2019c).

The site specific triggers are defined based on the intensity of the water quality parameters and the total cumulative duration that the intensity was exceeded over durations relevant to the maintenance dredging at the Port of Weipa. The frequency of occurrence of events has been undertaken over two different duration periods:

- **20 days**: this is approximately representative of the duration of a typical annual maintenance dredging program at the Port of Weipa with a volume of 400,000 m^3; and
- **40 days**: this is approximately representative of the duration of an annual maintenance dredging program at the Port of Weipa following a tropical cycle (TC) with a volume of 800,000 m^3 undertaken by the Trailer Suction Hopper Dredger (TSHD) Brisbane or a worst case volume of 2,500,000 m^3 removed by two dredgers (a small and a large TSHD) working concurrently (as in 2019).

3. Ecological Thresholds

3.1. Introduction

Ecological thresholds refer to the point at which changes or disturbance in external conditions can cause a rapid change in an organism or habitat, noted as tolerance limits of a particular receptor. When these points of tolerance have been exceeded, potentially irreversible impacts can occur. In the marine environment, where activities such as dredging or disposal can cause changes to water quality parameters, thresholds are generally expressed as concentrations, levels or rates, or calculated as an intensity, duration and frequency over relative periods of time.

Ecological thresholds can be determined for any sensitive receptors present in the environment which could potentially be impacted. Seagrass beds are the primary sensitive receptor located in the area surrounding the Port of Weipa where maintenance dredging could potentially result in changes to the water quality parameters. JCU undertake annual seagrass surveys in the Port of Weipa and surrounding area on behalf of NQBP. During the May 2019 survey, four species of seagrass were identified (McKenna and Rasheed, 2019). These include the dominant seagrass species *Enhalus acoroides,* as well as *Halodule uninervis, Halophila ovalis* and *Thalassia hemprichii.* There are also some coral species present in the Weipa region (located at the southern end of Albatross Bay close to Amrun Port). Model simulations of plume dispersion for sediments disturbed by dredging and associated disposal at the Port of Weipa indicates that areas where coral are present are beyond the area where increased turbidity occurs (PCS, 2019c). However, the presence of coral in the area may help characterise the natural water quality conditions, and assist in quantifying applicable turbidity thresholds, particularly in view of the lack of quantitative turbidity thresholds for seagrass in the literature (see Section 3.3).

To assist in ensuring that ecological thresholds are not exceeded during dredging operations, water quality management triggers can be adopted. Trigger values are typically defined at a precautionary level below ecological thresholds to account for the potential delay between exceedance occurring and response (i.e. implementation of management measures), thus reducing the risk to habitats arising from a degradation of water quality conditions.

In order to define relevant trigger values at the Port of Weipa, a literature review to understand existing information on threshold values relevant to the receptors at the Port of Weipa has been undertaken. This review also considers the threshold values applied in previous dredge programs. Following this review, the measured water quality data for the Weipa region has been analysed to assess the relevance of the threshold values from the literature to the local environment. Based on this assessment site-specific trigger values have been defined.

3.2. Relevant Literature

A review of published literature was undertaken to help support discussions around suitable site specific thresholds for ecologically significant species for the Port of Weipa. The natural water quality conditions in the region can then be compared with the ecological thresholds from the literature for the key sensitive marine habitats known to occur in and around the Port of Weipa. The analysis will provide the basis for developing suitable triggers to inform adaptive management of dredging operations, and to support the analysis of dredge plume modelling results.

The following reports give the best summary of relevant literature, providing a synthesis of information and guidance for developing suitable trigger values for seagrasses and corals:

- Erftemeijer and Lewis, 2006. Environmental impacts of dredging on seagrasses: A review;

- Erftemeijer *et al*., 2012. Environmental impacts of dredging and other sediment disturbances on corals;
- Collier *et al.,* 2016. Light thresholds for seagrasses of the GBRWHA: a synthesis and guiding document; and
- Royal HaskoningDHV, 2018. Port of Hay Point: Environmental Thresholds, Maintenance Dredging Management and Monitoring.

3.3. Turbidity thresholds

Erftemeijer and Lewis (2006) reviewed the environmental impacts of dredging on seagrasses. In their review, they note that the effect of turbidity on seagrass ecosystems is two-fold, with material in suspension reducing benthic PAR and with subsequent settling of sediment on the bed resulting in smothering.

High turbidity has been identified as a major cause of loss of seagrasses worldwide (Shepherd *et al*., 1989; Green and Short, 2003). There are various reports of sublethal and lethal effects on seagrass meadows due to prologued exposure to high turbidity (and siltation) associated with dredging activities (for example Sabol *et al*., 2005). However, temporary fluctuations in turbidity may be accommodated by seagrasses, depending on the nature of the species (Westphalen *et al*., 2004).

Thresholds for seagrasses are typically defined in terms of benthic PAR rather than turbidity, as it is more biologically relevant to the health of benthic habitats such as seagrass, algae and corals (Waltham *et al.,* 2018). While benthic PAR is correlated with turbidity (with increases in material in suspension reducing the amount of light penetrating to the seabed), the relationship is complex with a dependency on the grain size, shape and type of particles in suspension and the depth of water. As such, extensive site specific data are required to be able to derive any meaningful relationships.

To try and determine indicative thresholds for turbidity at the JCU monitoring locations (based on thresholds for benthic PAR provided in the literature, see Section 3.4), the relationship between daily average turbidity and daily average benthic PAR was assessed. A general relationship whereby as turbidity increases, light levels decrease exponentially was found, as is well described by Beer-lambert's Law (Kirk, 1994). The relationship is shown in Figure 6.

Indicative equivalent turbidity intensity thresholds were derived by taking the 95th percentile value (to remove the effect of outliers) of daily turbidity obtained when the rolling mean benthic PAR was above the defined threshold for each season. These were derived for the wet season and the dry season for the following benthic PAR thresholds:

- 1.5 mol/m^2/day over a rolling 7 day average; and
- 3.5 mol/m^2/day over a rolling 14 day average.

Derived thresholds are provided in Table 4. Based on these results, a turbidity threshold of between 15 to 20 NTUe appears to relate to the benthic PAR thresholds from the literature for the dry season at the monitoring sites. This is equivalent to approximately 30 mg/l. A higher turbidity threshold of around 30 to 35 NTUe (equivalent to 50 to 60 mg/l) relates to the benthic PAR thresholds for the wet season.

These defined turbidity thresholds are expected to provide a conservative assessment of threshold values, since most of the seagrasses in the Port of Weipa region are located on the shallow mudlfats where benthic PAR will be higher than at the monitoring sites which are located on the seabed in deeper water (depths of 4-5 m below Mean Sea Level).

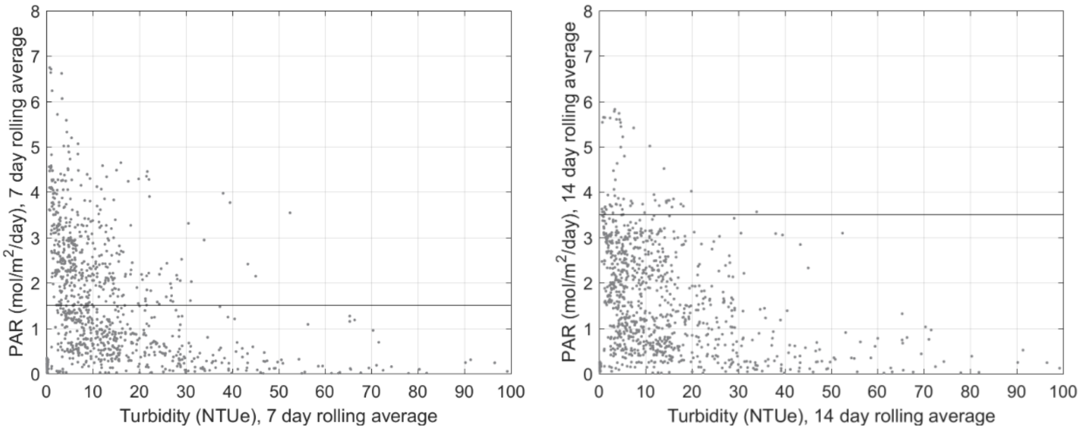

Figure 6. Relationship between turbidity and benthic PAR with a 7 day rolling average applied to PAR (left hand plot) and with a 14 day rolling average applied to PAR (right hand plot)

Table 4. Indicative turbidity thresholds relative to benthic PAR thresholds.

PAR threshold	Equivalent turbidity threshold			
	NTUe		mg/l	
	Wet Season	Dry Season	Wet Season	Dry Season
1.5 mol/m^2/day over a rolling 7 day average	31	19	51	30
3.5 mol/m^2/day over a rolling 14 day average	34	16	60	28

In addition to seagrasses, there are some coral species present in the Weipa region (located at the southern end of Albatross Bay close to Amrun Port) for which turbidity thresholds are available in the literature. These thresholds can be reviewed in the context of the available turbidity data for the Weipa region to better understand how they relate to the local conditions around the Port of Weipa.

The dominant coral families located in the Weipa region are considered to have a high to intermediate tolerance to SSC (Advisian, 2016). Based on Erftemeijer *et al*. (2012), the response matrix for intermediate tolerance corals is as follows:

- No effects at a continuous SSC of less than 20 mg/l (13 NTUe)[1];
- At a continuous SSC of 20-40 mg/l (13 to 26 NTUe) possible minor sublethal effects could occur;
- At a continuous SSC of 40-100 mg/l (26 to 67 NTUe) possible lethal and major sublethal impacts could occur; and
- At a continuous SSC of more than 100 mg/l (67 NTUe) lethal (partial mortality) and major lethal (mass mortality) effects could occur.

Comparison of these thresholds against the indicative turbidity thresholds derived from benthic PAR indicate that for the Weipa region, the lowest threshold value of 20 mg/l could be overly conservative. This will be considered further in section 3.3.1, through analysis of the natural water quality conditions in the Weipa region.

[1] *NTUe values based on an average conversion factor of 1.5 – this will actually vary on a site to site basis due to variations in conversion factors between sites*

3.3.1. Turbidity Local Context

A time series plot of turbidity at the Port of Weipa monitoring locations is shown in Figure 7. As discussed by PCS (2019a), there is a correlation between the turbidity and the tidal signal, with larger peaks in turbidity associated with the larger tidal range on spring tides, when flows are more energetic. There is also a correlation between turbidity and the wave activity with peaks in turbidity of more than 30 NTUe corresponding to periods when significant wave height (H_s) exceeded 0.75 m (PCS, 2019a).

Turbidity percentiles for NTUe for the three monitoring sites around the Port of Weipa are provided in Table 5. All measured data are included in the analysis, except for the period of the 2019 maintenance dredging program and a seven day period after completion of the dredging (to ensure that any artificially elevated SSC due to the dredging is not included in the analysis). For this period, results from the numerical model for just the natural SSC (converted to turbidity using the conversion factors in Table 3) were used instead of the measured data. In addition, any gaps in data return during the 2018/2019 wet season (December 2018 to April 2019) have also been filled using modelled SSC values, converted to NTUe. Similarly, the period of potentially erroneous data (after May 2019) at WQ4 has been partially filled using modelled values (between May 2019 and July 2019).

Table 5. Turbidity percentiles for the Port of Weipa monitoring sites

Site	Percentile Turbidity Intensity (NTUe)					Data Duration (days)	Turbidity to SSC conversion factor
	50th	80th	90th	95th	99th		
Wet Season							
WQ1	5.8	20	33.3	60.6	373.1	256.8	1.30
WQ2	9.8	46.8	204	338.9	661.5	222.1	1.34
WQ4	15.5	48.9	94.9	176.9	883.8	236.5	1.77
Dry Season							
WQ1	4.2	10.8	16.7	22.8	127.6	284.7	1.30
WQ2	2.4	6.8	14.7	30.4	120.4	282	1.34
WQ4	4.6	11.1	17.7	24.7	43.9	237	1.77
All Data							
WQ1	4.7	14.5	24	38	213.6	541.5	1.30
WQ2	3.9	19.6	50.1	187.7	449	504.1	1.34
WQ4	8.2	25.2	50.4	95.1	422.4	473.5	1.77

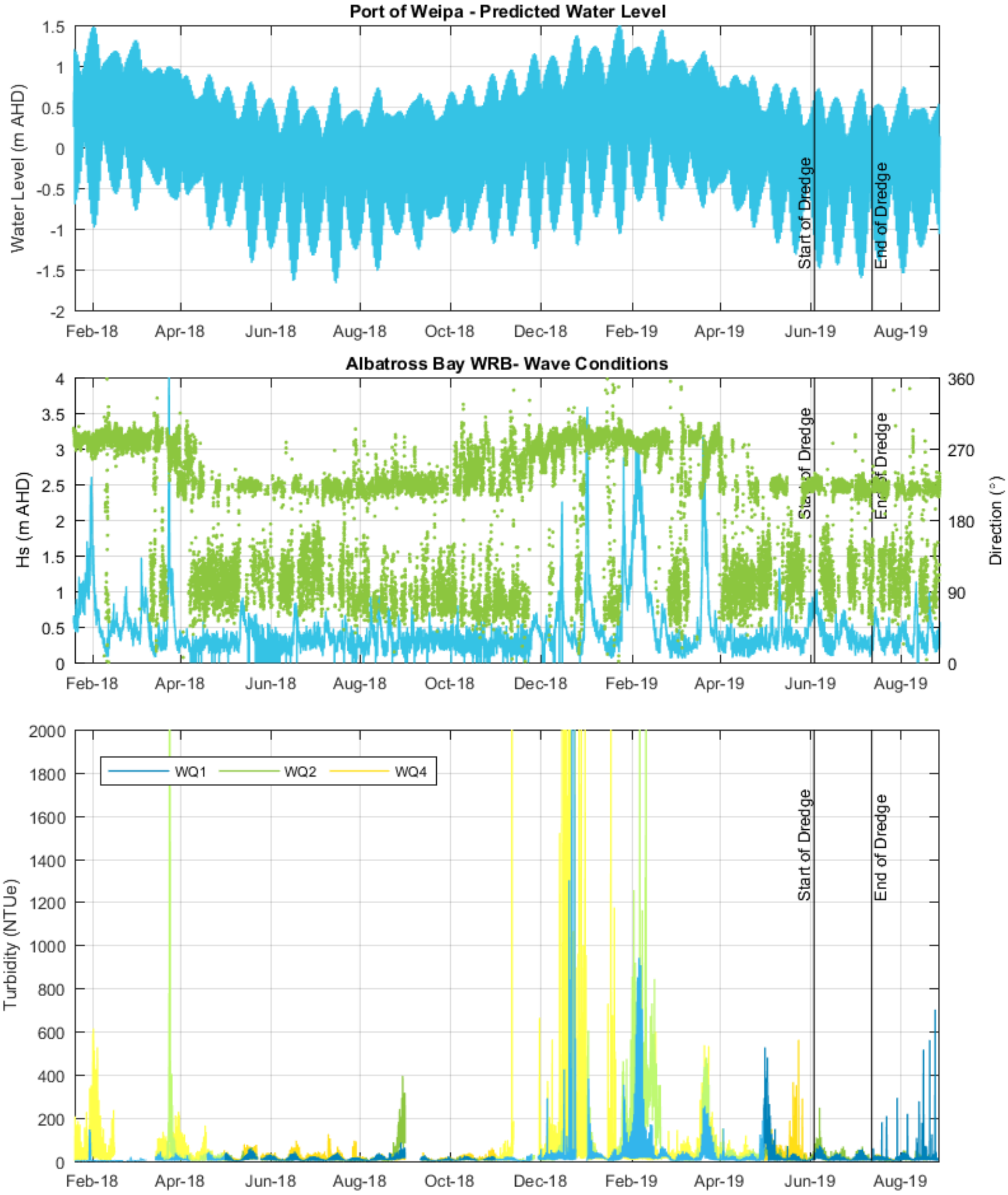

Figure 7. **Predicted water level (top), measured waves (middle) and benthic turbidity data (bottom) at the Port of Weipa. For turbidity, data for the wet season is shown as lighter colour and data for the dry season data as darker colour.**

The results from the turbidity data analysis show that:

- during the wet season, the median (50th percentile) natural turbidity is highest at WQ4 and lowest at WQ1. The high readings at WQ4 are influenced by localised enhanced turbidity across the adjacent areas of shallow mudflats, while the higher turbidity at WQ2 relative to WQ1 reflects the greater exposure of WQ2 to high energy wave events which influence the Albatross Bay region during the wet season.
- during the dry season, the median natural turbidity remains highest at WQ4, but is lowest at WQ2. During the dry season, when winds from the east and southeast sectors are more common, WQ1 is more exposed to locally generated wind waves.
- during the wet season, 20-40 mg/l is representative of:

- WQ1: 15 to 31 NTUe, representative of between the 50th and 90th percentile turbidity;
- WQ2: 15 to 30 NTUe, representative of between the 50th and 80th percentile turbidity; and
- WQ4: 11 to 23 NTUe, representative of between less than the 50th percentile and the 80th percentile.

- during the dry season, 20-40 mg/l is representative of:
  - WQ1: 15 to 31 NTUe, representative of between the 80th and 99th percentile turbidity;
  - WQ2: 15 to 30 NTUe, representative of between the 90th and 95th percentile turbidity; and
  - WQ4: 11 to 23 NTUe, representative of between just below the 80th percentile and the 95th percentile.

These results show that the natural environment in the Weipa region regularly experiences SSC in excess of 20 mg/l during the wet season (typically just under 50% of the time), while during the dry season the SSC exceeds 20 mg/l for less than 20% of the time. This highlights how the natural water quality varies seasonally and shows that an absolute SSC is unlikely to provide a realistic threshold for both seasons.

To further investigate this, the frequency and average duration that the intensity limit of 20 mg/l has been exceeded naturally has been calculated. The results are provided in Table 6, along with the SSC percentile at each site which is equal to 20 mg/l.

Table 6. Duration and frequency analysis of data at the Port of Weipa using a threshold of 20 mg/l

Site	20 mg/l as percentile	Average Duration (hrs)	Maximum Duration (hrs)	Frequency (times/season)
Wet Season				
WQ1	74	5.5	148.0	190
WQ2	59	7.4	641.2	198
WQ4	39	6.4	255.2	348
Dry Season				
WQ1	88	2.4	42.1	207
WQ2	90	2.7	167.0	189
WQ4	81	2.6	21.7	250
All Data				
WQ1	82	3.8	148.0	385
WQ2	76	7.7	641.2	234
WQ4	60	4.8	255.2	588

These results confirm that this threshold is regularly naturally exceeded during the wet season (25 to 60% of the time) and occasionally exceeded during the dry season (10 to 19% of the time). The average duration of exceedance is between 2 and 3 hours during the dry season and double this during the wet season. Further, the periods of exceedance can be significant, lasting for up to 6 days at WQ1 and 27 days at WQ2 during the wet season (and in the order of days and up to one week during the dry season). This suggests that this is not a suitable threshold to be applied for both periods due to the seasonal variability in turbidity which occurs in the region. Further, this threshold is more regularly exceeded at WQ4 than at WQ1 and WQ2, indicating that it may not be appropriate to apply a single threshold value across all sites.

Despite multiple Tropical Cyclones causing regular elevated SSC during the 2018/2019 wet season, no negative effects on seagrass were observed during subsequent monitoring in

May 2019 (McKenna and Rasheed, 2019). The instrument deployed at WQ2 continued to provide good data returns throughout some of the cyclonic periods, during which time peaks in SSC of more than 1,000 mg/l were recorded and sustained periods (of several weeks) with SSC of more than 200 mg/l occurred. While no adverse impacts on seagrass beds were found associated with these events, it is considered likely that the seagrass beds rely on periods of lower SSC during the dry season to recover (McKenna and Rasheed, 2019). Based on this, it is important that during the dry season the turbidity/SSC does not remain elevated for longer than naturally occurs during this season. Instead of adopting a set turbidity/SSC value for all sites and both seasons, it is proposed that adopting a set percentile would be the best approach, so that the variability between the sites and between the seasons can be allowed for.

For the latest maintenance dredge program at the Port of Weipa, near bed turbidity thresholds were defined as the 95th percentile of dry season turbidity readings at the JCU monitoring locations (PCS, 2019a). This threshold was considered applicable since it was not naturally exceeded that often but was still exceeded naturally during spring tides and when wave heights increased. At the time of analysis (May 2019), data were only available for a single dry season (2018) and based on these data the benthic turbidity thresholds were calculated to be 21 NTUe, 25 NTUe and 28 NTUe at WQ1, WQ2 and WQ4, respectively. Extending the analysis to include the 2019 dry season results in higher 95th percentile values at WQ 1 and WQ2 of 23 NTUe and 30 NTUe, respectively. At WQ4 the 95th percentile value at WQ4 (25 NTUe) is slightly reduced with the 2019 dry season included.

3.3.2. Defining Intensity Thresholds

Consistently applying set percentile values for the wet and dry season across all monitoring sites enables a comparable interpretation of natural SSC/NTUe and dredge related changes in intensity and duration.

Taking account of the results from the percentile analysis (Table 5) combined with the derived turbidity thresholds based on the benthic PAR limits, a 90th percentile turbidity has been adopted as a turbidity intensity threshold. This percentile can be used to define site specific turbidity intensity and duration thresholds which can be adopted if required for future maintenance dredging programs to ensure the turbidity remains within the natural range.

As the proposed 90th percentile turbidity/SSC threshold is on average only naturally exceeded for 10% of the time, it can be considered to be representative of a threshold for short duration acute impacts due to high turbidity/SSC, as opposed to longer duration chronic impacts due to prolonged periods of lower SSC.

During the wet season the 90th percentile turbidity/SSC threshold is representative of a much higher turbidity/SSC than during the dry season. Dredging is unlikely to be undertaken during the wet season when the more extreme wind and wave events can result in very high turbidity due to vessel operability restrictions. While dredging could be scheduled to occur at the end of the wet season, this would only go ahead provided the metocean conditions are favourable for the dredge vessel. Comparison of the wave conditions against turbidity (Figure 7) indicates that turbidity rapidly reduces to levels comparable with dry season turbidity once wave heights reduce towards the end of the wet season.

3.3.3. Defining Duration Thresholds

The threshold development approach is based around the assumption that as long as the turbidity remains within the natural range, then the dredging will not have contributed to potential impacts. The IDF results presented in Table 6 were based on data collected over the whole of the dry and wet season periods. To allow adaptive management to be effective, it is important to define a range of thresholds based on IDF analysis over discrete periods of time (20 days and 40 days in this case). This gives an understanding of the typical natural conditions over the likely range of durations of future dredging programs. It is therefore important to understand the range of natural conditions which can occur and to factor this into any adaptive management approaches.

Therefore, different duration thresholds are required to represent the limits when different management actions would be adopted. The duration thresholds have been defined assuming the 90th percentile turbidity intensity for both the wet season and dry season, as follows:

- average cumulative duration (as time in hours) that conditions exceed the 90th percentile turbidity (i.e. 10 % of the time);
- the 90th percentile of all the cumulative durations (as time in hours) that conditions exceed the 90th percentile turbidity for both the wet and dry seasons, over typical periods equivalent to the dredge duration (20 days and 40 days). This provides an indication of a known duration that intensity limits have naturally exceeded over a period of time without resulting in known impacts to seagrass; and
- the maximum cumulative duration (as time in hours) that conditions exceed the 90th percentile turbidity for both the wet and dry seasons, over typical periods equivalent to the dredge duration (20 days and 40 days). This provides an indication of the maximum duration that intensity limits have naturally been exceeded over a period of time without resulting in known impacts to seagrasses. Therefore, if these conditions are exceeded there is a potential that impacts to seagrasses could occur.

Intensity and duration values are suggested which consider both the intensity and duration of the natural conditions and events. The values provide the basis for potential trigger limits if adaptive monitoring is required and have been defined over a 20 day and 40 day period (relevant to potential dredging program durations). The calculated IDF parameters for the NTUe (and SSC) data measured at the three ambient water quality monitoring sites, for both the 20 day and 40 day periods for the wet and dry seasons are presented in Table 7 and Table 8.

Table 7. Suggested SSC/NTUe intensity and duration triggers at the three water quality monitoring sites around the Port of Weipa, based on a 20 day period

Site	Intensity (mg/l)	Intensity (NTUe)	Average Duration (hours)	90th Percentile Duration (hours)	Maximum Duration (hours)
Wet Season (90th percentile data)					
WQ1	43	33	48	116	251
WQ2	273	204	48	176	359
WQ4	168	95	48	115	225
Dry Season (90th percentile data)					
WQ1	22	17	48	97	133
WQ2	20	15	48	123	238
WQ4	31	18	48	109	173

Table 8. Suggested SSC/NTUe intensity and duration triggers at the three water quality monitoring sites around the Port of Weipa, based on a 40 day period

Site	Intensity (mg/l)	Intensity (NTUe)	Average Duration (hours)	90th Percentile Duration (hours)	Maximum Duration (hours)
Wet Season (90th percentile data)					
WQ1	43	33	96	271	324
WQ2	273	204	96	366	396
WQ4	168	95	96	237	252
Dry Season (90th percentile data)					
WQ1	22	17	96	142	155
WQ2	20	15	96	239	273
WQ4	31	18	96	194	248

The 90th percentile and maximum durations of exceedance at WQ1 during the dry season are considerably shorter than the equivalent values at WQ2 and WQ4 and do not show much of an increase relative to the mean duration. This is due to the turbidity conditions at WQ1 being influenced less by extreme conditions than at the other two sites.

3.3.4. Applying IDF Results for Adaptive Management

As the dredge plume modelling has shown that all three water quality monitoring sites could experience increased turbidity due to maintenance dredging (PCS, 2019c), it is considered that all three water quality monitoring sites could be used as trigger sites.

It is important that the variability of the natural environment shown by the IDF analysis be considered as part of any adaptive management approaches. Understanding the variability of the natural environment relevant to SSC/NTUe will help to ensure that:

- any increases in SSC/NTUe due to maintenance dredging are managed and do not result in SSC/NTUe conditions which could result in impacts to the natural receptors; and
- any natural fluctuations in SSC are not misinterpreted as impacts due to dredging.

To further test the proposed thresholds, near bed turbidity data collected during the 2019 maintenance dredge program have been analysed and the total duration above the thresholds defined by this assessment quantified. Data collected at WQ4 after May 2019 (including the period of the 2019 maintenance dredging) were considered to be erroneous, or representative of a very localised process influencing the near bed turbidity (see Section 2.2) and therefore the analysis at WQ4 is based on modelled data. Results are presented in Table 9, along with the 90th percentile and maximum duration of exceedance for a 40 day period. The 2019 maintenance dredging was completed in 39 days with a dredge volume of approximately 2.4 million m^3 in-situ removed as part of the program. This is a significantly larger dredge program than typical due to the high levels of accretion resulting from very high wave activity during the 2018/2019 wet season (PCS, 2019a).

The duration of time the turbidity was above the threshold (17 NTUe) at WQ1 was more than what would be expected to occur naturally (above the maximum duration). At WQ2 and WQ4, while the duration of time the thresholds were exceeded appear high, the duration of time the turbidity was above the thresholds was within the range of what naturally occurs (with the period of exceedance being less than the 90th percentile duration).

Results from the plume model were also analysed to determine the increase in duration above the threshold intensity value directly due to the dredging program (Table 9). These predicted increases are consistent with the results obtained from the data analysis and show that the highest increases in the threshold exceedance occurred at WQ1 and WQ2. The modelled total duration of exceedance agrees well with the measured data, providing confidence that the model can be reliably applied to assess the effect of different dredge scenarios (including more typical maintenance dredge volumes for the Port of Weipa).

Table 9. Comparison of duration of time above threshold for natural dry season conditions and during the 2019 maintenance dredge.

Site	Thresholds based on a 40 day period			Measured duration of exceedance during dredging (hours)	Modelled increase during dredging (hours)	Modelled duration of exceedance during dredging (hours)
	Average Duration (hours)	90th Percentile Duration (hours)	Maximum Duration (hours)			
WQ1	96	142	155	220	71	171
WQ2	96	239	273	192	90	186
WQ4	96	194	248	111*	15	111
**Due to issues with data quality at WQ4, this result is based on the model results*						

The numerical model has been used to investigate the combined (natural plus dredge) variability in SSC/NTUe for a range of dredge scenarios with placement at the existing Albatross Bay DMPA (PCS, 2019c), including:

- a typical dredge volume (400,000 m^3 in-situ) taking 24 days to complete with one dredger;
- a cyclonic dredge volume (800,000 m^3 in-situ) taking 48 days to complete with one dredger; and
- a worst-case dredge volume (2,500,000 m^3 in-situ) taking 33 days to complete with two dredgers.

The results have been analysed to quantify the increase in duration that turbidity is above the defined intensity threshold due to the dredging. The results indicate that the increase in duration above the intensity threshold for the typical and cyclonic dredge scenarios is unlikely to be detectable in the context of the natural variations which occur (being less than the 90th percentile minus the average duration that occurs naturally). On this basis, monitoring during maintenance dredging is not considered necessary during years when the dredge volume is within its normal range and the dredging can be undertaken by a single dredger. However, for the worst-case dredge scenario (such as the 2019 program) the duration increase is greater than the 90th percentile minus the average duration that occurs naturally at WQ1 and as such there is the potential for maintenance dredging to result in the natural range of turbidity conditions to be exceeded. Therefore, it is recommended that monitoring should be undertaken so that adaptive management can be implemented if required in years when the maintenance dredging volume requires multiple dredge vessels to be working concurrently.

Table 10. **Increase in duration of exceedance associated with different dredge volumes for the dry season.**

Site	Increase in duration of exceedance (hours)		
	Typical Dredging	Cyclonic Dredging	Worst-case Dredging
WQ1	5	14	**59**
WQ2	6	22	57
WQ4	0	5	5

Values in bold blue indicate an increase in duration greater than the natural variability in duration (defined as the 90th percentile minus the mean duration that occurs naturally)

3.4. Benthic PAR thresholds

As noted in Section 3.3, seagrass and corals rely on sunlight to photosynthesise, grow and reproduce. There is a considerable range of values reported in the literature for the minimum light requirements of seagrasses, varying between different seagrass species as well as within a single seagrass species. In addition to varying requirements for minimum light levels, the length of time that different species can survive at low levels is also highly variable (Erftemeijer and Lewis, 2006; Collier *et al.,* 2016; Statton *et al.,* 2017).

Variability between different seagrass species in their ability to endure and recover from periods of reduced light is related to their differing morphological and physiological characteristics (Chesire, *et al.,* 2002). These characteristics represent different strategies for survival in the face of stress or disturbance. Smaller fast growing (short-lived) species such as *Halophila ovalis* do not endure long once environmental conditions are beyond that to which they can adapt, but they tend to recolonise quickly following an impact. Larger seagrass species such as *Thalassia* sp. tend to have greater stored reserves that can be mobilised to sustain the plant temporarily during periods of reduced light (below their minimum light requirements). These species tend to be slow growing and long-lived and are more resistant to short-term to medium-term disturbances (of the order of week to months) (Erftemeijer and Lewis, 2006). If however, the impact persists to the point where these plants have depleted all their reserves, they die and once lost, recolonization of these species is unlikely, or at best slow. *Enhalus acoroides* is a persistent species that is capable of storing large amounts of carbohydrate energy reserves in below ground structures that can sustain the plant during various weather events and natural periods of low light throughout the wet season (Kilminster *et al,* 2015). However, it is considered likely that *Enhalus acoroides* relies on good light conditions during the dry season to recover their energy reserves each year.

For the species present in and around the Port of Weipa, thresholds of 2 mol/m^2/day over a rolling 7 day average (for *Halophila ovalis*) to 5 mol/m^2/day over a rolling 14 day average (for *Halodule uninervis* , *Thalassia hemprichii* and *Enhalus acoroides*) have been recommended (Collier *et al.,* 2016).

The effects of sub-optimal levels of light between species varies depending on the period of time the conditions persist and this should be considered during threshold development (Statton *et al*. 2017). For example, for *Halophila ovalis* thresholds of between 0.9 mol/m^2/day and 2.3 mol/m^2/day were recommended for periods of 3 weeks and 9 weeks, respectively (Statton *et al.,* 2017). Similarly, for *Halodule uninervis* thresholds of between 5 mol/m^2/day and 13 mol/m^2/day were recommended for periods of 6 weeks and 12 weeks, respectively.

As noted by Collier *et al*., (2016), in some locations, investments into research and monitoring has enabled the development of site-specific compliance standards for adaptive management. For example, McKenna *et al*. 2015 recommended the following thresholds for application at Abbot Point where *Halophila ovalis* and *Halodule uninervis* were among the seagrass species present:

- for the offshore areas of deepwater *Halophila* species, the threshold is 1.5 mol/m^2/day over a rolling 7 day average; and
- for the shallow inshore areas dominated by *Halodule uninervis*, the threshold is 3.5 mol/m^2/day over a rolling 14 day average.

Recommended thresholds were not provided for *Thalassia hemprichii* and *Enhalus acoroides*, however on the basis that the review by Collier *et al.,* (2016) recommended the same threshold for these species as *Halodule uninervis*, it would be reasonable to assume that if these species were present at Abbot Point, the modelling threshold for these would be 3.5 mol/m^2/day over a rolling 14 day average.

3.4.1. Benthic PAR Local Context

A time series of benthic PAR at the monitoring sites close to the Port of Weipa is shown in Figure 8. As noted in Section 3.3, there is an inverse relationship between benthic PAR and NTUe, with periods of high NTUe corresponding to periods of low benthic PAR (compare with Figure 7). This is because, suspended solids in the water column will reduce the amount of light reaching the seabed by the process of absorption or reflection.

Benthic PAR percentiles have been calculated for the wet and dry season (and for all data) and results are presented in Table 11. For benthic PAR the lower percentiles represent the higher light conditions at the seabed, with the amount of light reducing as the percentile increases. For example, the 20th percentile value of 2.9 mol photons/m^2/day at WQ1 shows that for 20% of the time benthic PAR is above this value (i.e. there is more light than this) and for 80% of the time benthic PAR is below this (i.e. there is less light than this). Lower percentile values have been included to show the higher benthic PAR values which relate to thresholds detailed in the published literature.

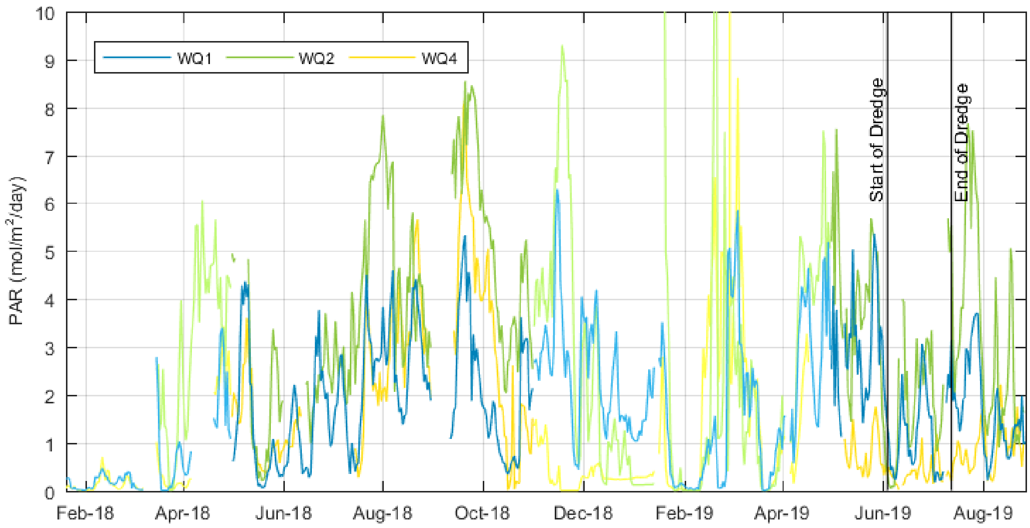

Figure 8. Time series of PAR data (wet season data shown as lighter colour, dry season data as darker colour).

Table 11. PAR percentiles for the Port of Weipa monitoring sites

Site	Percentile PAR Intensity (mol photons/m²/day)						Data Duration (days)
	1st	5th	10th	20th	50th	80th	
Wet Season							
WQ1	5.8	4.3	3.6	2.9	1.2	0.1	258
WQ2	13.0	7.8	5.6	4.5	1.8	0.1	221
WQ4	5.7	4.2	2.8	1.6	0.3	0	243
Dry Season							
WQ1	5.1	4.4	3.9	3.2	1.9	0.7	244
WQ2	8.4	7.5	6.9	5.8	3.5	2.0	222
WQ4	7.2	5.5	4.2	3.3	1.5	0.6	202
All Data							
WQ1	5.4	4.3	3.8	3.0	1.5	0.4	502
WQ2	10.7	7.5	6.7	5.1	3.0	1.0	443
WQ4	6.5	4.9	3.7	2.6	0.8	0.1	445

NQBP's ambient seagrass monitoring program shows that seagrass habitats are present close to the locations of monitoring sites WQ1 and WQ4 (McKenna and Rasheed, 2019). Based on the percentiles presented, the benthic PAR at WQ1 and WQ4 is below the higher 3.5 mol/m²/day benthic PAR threshold defined in the literature for close to 90% of the time during the wet season and more than 80% of the time during the dry season. The benthic PAR at WQ1 is below the lower benthic PAR threshold of 1.5 mol/m²/day defined in the literature for approximately 50% of the time during the wet and the dry seasons at WQ1 and for approximately 80% of the time during the wet season and 50% of the time during the dry season at WQ4.

Further analysis of the results was undertaken to provide an assessment of the duration and frequency of the lower levels of PAR (refer to Table A4 to Table A6 in Appendix A). Results show that in the context of the upper PAR threshold (of 3.5 mol/m²/day over a 14 day rolling average), during the dry season:

- WQ1: PAR is less than 3.2 mol/m²/day for 80% of the time, with an average consecutive duration of 26.8 days;
- WQ2: PAR is less than 3.5 mol/m²/day for 50% of the time, with an average consecutive duration of 16.3 days; and
- WQ4: PAR is less than 3.7 mol photons/m²/day for 80% of the time, with an average consecutive duration of 30.9 days.

In the context of the lower PAR threshold (of 1.5 mol/m²/day over a rolling 7 day average), during the dry season:

- WQ1: PAR is less than 1.9 mol/m²/day for 50% of the time, with an average consecutive duration of 15.6 days;
- WQ2: PAR is less than 2 mol/m²/day for 20% of the time, with an average consecutive duration of 5.2 days; and
- WQ4: PAR is less than 1.8 photons/m²/day for 50% of the time, with an average consecutive duration of 18.8 days.

These results indicate that seagrass species requiring 3.5 mol/m²/day would likely struggle at the monitoring sites as they only receive more light for 20% of the time during the dry season. The lower benthic PAR threshold of 1.5 mol/m²/day is more representative of the benthic PAR conditions at the Port of Weipa monitoring locations, although the average consecutive durations show that the benthic PAR is still often below the threshold for more than the 7 days stated in the literature. To further investigate this, the IDF analysis was undertaken on the benthic PAR data (Table 12). The table shows that even during the dry season the benthic PAR at the monitoring sites can be below the intensity threshold for up to 28 days at WQ4, which is significantly longer than the 7 day duration noted in the literature. However, it is important to note that the monitoring sites were selected to be close to the seagrass beds but not actually at the seagrass beds. Therefore, the water depths where monitoring has been undertaken are deeper than where seagrass is present and consequently benthic PAR at the monitoring locations are likely to be lower than at the adjacent shallower seagrass beds. This difference may partially account for the presence of seagrass beds in and around the Port of Weipa, despite the measured data showing conditions regularly being below benthic PAR thresholds defined in the published literature (sometimes for periods of several weeks at a time).

Table 12. Duration and frequency analysis of PAR data at the Port of Weipa using a threshold of 1.5 mol/m^2/day

Site	1.5 mol/m^2/day as percentile	Average Duration (days)	Maximum Duration (days)	Frequency (times/season)
Wet Season				
WQ1	42	6.3	29	10
WQ2	52	7.6	25	9
WQ4	21	9.5	74	12
Dry Season				
WQ1	60	7.0	24	8
WQ2	88	3.0	12	5
WQ4	65	4.0	28	11
All Data				
WQ1	51	7.0	29	17
WQ2	71	5.8	25	14
WQ4	37	15.5	74	7

3.4.2. Applying IDF Results for Adaptive Management

The analysis in this report indicates that the upper threshold values of benthic PAR from the literature are not suitable for the development of thresholds for adaptive management of dredging activities at the Port Weipa for areas where seagrass occurs. This is because the threshold values are regularly exceeded naturally at the monitoring sites. The lower threshold value of benthic PAR as recommended in the literature is less frequently exceeded naturally, however the duration of these natural exceedances can be longer than the duration of a typical maintenance dredge program at the Port of Weipa and longer than the duration values noted in the literature. On this basis, and in view of practical limitations associated with obtaining accurate benthic PAR readings in real time during dredging operations, it is not recommended that benthic PAR is adopted as a trigger for adaptive management of maintenance dredging at the Port of Weipa.

Recent research in Western Australia on thresholds and indicators of seagrass response to dredging pressures also confirmed that there remains considerable uncertainty in the accuracy of predicting impacts of benthic PAR on seagrasses (Lavery *et al*. 2017; Statton *et al*. 2017a,b). Of particular relevance to the Port of Weipa, research undertaken around the response and recovery of seagrasses to variations in the frequency and intensity of light deprivation noted that thresholds for *Halophila ovalis* could not be provided as responses to light reduction treatments were unreliable (with no significant difference among treatments prior to the point where the control plants began to show stress) (Statton *et al*. 2017a,b).

It is proposed that ongoing ambient monitoring of benthic PAR should continue, along with the annual seagrass surveys, to better the understanding of the relationship between the seagrass species present and the benthic light in and around the Port of Weipa.

3.5. Deposition Rate Thresholds

Several studies have documented deterioration of seagrass meadows by smothering due to excessive sedimentation. The effect of sedimentation on seagrasses varies significantly between species and also between studies (Duarte *et al.,* 1997; Vermaat *et al.* 1997; Cabaco *et al*., 2008).

Vermaat *et al.* (1997) provided the following critical threshold sedimentation rates relevant to seagrass species in the Weipa region:

- *Halophila ovalis:* 2 cm/yr (this is equivalent to an average rate of 1.6 $mg/cm^2/day$ assuming a bed density of 300 kg/m^3); and
- *Enhalus acoroides:* 10 cm/yr (this is equivalent to an average rate of 8.0 $mg/cm^2/day$ assuming a bed density of 300 kg/m^3).

No threshold sedimentation rates were provided for *Halodule uninervis* and *Thalassia hemprichii* by Vermaat *et al*. (1997), however other studies which did consider these species (at least in terms of burial) suggested that *Halodule uninervis* has a similar tolerance to burial as *Halophila ovalis* and *Thalassia hemprichii* has a tolerance somewhere between that of *Halophila ovalis* and *Enhalus acoroides*. On this basis, the thresholds of these two species can be considered to represent the lower and upper threshold values for seagrasses at the Port of Weipa.

As noted in Section 3.3, in addition to seagrasses, there are some coral species present in the Weipa region, although plume modelling indicates that these are outside of the area of impact. The following values are therefore only provided for context. The dominant coral families located in the Weipa region have a sensitive (foliose or laminar form) or intermediate (massive or dome shaped) tolerance to elevated sedimentation rates (Erftemeijer *et al.* 2012). Extended periods of sedimentation values of 10 $mg/cm^2/day$ may have sub-lethal impacts on corals of these growth forms. Lethal impacts may not occur until these colonies are exposed to extended periods of sedimentation (up to 2 weeks) of more than 50 $mg/cm^2/day$.

3.5.1. Deposition Local Context

Deposition has been measured in the Weipa region over a nineteen month period using optical backscatter sensors which determine deposition based on the backscatter of light detected by the sensor (Waltham *et al.,* 2018). During deployment, the sensor is wiped clean every 2 hours to prevent the deposition from becoming too thick for the sensor to measure. The instruments can therefore accurately measure deposition over time, but they can only measure erosion of any sediment which has been deposited over the previous 2 hours. For example, a period of consistent erosion would only be shown as zero deposition by the sensor. As such, the instruments are not able to define the net deposition/erosion which has occurred, but the gross deposition over time. On this basis, the deposition rates derived from the instrumentation are not directly comparable to (and are expected to be higher than) the threshold values defined in the literature, which consider a net deposition rate. This is a limitation of most instruments which can accurately measure deposition and remotely log it over time (Royal HaskoningDHV, 2018).

A time series of deposition rates at the three monitoring locations is shown in Figure 9. Daily deposition rates are typically of the order of tens of $mg/cm^2/day$ but with many 'spikes' of far higher daily deposition (of several hundred $mg/cm^2/day$).

To provide further quantification of the daily deposition data, percentile values are presented in Table 13. The median (50th percentile) sedimentation rates at the sites were as follows:

- WQ1: 4.8 mg/cm²/day during the wet season and 19.5 mg/cm²/day during the dry season;
- WQ2: 10.7 mg/cm²/day during the wet season and 13.5 mg/cm²/day during the dry season; and
- WQ4: 21.3 mg/cm²/day during the wet season and 33.3 mg/cm²/day during the dry season.

These median values are (with the exception of sedimentation rate at WQ1 during the wet season) above both the lower (1.6 mg/cm²/day) and upper (8 mg/cm²/day) sedimentation thresholds in the literature for seagrass.

Comparison of deposition rates in the wet and dry season indicate that on average, deposition is higher in the dry season, but there are larger 'spikes' (i.e. greater extremes) in deposition in the wet season. This finding appears to contradict the long-term observations at the Port of Weipa where the majority of the sedimentation in the dredged areas of the Port occurs during the wet season, with limited sedimentation occurring during the dry season.

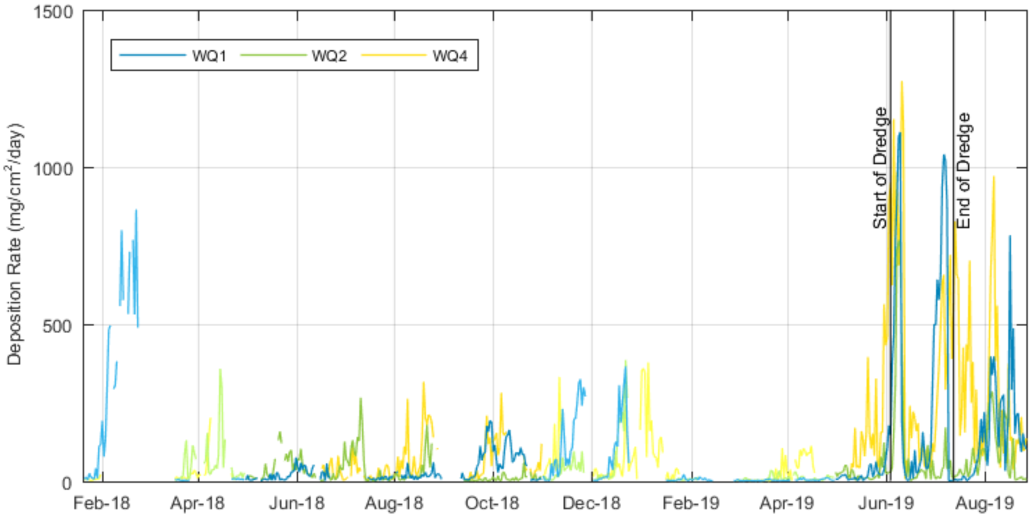

Figure 9. Time series of deposition rate data (wet season data shown as lighter colour, dry season data as darker colour).

Table 13. Deposition rate percentiles for the Port of Weipa monitoring sites.

Site	Percentile Deposition rate Intensity (mg/cm²/day)					Data Duration (days)
	50th	80th	90th	95th	99th	
Wet Season						
WQ1	4.8	107.4	298.6	487.9	786.1	190
WQ2	10.7	38.7	84.4	152.9	346.5	167
WQ4	21.3	86.9	136.7	321.9	483.3	152
Dry Season						
WQ1	19.5	90.7	155.3	217.5	426	217
WQ2	13.5	63.4	115.5	157.8	265.4	231
WQ4	33.3	115.7	153.0	205.8	294.8	108
All Data						
WQ1	11.8	95.8	197	311.7	746.2	407
WQ2	12.2	55.6	103.6	157.4	275.5	398
WQ4	26.1	97.8	148.8	208.8	375.3	260

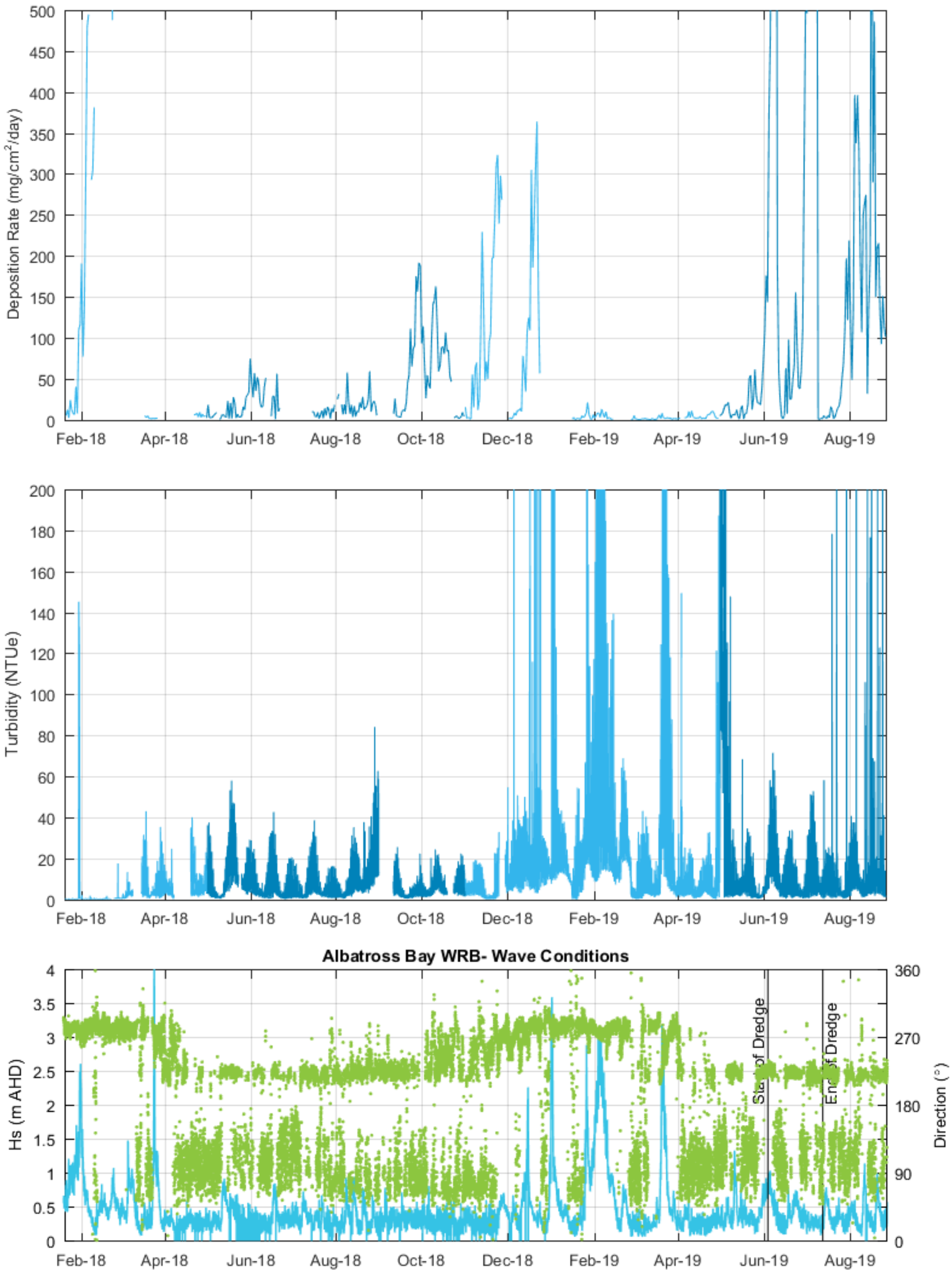

Figure 10. **Time series of deposition rate data (top), benthic turbidity data (middle) and measured waves (bottom) at WQ1. For deposition and turbidity wet season data shown as lighter colour, dry season data as darker colour.**

To better understand the deposition data, the correlation between deposition rate, turbidity and wave activity has been investigated. A time series of concurrent deposition and turbidity at WQ1, along with wave data at the Albatross Bay Wave Rider Buoy (WRB) is presented in Figure 10. In general, the periods of enhanced wave activity (which as noted in Section 3.3.1 correlates with elevated turbidity), coincide with low rates of deposition, particularly during the 2018/2019 wet season. However, at times during the dry season higher deposition rates coincide with periods of enhanced wave activity and turbidity (for example in June 2019).

Based on this, it is possible that the measured deposition data is showing such high deposition rates as sediment is regularly deposited during periods of slack water (high water and low water) but then much of the deposited sediment is subsequently resuspended during the following flood or ebb currents. However, the instrument is only able to measure the cumulative deposition and so the erosion resulting after the deposition is not included in the measurements.

Despite the concerns/limitations with the measured deposition data, IDF analysis has been undertaken on the data. The calculated IDF parameters for the daily deposition data for periods of both 20 days and 40 days are presented in Appendix A, Table A7 to Table A9.

3.5.2. Applying IDF Results for Adaptive Management

Considerable research has highlighted that existing methods for monitoring of deposition using in-situ benthic instruments are inherently unreliable and not suitable for adaptive management monitoring. Research has demonstrated that sediment deposition rates are sometimes over-estimated by an order of magnitude when using conventional techniques (e.g. sediment traps) for sampling (Whinney *et al.* 2017).

In addition to concerns over the accuracy of measured deposition rates and the inability to accurately measure net deposition/erosion, consideration should be given to the lack of suitable adaptive management responses available if deposition thresholds are exceeded. As an example, if a deposition trigger was reached (set against a defined threshold), and the management response was to stop dredging, clarity around when dredging could safely resume cannot be easily defined as the deposited sediment would potentially remain in location and most instruments cannot show when erosion has occurred.

While deposition data are of limited use for adaptive monitoring purposes, they are considered relevant to providing context to the interpretation of impacts to marine habitats and organisms following dredging (Whinney *et al.,* 2017). This aligns with the recommendations of Sinclair *et al*., (2013) who suggest that deposition should be included as part of ongoing water quality investigations, rather than being linked to operational management responses. Based on this, along with the measured deposition data at the monitoring sites showing very high rates relative to the thresholds in the literature, it is recommended that deposition rates continue to be monitored as part of the ongoing ambient monitoring program but that they are not adopted for any adaptive management monitoring.

3.6. Recommended Monitoring Approach

The IDF results indicate that turbidity data is the most appropriate parameter for monitoring during dredging operations when real-time monitoring is required to inform adaptive management. However, it is recommended that monitoring of both benthic PAR and deposition (as well as turbidity) continues to better the understanding of the relationship between these parameters and seagrass species present in and around the Port of Weipa and to provide context to the interpretation of impacts to marine habitats and organisms following natural or anthropogenic events (e.g. maintenance dredging).

Based on the results from numerical modelling undertaken as part of the Port of Weipa SSM Project (PCS, 2019c), for typical and cyclonic maintenance dredge volumes (400,000 and 800,000 m^3) which only require a single dredger, it is considered sufficient to rely on benthic turbidity data retrieved every two weeks during dredging to examine the data and ensure that the effects on turbidity are in line with expectations. This is because any increases in the duration of time above the turbidity thresholds were predicted by the modelling to be small and so are considered unlikely to be detectable in the context of naturally occurring variations. However, it is recommended that real-time adaptive monitoring be undertaken for worst case sedimentation years (in the order of 2.5 Mm^3) similar to the 2019 maintenance dredge program when two dredgers are required to work concurrently. This is because both the in-situ measured water quality data and the numerical modelling results indicate that such a large dredge program has the potential to result in elevated turbidity for longer durations than would naturally occur and there is therefore the potential that impacts to seagrasses could occur.

In terms of monitoring during any dredge program where adaptive management may be required (such as for a dredge volume in the order of 2.5 million m^3 which requires two dredgers working concurrently), it is recommended that surface turbidity data are collected and analysed in real-time. The use of surface turbidity over near-bed turbidity is to avoid logistical constraints with collecting and telemetering results from an instrument deployed on the bed (due to cables becoming tangled or broken). The thresholds derived in this report represent near bed turbidity, for application to monitoring of surface turbidity during dredging they would need to be converted to equivalent surface turbidity. Conversion factors should be derived by comparison of concurrent near bed and surface turbidity readings. This approach was adopted by PCS (2019d) and the derived conversion factors are considered applicable for future monitoring. The real time surface turbidity readings should be cross checked with benthic data every couple of weeks when servicing is undertaken and benthic data retrieved.

At the water quality monitoring sites, the real time data should be used to calculate the cumulative duration of time the measured turbidity data exceed the threshold turbidity intensity value. The calculated near bed NTUe values and equivalent surface NTU values are provided along with the duration for the trigger points in Table 14. Results are presented for the dry season since they are considered applicable to the periods during which maintenance dredging would occur.

An example plot showing how the various duration thresholds could fit into different adaptive management zones is provided in Figure 11. While the cumulative duration remains below the average duration, then the water quality conditions fall within Management Zone A. In this Management Zone no response is required and dredging can operate as normal. If the cumulative hourly count increases above the average, 90^{th} percentile or maximum duration thresholds then pre-defined management actions would be initiated as part of the adaptive management process. These would likely include investigating the cause for the threshold exceedance (i.e. natural or dredging related) and responding to the elevated turbidity (e.g. implementing adaptive management measures).

Table 14. Threshold values at water quality monitoring sites based on a 40 day period

Site	Turbidity threshold		Duration (hours)		
	Near bed (NTUe)	Surface (NTU)	Average	90th Percentile	Max.
WQ1	17	9.0	96	142	155
WQ2	15	7.9	96	239	273
WQ4	18	9.5	96	194	248

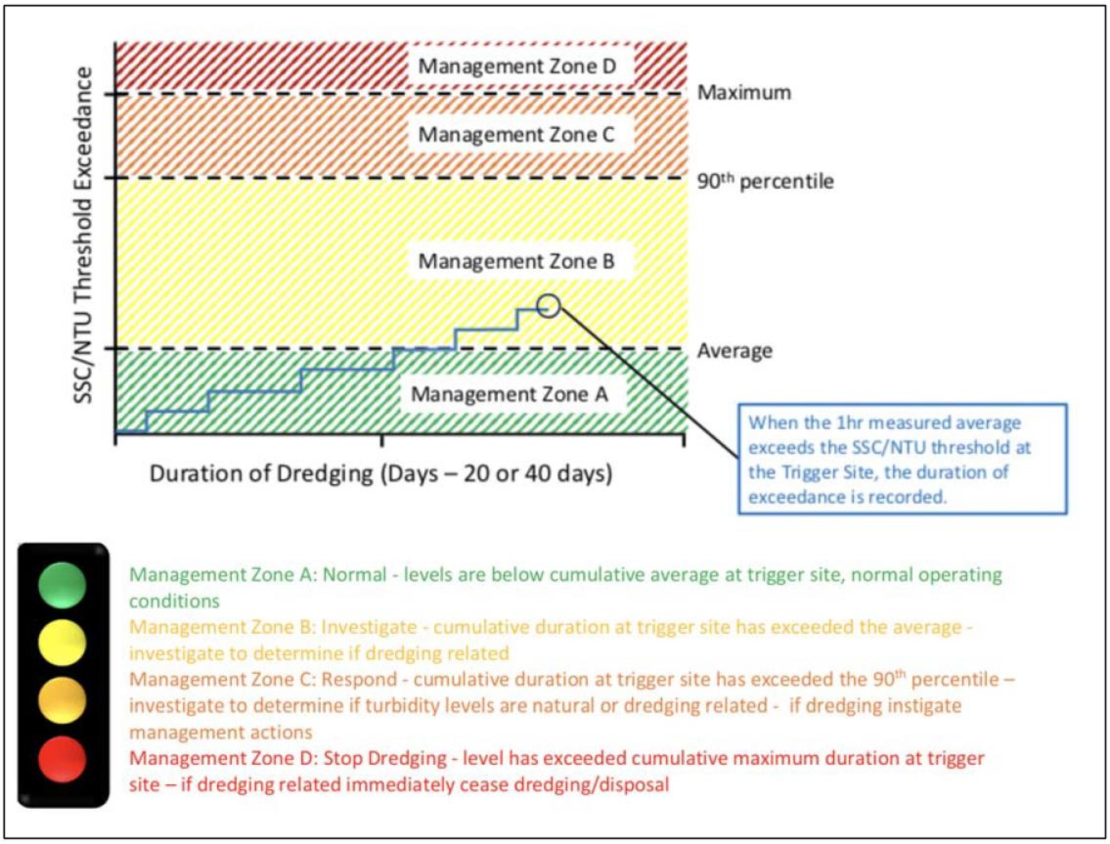

Figure 11. Hypothetical example of plot showing duration trigger limits and management zones (NQBP, 2018).

4. Summary

This study had the aim of understanding the natural variability of turbidity, benthic PAR and deposition at the Port of Weipa. Based on a review of information in the literature and an analysis of measured data, relevant ecological thresholds have been defined. The data analysis has applied an intensity, duration and frequency (IDF) approach to define the water quality conditions to enable the recommendation of appropriate water quality triggers that can be considered for use in future adaptive monitoring.

The results of the IDF analysis for turbidity, benthic PAR and deposition are summarised below:

Turbidity:

- the highest turbidity was found at site WQ4 during both the wet and the dry season;
- the lowest turbidity was found at site WQ1 during the wet season and at WQ2 during the dry season;
- significant difference in the IDF parameters for wet and dry season are evident with significantly higher turbidity occurring in the wet season. Adoption of a percentile threshold was therefore considered the most appropriate approach to define turbidity intensity thresholds;
- based on correlations between turbidity and benthic PAR data and the benthic PAR thresholds defined in the literature, the 90th percentile turbidity was considered an appropriate turbidity intensity threshold; and
- turbidity data were found to be a suitable parameter for monitoring in real-time as part of any future adaptive management required.

PAR:

- the benthic light percentiles calculated based on the measured data show significant variability between the sites and seasons;
- during the wet season the 80th percentiles are typically close to 0 mol/m^2/day (i.e. no benthic light);
- the benthic PAR is below the upper light threshold defined in the literature for the seagrass present in the region of 3.5 mol/m^2/day for more than 50 % of the dry season (and for closer to 80% of the wet season);
- typical durations below the lower light threshold defined in the literature for the seagrass present in the region of 1.5 mol/m^2/day can persist for periods of several weeks during the dry season; and
- benthic PAR was not considered useful for application in adaptive management at the Port of Weipa as the measured data showed that naturally it was regularly lower than published minimum light requirements (and for longer continuous durations) for the relevant seagrass species.

Deposition:

- the deposition percentiles calculated based on the measured data show significant variability between sites;
- the median deposition rates were typically higher than the thresholds defined in the literature for seagrass species present at and around the Port of Weipa;
- the typical durations of exceedances of the percentiles presented were of the order of 1 to 5 days; and

- deposition was not considered useful for application in adaptive management at the Port of Weipa on the basis that monitoring with current conventional methods is considered unreliable and because the natural variations in deposition rates are often much higher that the thresholds noted in the literature.

In combination with available information from relevant literature, the outcomes of the data analysis presented in this report:

- provide a better understanding of the natural environment and its temporal and spatial variability in and around the Port of Weipa;
- define relevant triggers that can, when required, be used in adaptive management of future maintenance dredging activities at the Port of Weipa; and
- define triggers that can be adopted for processing of plume modelling results at the Port of Weipa for various dredging activities.

The defined trigger limits are based on 20 day and 40 day periods (relevant to potential dredging programs). Based on results from plume modelling undertaken as part of the SSM Project, real-time monitoring for use in adaptive management is only considered to be required for worst-case dredge programs when multiple dredgers are required to be working concurrently (i.e. dredge volumes in the order of the 2019 maintenance dredge program (2.4 Mm^3)). This is because any increase in turbidity resulting from dredging for smaller dredge programs which only require a single dredger has been found to be unlikely to be detectable above the natural variability in turbidity. The intensity and duration thresholds for the dry season, calculated over the 40 day period, are considered most applicable for adaptive management of this type of dredging program due to the likely duration of the program (Table 14).

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Appendices

Appendix A – Summary IDF Tables

In the following tables, the 'Duration' is the average duration of the exceedance above the thresholds and 'Frequency' is the average number of occurrences of exceedance above the threshold in a defined period (of either 20 days or 40 days).

A1.1 Statistical Analysis Results for Turbidity

Table A1. Calculated IDFs for SSC (mg/L) and turbidity (NTU) for WQ1 for both wet and dry seasons

WQ1					
Percentile (%ile)	Intensity (mg/l)	Intensity (NTUe)	Duration (hrs)	Frequency	
				(20 days)	(40 days)
Wet Season					
80th	25.9	20	4.8	19	37
90th	43.1	33.3	4.2	11	22
95th	78.5	60.6	3.7	6	12
99th	483.2	373.1	2.6	2	4
Dry Season					
80th	14	10.8	3.3	26	50
90th	21.6	16.7	2.2	20	38
95th	29.5	22.8	2.0	11	21
99th	165.3	127.6	2.5	1	2

Table A2. Calculated IDFs for SSC (mg/L) and turbidity (NTU) for WQ2 for both wet and dry seasons

WQ2					
Percentile (%ile)	Intensity (mg/l)	Intensity (NTUe)	Duration (hrs)	Frequency	
				(20 days)	(40 days)
Wet Season					
80th	62.6	46.8	5.6	22	43
90th	272.7	204	3.8	13	26
95th	453.1	338.9	2.4	10	20
99th	884.4	661.5	2.2	2	4
Dry Season					
80th	9.1	6.8	3.6	27	51
90th	19.6	14.7	2.7	20	38
95th	40.7	30.4	2.6	11	21
99th	161	120.4	2.7	1	3

Table A3. Calculated IDFs for SSC (mg/L) and turbidity (NTU) for WQ4 for both wet and dry seasons

WQ4					
Percentile (%ile)	Intensity (mg/l)	Intensity (NTUe)	Duration (hrs)	Frequency	
				(20 days)	(40 days)
Wet Season					
80th	86.6	48.9	2.9	30	52
90th	168	94.9	2.3	19	33
95th	313.2	176.9	2.1	11	19
99th	1564.3	883.8	1.5	3	6
Dry Season					
80th	19.6	11.1	2.7	32	62
90th	31.3	17.7	1.9	23	45
95th	43.7	24.7	1.5	14	28
99th	77.7	43.9	1.2	4	7

A2 Statistical Analysis Results for PAR

Table A4. Calculated IDFs for daily PAR for WQ1 for both wet and dry seasons

WQ1				
Percentile (%ile)	Intensity ($mol/m^2/day$)	Duration (days)	Frequency (20 days)	Frequency (40 days)
Wet Season				
1st	5.8	31.9	0.4	0.7
5th	4.3	20.4	0.5	1.2
10th	3.6	16.6	0.8	1.6
20th	2.9	12.9	1.1	1.8
50th	1.2	9.9	0.9	1.6
80th	0.1	5.8	0.7	1.1
Dry Season				
1st	5.1	34.6	0.5	0.7
5th	4.4	19.3	0.8	1.5
10th	3.9	15.7	1	1.6
20th	3.2	8.9	1.6	2.8
50th	1.9	7.2	1.3	1.9
80th	0.7	5.4	0.7	1.3

Table A5. Calculated IDFs for daily PAR for WQ2 for both wet and dry seasons

Percentile (%ile)	WQ2 Intensity ($mol/m^2/day$)	Duration (days)	Frequency (20 days)	Frequency (40 days)
Wet Season				
1st	13	33.6	0.7	1.1
5th	7.8	20.5	0.7	1.3
10th	5.6	14.4	0.9	1.9
20th	4.5	10.4	1.2	2.4
50th	1.8	7.9	1.6	2.7
80th	0.1	5.8	1	1.4
Dry Season				
1st	8.4	24.4	0.8	1.1
5th	7.5	16.2	1.1	1.7
10th	6.9	14.3	1	1.7
20th	5.8	9.3	1.6	2.8
50th	3.5	5.8	1.4	2.5
80th	2	4.4	0.8	1.2

Table A6. Calculated IDFs for daily PAR for WQ4 for both wet and dry seasons

Percentile (%ile)	WQ4 Intensity ($mol/m^2/day$)	Duration (days)	Frequency (20 days)	Frequency (40 days)
Wet Season				
1st	5.7	26.8	0.5	1
5th	4.2	19.5	0.6	1.3
10th	2.8	15.6	0.8	1.7
20th	1.6	12.8	0.8	1.8
50th	0.3	8.9	1.2	2.0
80th	0	4.9	0.9	1.5
Dry Season				
1st	7.8	20.2	0.9	1.5
5th	5.7	13.01	1.1	1.9
10th	4.7	9.8	1.6	2.9
20th	3.7	6.2	2	3.6
50th	1.8	4.6	2	3.3
80th	0.7	2.6	1.3	2.4

A3 Statistical Analysis Results for Deposition

Table A7. Calculated IDFs for daily deposition for WQ1 for both wet and dry seasons

Percentile (%ile)	WQ1 Intensity (mg/cm^2/day)	Duration (days)	Frequency (20 days)	Frequency (40 days)
Wet Season				
80th	107.4	4.2	0.5	1.1
90th	298.6	2.4	0.2	1.0
95th	487.9	2.3	0.2	0.5
99th	786.1	1.0	0	0.3
Dry Season				
80th	90.7	5.4	0.8	1.1
90th	155.3	2.4	0.8	0.8
95th	217.5	2.8	0.3	0.2
99th	426	1.0	0	0

Table A8. Calculated IDFs for daily deposition for WQ2 for both wet and dry seasons

Percentile (%ile)	WQ2 Intensity (mg/cm^2/day)	Duration (days)	Frequency (20 days)	Frequency (40 days)
Wet Season				
80th	38.7	2.5	1.3	2.4
90th	84.4	2.1	0.7	1.4
95th	152.9	2.8	0.1	0.4
99th	346.5	1.0	0.1	0.4
Dry Season				
80th	63.4	2.7	1.1	2
90th	115.5	2.3	0.6	1.0
95th	157.8	3.0	0.3	0.4
99th	265.4	1.5	0.1	0.1

Table A9. Calculated IDFs for daily deposition for WQ4 for both wet and dry seasons

WQ4				
Percentile (%ile)	Intensity (mg/cm^2/day)	Duration (days)	Frequency (20 days)	Frequency (40 days)
Wet Season				
80th	86.9	1.7	1.7	3.3
90th	136.7	1.5	0.5	1.6
95th	321.9	1.3	0.3	0.9
99th	483.3	1.0	0	0.1
Dry Season				
80th	115.7	2.2	1.2	2.3
90th	153.0	1.6	1.2	2.2
95th	205.8	1.0	0.8	1.2
99th	294.8	1.0	0.2	0.2