Effects of dredging and dredging related activities on water quality: Spatial and temporal patterns

Rebecca Fisher[1,2,3], Clair Stark[3,4], Peter Ridd[3,4], Ross Jones[1,2,3]

[1] Australian Institute of Marine Science, Perth, Western Australia, Australia

[2] UWA Oceans Institute, Perth, Australia, Perth, Western Australia, Australia

[3] Western Australian Marine Science Institution, Perth, Western Australia, Australia

[4] School of Engineering and Physical Sciences, James Cook University, Townsville, Australia

WAMSI Dredging Science Node

Theme 4 Report

Project 4.2

April 2017




WAMSI Dredging Science Node

The WAMSI Dredging Science Node is a strategic research initiative that evolved in response to uncertainties in the environmental impact assessment and management of large-scale dredging operations and coastal infrastructure developments. Its goal is to enhance capacity within government and the private sector to predict and manage the environmental impacts of dredging in Western Australia, delivered through a combination of reviews, field studies, laboratory experimentation, relationship testing and development of standardised protocols and guidance for impact prediction, monitoring and management.

Ownership of Intellectual property rights

Unless otherwise noted, any intellectual property rights in this publication are owned by the Western Australian Marine Science Institution, the Australian Institute of Marine Science and the University of Western Australia.

Funding Sources

The $20million Dredging Science Node is delivering one of the largest single issue environmental research programs in Australia. This applied research is funded by **Woodside Energy, Chevron Australia, BHP Billiton and the WAMSI Partners** and designed to provide a significant and meaningful improvement in the certainty around the effects, and management, of dredging operations in Western Australia. Although focussed on port and coastal development in Western Australia, the outputs will also be broadly applicable across Australia and globally.

This remarkable **collaboration between industry, government and research** extends beyond the classical funder-provider model. End-users of science in regulator and conservation agencies, and consultant and industry groups are actively involved in the governance of the node, to ensure ongoing focus on applicable science and converting the outputs into fit-for-purpose and usable products. The governance structure includes clear delineation between end-user focussed scoping and the arms-length research activity to ensure it is independent, unbiased and defensible.

And critically, the trusted across-sector collaboration developed through the WAMSI model has allowed the sharing of hundreds of millions of dollars worth of environmental monitoring data, much of it collected by environmental consultants on behalf of industry. By providing access to this usually **confidential data,** the **Industry Partners** are substantially enhancing WAMSI researchers' ability to determine the real-world impacts of dredging projects, and how they can best be managed. Rio Tinto's voluntary data contribution is particularly noteworthy, as it is not one of the funding contributors to the Node.

Funding and critical data

Critical data

Legal Notice

Year of publication: 2017

Metadata: http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=a884e0ab-1a82-4871-8f39-18c20ab4c9fb

Citation: Fisher R, Stark C, Ridd P and Jones R (2017) Effects of dredging and dredging related activities on water quality: Spatial and temporal patterns. Report of Theme 4 – Project 4.2, prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 106 pp.

Author Contributions: Conceived and designed the experiments: RJ RF CS PR. Analysed the data: RJ RF CS PR. Wrote the underlying papers: RJ RF CS PR.

Corresponding author and Institution: Ross Jones (Australian Institute of Marine Science, Perth, WA Australia).

Competing Interests: The commercial investors and data providers had no role in the data analysis, data interpretation, the decision to publish or in the preparation of the manuscript. The authors have declared that no competing interests exist.

Acknowledgements: We thank industry for making this data available for scientific research, M. Puotinen for providing information on cyclone activity, and several anonymous reviewers for extensive comments to earlier versions of the constituent manuscripts. Dr Ray Masini and Mr Kevin Crane (WAMSI Dredging Science Node, Node Leadership Team) for their advice and assistance during the project and the preparation of this report.

Collection permits/ethics approval: No collection occurred in the production of this report

Publications supporting this work:

Jones R, Fisher R, Stark C, Ridd P (2015) Temporal patterns in water quality from dredging in tropical environments. PlosOne 10:e0137112. doi:0137110.0131371/journal.pone.0137112

Fisher R, Stark C, Ridd P, Jones R (2015) Spatial patterns in water quality changes during dredging in tropical environments PLoS ONE 10:e0143309. doi:10.1371/journal.pone.0143309

Front cover images (L-R)

Image 1: Trailing Suction Hopper Dredge *Gateway* in operation during the Fremantle Port Inner Harbour and Channel Deepening Project. (Source: OEPA)

Image 2: Close up image of the reef flat at Scott Reef (Source: AIMS)

Image 3: Dredge Plume at Barrow Island. Image produced with data from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) taken on 29th August 2010.

Image 4: Close up image of the reef flat at Scott Reef (Source: AIMS)

Contents

Executive summary

Dredging and dredge material (spoil) disposal releases sediment into the water column, creating turbid plumes that can drift onto nearby marine habitats where they can have a range of effects on underlying communities. There is some satellite imagery showing plumes extending large distances in a qualitative sense, but there is very little published, quantitative information (or even grey literature) on the spatial and temporal changes in water quality associated with capital or maintenance dredging projects. Furthermore, there is a body of literature on the effects of sediments on corals, but in the absence of quantitative data on real-world pressure fields, it is difficult to contextualize the results from past experiments and apply the findings to inform the environmental impact assessment and management of dredging.

Establishing an evidence-based footprint of water quality impacts associated with dredging is clearly important for a range of stakeholders, including the public, so they have a clear and common perception of the nature and scale of pressures associated with dredging projects[1]. It is also important for impact prediction purposes and the requirement in Western Australia (WA) for dredging proponents to assess and manage projects according to a spatially-based zonation scheme. Knowledge of how pressure fields (a pressure is a physical, chemical or biological change that has the potential to cause environmental change) vary in space and time, will allow laboratory-based studies examining dose-response relationships to be conducted with realistic or relevant exposure conditions. To address these issues, the water quality monitoring data available from several large scale capital dredging projects in recent years have been subject to detailed study.

The dredging projects were significant by global standards and occurred in sensitive tropical marine environments containing coral reefs and other benthic primary producer habitats and filter and suspension feeding communities. They also occurred in very different marine settings including (1) an offshore, 'clear water' environment (Barrow Island)[2], (2) nearshore communities adjacent to an exposed headland (Cape Lambert)[3] and (3) an enclosed inshore turbid reef environment (Mermaid Sound, Burrup Peninsula) in the Dampier Archipelago[4]. Water quality data are also available from a fourth large scale capital dredging project, the Wheatstone project[5]. This project occurred in another type of marine setting, a coastal, river-influenced location with a natural nearshore to offshore gradient in turbidity. Water quality analyses associated with that project are described in Theme 6[6].

Light (photosynthetically active radiation, PAR) data and turbidity (water cloudiness) data (as nephelometric turbidity units, NTU) were collected at the seabed at multiple locations across all 4 dredging projects and in some instances included sites as close as ~200 m from the dredging, to reference sites up to 30 km away. Monitoring was continuous, at sub-hourly time frames over the duration of the projects (which were all more than 1 year in duration), and data for many sites included extended pre-dredging, baseline periods. All turbidity data were aggregated for all sites and retained at the finest temporal resolution (10 or 30 min, depending on the project). Light data were modelled to determine the sum of the per second quantum flux measurements, giving a daily light integral (DLI) as mol photons m^{-2} d^{-1}. As much as possible all types of analyses were performed on all data sets, although in some projects the spatial and temporal coverage was more comprehensive.

A running means analyses was conducted for all 4 dredging programs for light (where available) and turbidity,

[1] EPA (2016) Environmental Protection Authority 2016, Technical Guidance – Environmental Impact Assessment of Marine Dredging Proposals, EPA, Western Australia

[2] Gorgon Project (Barrow Island): WA Environmental Protection Authority Bulletin 1221 Ministerial Statement No. 800

[3] Cape Lambert B Project: WA Environmental Protection Authority Bulletin 1357, Ministerial Statement 840

[4] Pluto Project (Burrup Peninsula): WA Environmental Protection Authority Bulletin 1259, Ministerial Statement No. 757

[5] Wheatstone Development: WA Environmental Protection Authority Bulletin 1404 Ministerial Statement No. 873

[6] Abdul Wahab MA, Fromont J, Gomez O, Fisher R, Jones R (2017) Comparisons of benthic filter feeder communities before and after a large-scale capital dredging program. Report of Theme 6 - Project 6.3, prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia.

with increasing time periods from 1 h (for NTU) or 1 d (for PAR) through to 21 d to 28 d. Once running means were calculated for each period, percentile (*P*) values (P_{50}, P_{80}, P_{95}, P_{99}, P_{100} for NTU and P_{50}, P_{20}, P_5, P_1, and P_0 for PAR) were calculated and plotted as a function of the running mean time span for the pre-dredge (when available) and dredging periods.

The effects of distances from the dredge activities were examined using summarized (median) quarterly data for each year of data, from both the baseline and dredging periods, and a generalised additive mixed modelling (GAMM) approach was used to examine the influence of distance from dredging on a range of turbidity and light summary metrics. Two other analyses were conducted, including an examination of the intensity (I), duration (D) and frequency (F) of turbidity events at hourly and daily intervals, and for the light data, the characteristics of low light periods caused by the high turbidity were examined using various cut-off points (to define semi-darkness) and define the durations of these 'twilight' periods.

There were clear shifts in ambient turbidity associated with dredging for all 3 projects, with turbidity increasing by over an order of magnitude across a range of time scales. Very close to dredging i.e. <500 m away, a characteristic feature of these particular case studies was very high temporal variability with fluctuations of 2–3 orders of magnitude over the course of a day common. These occurred during natural baseline conditions at some locations, but are very pronounced during dredging. Over several hours suspended sediment concentrations (SSCs) reached 100–500 mg L^{-1}, less turbid conditions (10–80 mg L^{-1}) persisted over several days, but over longer periods (weeks to months) averages were <10 mg L^{-1}.

Given this variability, the summary statistics used in analysing water quality (mean versus median etc), as well as the temporal scale adopted (hours, days, weeks) can dramatically affect interpretation of the data. Compared to pre-dredging conditions, dredging increased the intensity, duration and frequency of the turbidity events by 10-, 5- and 3-fold respectively (at sites <500 m from dredging). However, when averaged across the entire dredging period of 80–180 weeks, turbidity values only increased by 2–3 fold above pre-dredging levels. Similarly, the upper percentile values (e.g. P_{99}, P_{95}) of seawater quality parameters can be highly elevated over short periods, but converge to values only marginally above baseline states over longer periods. Dredging in these studies altered the overall probability density distribution, increasing the frequency of extreme values.

During turbidity events all benthic light was sometimes extinguished, even in the shallow reefal environment. However, a much more common feature was very low light 'caliginous' or daytime twilight periods, with corals experiencing up to more than 30 consecutive days below a DLI of 0.8 mol photons m^{-2} d^{-1} at sites very near dredging. Benthic light was highly seasonal, with the lowest low light periods occurring during the winter months. Extended darkness or semi-dark periods represent significant challenges to benthic primary producers, which usually only naturally experience such events over much shorter time periods. Longer term periods may present physiological challenges for corals beyond those of a temporary energy deficit, including inducing bleaching or the dissociation of the coral-algal symbiosis.

For the Barrow Island, Cape Lambert and Burrup Peninsula projects, periodicity or cycles in the turbidity data sets, and in locally collected wind data, were examined using wavelet analyses (a spectral analysis technique similar to a Fourier transformation). Changes in turbidity were sometimes cyclical and periodicities were found in the data during both the baseline and dredge studies. They occurred semi-diurnally associated with tides, diurnally associated with daily sea breezes characteristic of the WA coast, and fortnightly associated with spring-neap cycles. Longer cycles from 1 week to several months were also observed and the higher energy regions appearing in the 30–100 d range, centered on 40 d, were possibly due to the Madden Julian Oscillation (MJO). A strong seasonal cycle was evident in the wind data across the three study regions, but weaker in the wave spectrum at Barrow Island, and was either weak or not present in the turbidity global spectra at Barrow Island and the Burrup Peninsula.

For Barrow Island, and to a lesser extent Burrup Peninsula and Cape Lambert, there was strong evidence of a relationship with distance from dredging with all the water quality metrics examined, supporting the use of spatially-based zonation scheme to manage dredging projects in WA. Impacts of dredging tend to follow an exponential decay, with sites near dredging experiencing greater changes to water quality than sites further away. The spatial extent of a water quality impact was defined as when the median value (P_{50}) exceeded the P_{80} of the baseline data, and was somewhat variable among and between studies, as well as the specific water quality metric being examined. For the most part, water quality impacts appeared to extend distances of up to around 3–5 km from the dredging. However, there were instances of an impact on water quality extending up to 15–19 km away for the Barrow Island project. It should be recognized that this was a very large scale capital dredging operation (8 Mm^3) with multiple dredges working 24 hours a day. It was conducted in a clear water environment, and with an unusual oceanographic feature of unidirectional flow over the duration of the project. As such, we consider that the southerly extension of the plume represents an upper bound on the distances at which dredging might be expected to cause 'measurable perturbations' (as defined by the P_{50}–P_{80} approach). Overall, the strength of the relationship with distance from dredging was much weaker for the Cape Lambert and Burrup Peninsula projects in part because there were much fewer water quality monitoring sites close to the dredging activities. The dredging also occurred over a larger area and associated with entrance channels than the Barrow project where dredging was more concentrated in a few locations.

While distance from dredging patterns are relatively consistent once potential effects of overall plume direction are taken into account, the reality is that at any given time turbidity plumes appear to be highly spatially heterogeneous on fine temporal scales. Such fine-scale spatial heterogeneity suggests that hierarchical sampling of water quality parameters may be necessary, and/or that extreme care must be taken in ensuring that reference sites adequately represent impact locations.

Considerations for predicting and managing the impact of dredging

Pre-development Surveys

Natural turbidity plumes are highly spatially and temporally variable in the Pilbara, and this has important implications for the design of pre-development surveys. Across the major dredging capital dredging campaigns, natural conditions of extreme turbidity (>100 NTU over several days) occur as a result of strong wind and wave/swell induced resuspension, largely associated with cyclones. Across the 5½ years of water quality monitoring undertaken during the Barrow Island, Cape Lambert and Burrup Peninsula dredging campaigns, as many as 6 cyclones occurred in the vicinity of these sites, in some cases generating high turbidity events even at reference locations (>100 NTU). Across the 4 year duration of water quality monitoring data associated with the Wheatstone dredging campaign at Onslow, 5 cyclones passed nearby the study site (nearest gales from <10 km to >150 km away), with a 6th, Cyclone Olwyn, passing directly over the study area when dredging had just been completed[6]) **Where baseline data will form a key element of impact prediction and/or the derivation of management thresholds, it is essential that the baseline period captures representative conditions across the full range of likely natural turbidity profiles, through ensuring that both extreme and typical weather events are represented appropriately.** The occurrence of naturally occurring high turbidity events can be critical in the accurate derivation of baseline percentile values, and provides an essential understanding of the natural range of possible turbidity values that can be expected, to which changes during dredging can be compared.

In addition to naturally occurring extreme events, we also found evidence of temporal cycles in the water quality data examined. Benthic light (particularly expressed in the form of a daily light integral (DLI) as mol photons m^{-2} d^{-1}) is highly seasonal, and there was evidence that a spring-neap tidal cycle, as well as a Madden-Julian Oscillation in the turbidity time series data (see Appendix 1)**. Evidence of periodicity in water quality time series means that care should be taken to ensure that natural cycles are accounted for appropriately in pre-development sampling to ensure that the baseline state accurately represents inherent background conditions.** Light levels are inherently much lower in winter than in summer because of shorter day lengths and seasonal solar declination. If DLIs are to be used as management triggers and dredging is likely to occur across winter months, it essential natural light levels during this period are captured during baseline surveys. **Pre-development surveys should be sufficient to assess the occurrence of underlying natural turbidity cycles associated with spring neap-tides, and other cyclic weather conditions.**

Across a management area, natural patterns in water quality (and underlying sediments) can occur, and this was particularly evident across the study sites monitored during the Wheatstone dredging program off Onslow, which showed a strong nearshore–offshore gradient[6]. It is important that the spatial extent and distribution of water quality sampling (and associated benthic monitoring sites, where relevant) covers the full range of natural spatial variation in turbidity, and attempts should be made to identify multiple (replicate) potential reference locations that are representative across this natural range**. Estimates of likely spatial extents of dredging related turbidity should be modelled specifically for individual projects, preferably before pre-development surveys are undertaken to aid in the selection of appropriate reference locations.** Where this is not possible estimates based on previous dredging programs may be a useful guide.

Because of the physical properties of attenuation of light through the water column, benthic light is highly dependent on depth. **Where light sensitive benthic taxa occur in the management area, it is important to ensure that surveys of relevant benthic taxa as well as baseline light environment conditions provide adequate representation across the range of relevant depths**.

Impact Prediction

Dredging causes changes in both ambient turbidity and light. Extreme peaks in turbidity (>100 NTU) can occur under calm sea conditions and can result in significant sedimentation events. Turbidity can increase near dredging by over an order of magnitude across a range of time scales (days to weeks), and represents a significant pressure to sensitive receptors. Elevated turbidity leads to benthic light being sometimes extinguished, even at relatively shallow locations, and extended 'caliginous' periods are common near dredging, with corals and other benthic taxa sometimes experiencing >30 consecutive days below a DLI of 0.8 mol photons m^{-2} d^{-1}. **Changes to environmental conditions across all three primary cause effect pathways of mortality (deposited sediments, reduced availability of benthic light, turbidity and suspended sediments) highlight the need to consider indicators of all three during impact prediction.**

The ephemeral nature of dredging related turbidity plumes means that summary statistics, as well as the time scale over which summaries are captured, are critically important when trying to predict the impact of dredging activities, both on water quality conditions, as well as the resulting impact on benthos. Our water quality analyses showed that dredging increases the intensity, duration and frequency of episodic peaks in turbidity (i.e. acute effects) as well as more extended (chronic) elevations in turbidity. **To characterize temporal variability and capture both acute and chronic scales, it is recommended that water quality statistics be compiled over multiple time periods (from 1 h to 30 d running mean intervals), for the 50th percentile values (P_{50}) as well as the P_{80}, P_{95} and P_{100} for turbidity (NTU), and P_{20}, P_{10}, P_5 and P_0 for daily light integrals (DLI)** .

Importantly, the development of water quality thresholds for impact prediction must be relevant to the temporal scales to which the benthic organisms respond, and **more than one temporal scale may in fact be relevant**. Where uncertainty in the response of biota to exposure time scales exists, during the EIA, the safest approach may be to **adopt impact prediction thresholds that can integrate over a range of temporal scales** (such as the running means analysis presented here).

A generally accepted model for how corals tolerate turbidity is that they survive short term periods of high SSCs by shifting between phototrophic and heterotrophic dependence, by relying on energy reserves, and by rapidly replenishing reserves in periods between turbidity events. **The ephemeral nature of plumes and the potential for corals to recover from individual turbidity events, means dredging programs can be managed by considering cumulative pressure.** Implicit in this concept is that natural turbidity events (or periods of low light), are an integral component of the total pressure. That is, **corals or other epi-benthic organisms cannot differentiate between natural turbidity events and dredging-related events, and they should not be distinguished between during water quality monitoring programs associated with dredging campaigns.**

Where there are substantial natural gradients in water quality conditions (e.g. benthic light availability with depth; turbidity with distance to river mouth), thresholds for impact prediction should only be altered where there is strong evidence that the target receptors are well adapted to these natural conditions and not already at their physical tolerance limits.

The results from the 3 dredging projects – and also the Wheatstone project – have generated a matrix of data showing the sorts of turbidity elevations and light reductions that can occur during dredging over multiple running mean time periods. The results are presented on a percentile basis showing how these vary with increasing distance from dredging and with respect to baseline conditions. **For experimental studies designed to examine cause-effect pathways and derive dose-response relationship, these 'hazard profiles' should be consulted carefully for contextual purposes, and to ensure experimental exposure scenarios are environmentally relevant and realistic.**

The spatial extent of impact predictions should cover the full range of likely to-be-impacted area, but this is likely to be much less than 20 km, and more typically in the order of 3–5 km based on our distance analysis of 'measurable perturbations' in water quality for 3 previous dredging projects. The spatial influence of dredge plumes can be highly directional in some cases. When this occurs, distances of impact may be much further than anticipated. In other regions, with very different sediment characteristics, dredging impacts on water quality may extend beyond that maximum of approximately 20 km observed here.

Monitoring

The ephemeral nature of dredging related turbidity plumes means that **summary statistics, as well as the time scale over which summaries are captured, are critically important considerations for monitoring** to support adaptive management of dredging. **The frequency that each indicator is monitored should be determined based on the pressures and risks, as well as the objective to be achieved, and also accounting for inherent seasonal and/or other cyclical patterns.** The spring-neap tidal cycle was sometimes a feature in the time series data, and care should be taken to ensure that such natural cycles are accounted for by the monitoring frequency and reporting frequencies. There was also evidence that dredging may increase the intensity of turbidity within these cycles, presumably because of the increased availability of finer sediments for suspension.

Dredging alters the intensity, duration and frequency of turbidity events on both short (acute) and longer (chronic) time scales. In the absence of a clear understanding of how water quality conditions across these scales impact relevant sensitive receptors, is seems wise to undertake monitoring such that a good understanding of the dredging related hazard profile is captured across both scales. **Monitoring on sub-hourly time scales is essential to capture extreme (acute) events**, as daily, or even weekly means can be up to 13 to 90 times lower respectively.

Importantly, however, regardless of the temporal scale of monitoring actually performed, **summary metrics (indicators) derived from raw parameters (e.g. PAR or NTU) included in reporting should accurately reflect the timescales and/or profile of exposure that was used in the impact prediction phase, and for the development of EQCs**. If extreme short term conditions are important, then maximums and upper percentiles over the relevant times scale should be reported. Where responses of receptors are shown to relate to change in long term, median conditions, monitoring results should be reported as such. For the particular receptors of interest, different summary statistics may be relevant.

Monitoring in the immediate vicinity of dredging activity and along pressure gradients can provide valuable information on the attenuation of dredging pressure with distance to validate predictions and inform management. Knowledge of how dredging pressures and impacts attenuate with distance at the actual site of dredging is a useful evidence base for refining the management of this and future dredging campaigns. While not usually required by ministerial conditions, such monitoring is extremely valuable in demonstrating how dredging impacts change with distance, providing much greater certainty in the spatial extent of impacts, as was evident in the relative strength of distance decay relationships for the Barrow Island dredging project, compared to either Cape Lambert or Burrup Peninsula. This is also useful information in terms of both public perception, and to confirm and validate impact prediction outcomes. Furthermore, monitoring in high impact zones allows *in situ* testing of impact predictions, and the development of *in situ* dose-relationships between dredging related exposure and sensitive receptor health.

The environmental monitoring data sets that have formed the basis of this report and Project 6.3[6] represent useful resources for laboratory-based studies on benthic sensitive receptors (such as filter feeders and corals), allowing testing to be conducted using environmentally realistic and relevant exposure scenario. **Dredging proponents should be encouraged to make all fully QA/QC'd data from water quality investigations available for future analysis to enable this resource to grow.**

Management

Implications for spatial zonation

Where impacts of dredging followed a power-law decay relationship, with sites near dredging experiencing much greater changes to water quality than the more distant ones. This pattern supports the use of spatial zoning to manage dredging projects as described as outlined in EPA (2016)[1].

The distances of potential impact presented here based on a P_{50}–P_{80} definition of 'measureable perturbation' on water quality probably represents a maximum likely extent for the outer limit of the zone of moderate impact (see EPA 2016[1]). The estimated distances are also based on water quality metrics (turbidity and light) that represent relatively far-field impacts. Distances of elevated dredging related sedimentation, as well as various sub-lethal (mucus) and lethal (elevated coral mortality) biological responses are explored elsewhere in Theme 4 Projects 4.4 and 4.6

Implications for threshold development

During threshold development, the full range of exposure pathways from dredging related stressors must be considered (loss of light, elevated suspended sediment concentrations and increased sediment deposition) across metrics that capture the full range of hazard profiles generated during dredging. This requires the development of candidate threshold indicators that represent short (e.g. daily running means) and long (e.g. monthly running means) time scales, that consider proportional exposure (total number of days of exceedance), and consecutive exposure (number of consecutive days of exposure).

There was only limited seasonality evident in the turbidity data, suggesting that single *turbidity based* thresholds (across seasons) would be appropriate for these studies. In other regions however, seasonal influences may be more substantial (i.e. riverine input during a wet season), and might need to be considered.

In line with comments above regarding impact prediction, thresholds should explicitly accommodate natural turbidity/low light events as part of the cumulative stress, and not be based on dredging-related effects only in excess of natural levels.

Residual knowledge gaps

Cyclones are a common feature of tropical coastal regions in Australia and can cause substantial turbidity events at both dredge impact and reference locations. A discussion of how the combined effects of cyclone and dredging generated turbidity should be managed are discussed in more detail elsewhere in Theme 4, Project 4.6. This issue is complex, and a greater understanding of how dredging alters the turbidity profiles generated during cyclones (both cumulative past impacts that have potentially altered sediment regimes in a management area, as well as real time dredging activities) would be highly beneficial. In addition, the development of swell and wind based trigger may prove useful during adaptive management of future dredging projects.

Spatial patterns of turbidity were highly complex, and it was often hard to match satellite images to *in-situ* measures of water quality on fine spatial and temporal scales. Hierarchical spatial sampling of *in situ* water quality time series is rarely performed, and it would be worthwhile to explore the temporal correlation of replicate loggers at a range of spatial scales to better understand appropriate minimum levels of replication.

RESEARCH ARTICLE

Temporal Patterns in Seawater Quality from Dredging in Tropical Environments

Ross Jones[1,2,4]*, **Rebecca Fisher**[1,2,4], **Clair Stark**[2,3], **Peter Ridd**[2,3]

1 Australian Institute of Marine Science, Perth, Western Australia, Australia, **2** Western Australian Marine Science Institution, Perth, Western Australia, Australia, **3** Intelligent Systems, Information and Modelling, College of Science, Technology and Engineering, Townsville, Queensland, Australia, **4** Oceans Institute, University of Western Australia, Perth, Western Australia

* r.jones@aims.gov.au

Citation: Jones R, Fisher R, Stark C, Ridd P (2015) Temporal Patterns in Seawater Quality from Dredging in Tropical Environments. PLoS ONE 10(10): e0137112. doi:10.1371/journal.pone.0137112

Editor: Kay C. Vopel, Auckland University of Technology, NEW ZEALAND

Received: February 28, 2015

Accepted: August 12, 2015

Published: October 7, 2015

Data Availability Statement: There are very detailed tables and Figures in the manuscript and in the supplementary files containing all the relevant data. A metadata record is available from the Australian Institute of Marine Science at: http://data.aims.gov.au/metadataviewer/faces/view.xhtml?uuid=a884e0ab-1a82-4871-8f39-18c20ab4c9fb.

Funding: This project was funded by the Western Australian Marine Science Institution as part of the WAMSI Dredging Science Node, and made possible through investment from Chevron Australia, Woodside Energy Limited, BHP Billiton as environmental offsets and by co-investment from the WAMSI Joint Venture partners. This research was

Abstract

Maintenance and capital dredging represents a potential risk to tropical environments, especially in turbidity-sensitive environments such as coral reefs. There is little detailed, published observational time-series data that quantifies how dredging affects seawater quality conditions temporally and spatially. This information is needed to test realistic exposure scenarios to better understand the seawater-quality implications of dredging and ultimately to better predict and manage impacts of future projects. Using data from three recent major capital dredging programs in North Western Australia, the extent and duration of natural (baseline) and dredging-related turbidity events are described over periods ranging from hours to weeks. Very close to dredging i.e. <500 m distance, a characteristic features of these particular case studies was high temporal variability. Over several hours suspended sediment concentrations (SSCs) can range from 100–500 mg L-1. Less turbid conditions (10–80 mg L-1) can persist over several days but over longer periods (weeks to months) averages were <10 mg L-1. During turbidity events all benthic light was sometimes extinguished, even in the shallow reefal environment, however a much more common feature was very low light 'caliginous' or daytime twilight periods. Compared to pre-dredging conditions, dredging increased the intensity, duration and frequency of the turbidity events by 10-, 5- and 3-fold respectively (at sites <500 m from dredging). However, when averaged across the entire dredging period of 80–180 weeks, turbidity values only increased by 2–3 fold above pre-dredging levels. Similarly, the upper percentile values (e.g., P99, P95) of seawater quality parameters can be highly elevated over short periods, but converge to values only marginally above baseline states over longer periods. Dredging in these studies altered the overall probability density distribution, increasing the frequency of extreme values. As such, attempts to understand the potential biological impacts must consider impacts across telescoping-time frames and changes to extreme conditions in addition to comparing central tendency (mean/median). An analysis technique to capture the entire range of likely conditions over time-frames from hours to weeks is described using a running means/percentile approach.

also enabled by data provided by Woodside Energy Ltd, Rio Tinto Iron Ore and Chevron. The commercial investors and data providers had no role in the data analysis, data interpretation, the decision to publish or in the preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exists. This arrangement with the commercial entities does not alter the authors' adherence to all PLOS ONE policies on sharing data and materials.

Introduction

Maintenance and capital dredging for ports and coastal infrastructure projects represents a potential risk to tropical marine environments. Dredging the seabed and subsequent dredge-material disposal releases sediment into the seawater column creating plumes that can drift onto nearby benthic habitats. Elevated suspended sediment concentrations (SSCs) can affect filter and suspension feeders by interfering with food collection [1] and the turbid plumes can reduce submarine irradiance, affecting benthic primary producers such as corals seagrasses and macroalgae [2]. Furthermore, sediments in the seawater column can eventually settle out of suspension, potentially smothering benthic and sessile organisms and forcing them to expend energy self-cleaning [1].

Many studies have attempted to quantify the effects of sediment on corals and coral reefs (reviewed in [1–4]) and the risks associated with dredging in coral reef environments have been well known for many years [5,6]. However, observational or time-series data of seawater quality conditions and behaviours during dredging around coral reefs have rarely been collected and described (but see [7,8]). A fundamentally important principle in ecotoxicology and risk assessment is hazard characterisation. Any attempts to relate a change in the biota to changes in environmental conditions needs a detailed understanding of exposure pathways and exposure conditions experienced by wildlife. Harris et al. [9] recently argued that one of the weakest aspects of many ecotoxicological studies is the exposure conditions and emphasised the need to justify the concentrations applied with those measured in the environment.

Temporal variability in turbidity

SSCs and related turbidity are naturally highly variable, both spatially and temporally, and influenced by a wide range of factors, such as waves, currents and bed type [10–18]. For muddy-bottomed sites on exposed inner-shelves, SSCs can frequently exceed 20 mg L^{-1}, and can regularly exceed 100 mg L^{-1} for 2–3 day periods during strong wave events [10]. Similarly, variation in turbidity at inshore coral reefs can also range from 0.1 to >100 NTU over relatively short periods [19], with >20 NTU typically occurring during high wind and wave events, and values greater than 50 NTU occurring during exceptionally high wind and wave events, such as cyclones [12,18,20,21]. Any attempt to characterise the extraordinary conditions and hazards posed by dredging must be carried out in the context of this natural variability, and accordingly, data needs to span a relatively long sample period (typically months). High frequency time series data of turbidity measurement over such long durations are expensive to implement and relatively rare [10].

One of important questions for examining the effects of poor seawater quality associated with dredging on benthic organisms is what the appropriate time frame for analysis is. This question should be framed within the context of the biology of the benthic organisms, the duration of their life-history stages and especially sensitive stages. For example, in corals, the life-cycle consists of multiple stages involving gametogenesis, spawning, fertilisation and embryonic and larval development, and then settlement and metamorphosis to a benthic adult stage. These stages can range from minutes to months and for the adults, years, and each are possibly susceptible to turbidity generation. Thus, an understanding of how seawater quality varies due to dredging (and naturally) across the full range of temporal scales from minutes to months will be required to characterise the hazards posed to corals generally.

Seawater-quality data are usually recorded at relatively fine temporal scales (e.g., minutes, [22]), and aggregated to coarser time scales for the purposes of reporting. The summary statistics used (mean versus median etc), as well as the temporal scale adopted (hours, days, weeks) can dramatically affect the interpretation of the data [10]. Short periods of high SSCs or low light are ecologically significant and the importance of these events are not clear or reflected in median values and especially over longer term averages [23,24]. If the hazards associated with dredging are to be characterised thoroughly, they need to be expressed both with respect to changes in central tendency, but also in terms of changes in upper (e.g., maximum, 95th percentile) and lower bounds.

Dredging programs in NW Australia

In tropical Australia there has been a recent sequence of major capital dredging campaigns associated with a resources boom and the need for coastal facilities for the export of minerals and petroleum products. Three of the most significant dredging campaigns occurred in the Pilbara region of Western Australia (WA), at the Burrup Peninsula in Dampier Archipelago, and at nearby Barrow Island and Cape Lambert. These projects involved dredging millions of cubic metres of sediment in the nearshore environment to create access channels, turning basins, berth pockets, jetties and material offloading facilities, and the subsequent disposal of the sediment at dredge material placement grounds [25]. The Pilbara projects were all large-scale capital dredging programs with multiple dredges operating nearly continuously (24 h a day for 7 days a week) and over extended periods. They were significant by global standards and occurred in sensitive tropical marine environments containing coral reefs and other benthic primary producer habitats [26]. The projects also occurred in three very different marine settings representing the range of environments that corals occupy in tropical Australia and elsewhere in the world: an offshore, 'clear seawater' environment (Barrow Island), an exposed nearshore cape or headland (Cape Lambert), and an enclosed inshore turbid reef environment (Mermaid Sound, Burrup Peninsula) of the Dampier Archipelago.

The state and federal regulatory conditions for the Pilbara dredging projects required detailed seawater quality monitoring programs involving measurements of turbidity and light levels on sub-hourly time scales at multiple reference and potential impact sites. Measurements were made at different distances from the dredging and over extended periods (months to years), and in some cases included extended pre-dredging baseline periods [25]. Data from these studies have been made available by the dredging proponents for scientific study, providing a unique opportunity to explore, for the first time, the impacts that dredging has on seawater quality in reef areas across broad temporal scales. These data include extensive baseline time series (in some cases), and thus allow the characterisation of the effects on seawater quality caused by dredging in the context of inherent natural variability.

The aim of this study is to thoroughly characterise the hazard caused by dredging activities altering seawater quality in reefal environments. We describe the conditions reef communities may encounter *in situ* as a result of dredging, including the nature and duration of episodic high SSC and low light 'turbidity events' and how the nature of these events varies over periods of time from minutes and hours to weeks and months. The results are valuable for future experiments and the design of more environmentally realistic laboratory-based, *ex situ* studies of the effects of turbidity and light on reef biota such as filter feeders (i.e. sponges and ascidians), fish, corals and other primary producers (i.e. seagrasses). Together with analyses of spatial patterns (i.e. distance from dredging) of seawater quality, and effects of the dredging projects on the underlying reef communities (both of which will be published elsewhere) the data are important for developing seawater quality thresholds for dredging programs to improve the ability to predict and manage the impact of future dredging projects.

Materials and Methods

Turbidity is a measure of light scattering caused mainly by suspended sediment, algae, microorganisms and other particulate matter [10,18] and in the seawater column is conventionally measured using a nephelometer as Nephelometric Turbidity Units (NTU). Turbidity is a

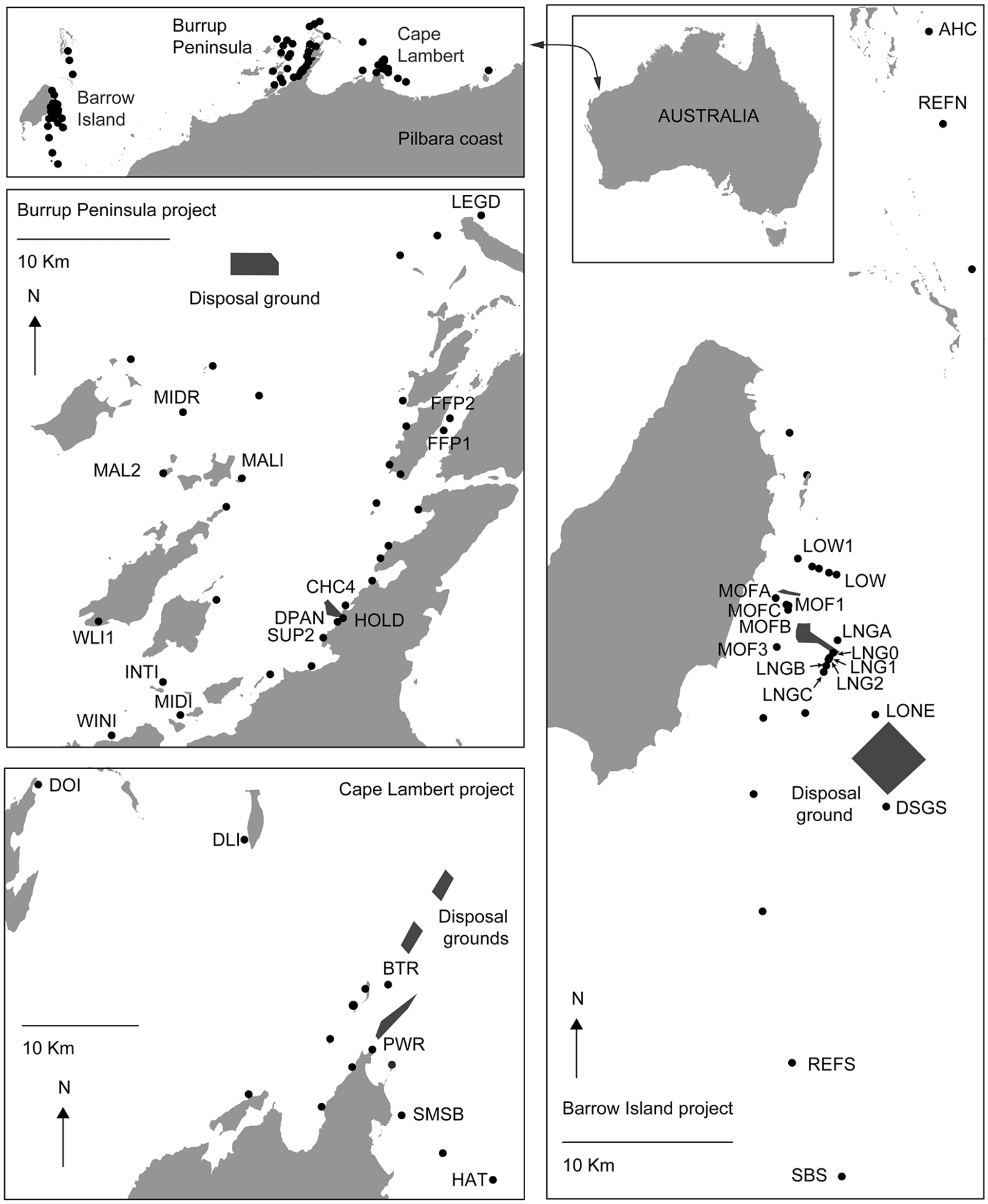


Fig 1. Seawater quality monitoring and reference (Ref.) sites for the Barrow Island (MS800), Burrup Peninsula (MS757), and Cape Lambert (MS840) dredging projects in the Pilbara region (Western Australia). Only sites that were near (<2 km) from the primary dredging activity and those that were considered un-impacted by dredging (references sites) were used in the analyses here and are labelled. Detail site information can be found in the (Table 1 and S1 File). The ministerial approval statements (MS) for these projects are available on the WA EPA website: http://www.epa.wa.gov.au. Dredge material placement sites (spoil grounds) and primary excavation areas are indicated as dark shaded boxes.

doi:10.1371/journal.pone.0137112.g001

function of suspended sediment concentrations although conversion between turbidity and SSC varies in response to a wide range of sediment characteristics, particularly those related to grain size and type, which also change with time [27]. In general SSC can be related to turbidity by a linear relationship with a conversion factor of between 1 and 4 [10].

Seawater quality data (turbidity) were collected at 32 sites for the Burrup Peninsula Project, 26 sites during the Barrow Island project, and 15 sites at the Cape Lambert project (Fig 1, Table 1). Many of these sites included baseline periods before dredging started with some

Table 1. Data type collected and instruments used across three major dredging projects in the Pilbara (Western Australia) since 2007 including start and finish dates and volumes dredged.

Burrup Peninsula (MS757)	
Project works	Capital dredging project to create a navigation channel (16 km, 12.5 m seawater depth), turning basin (600 m radius, 12.5 m seawater depth), and berth pocket (400 m × 60 m, 13.5 m seawater depth)
Volume dredged	~12.5 Mm^3
Dredging Period (d)	22 Nov 2007 to 21 May 2010 (911 days). Baseline days: Turbidity 5–123 (15) NTU, Light: 0–117(109) μmol photons m^{-2} $s^{-1.}$ Dredging days: Turbidity 47–984 (905) NTU, Light 0–82 (82) μmol photons m^{-2} s^{-1}
Instrumentation	(1) Optical backscatter (OBS) (JCU Geo-physical Lab), (2) Wetlabs (ECO-NTU-SB OBS turbidity recorder), (3) Alec Instruments (COMPACT CLW—Miniature Turbidity/ Chlorophyll Data Logger) (HOLD and DPAN only). Readings every 30 minutes. 32 sites in total (S1 File).
Sediment type:	Surficial sediments are mixed siliciclastic and carbonate unconsolidated sediments ranging from gravel to fine silts. For the nearshore sites, close to the dredging activities, surficial sediments were finer (sand, silt and clay = ~30%) and coarser (sand = 70%, silt 10%, clay 10%) at the more offshore sites. For the nearshore sites (DPAN, HOLD, CHC4) the SSC = Turbidity × 1.174.
Barrow Island (MS800)	
Project works	Capital dredging project to create a materials offloading facility (MOF) approach channel (1.6 km, 6.5 m seawater depth), Berthing Pocket dredged to approximately 8 m seawater depth. LNG Jetty access channel and turning basin (900 m circle, 13.5 m seawater depth). LNG berthing Pocket dredged to approximately 15 m seawater depth.
Volume dredged	~7.6 Mm^3
Dredging Period (d)	19 May 2010 to 31 Oct 2011 (530 days). Baseline days: Turbidity 2–786 (184) NTU, Light: 10–735 (241) μmol photons m^{-2} s^{-1}.Dredging days: Turbidity 361–566 (482) NTU, Light 388–548 (474) μmol photons m^{-2} s^{-1}
Instrumentation:	Sideways mounted optical backscatter device (nephelometer) and Photosynthetically Active Radiation (PAR) was recorded using a 2π quantum sensor (JCU Geo-physical Lab, see Thomas & Ridd 2005). Readings every 10 minutes. 36 sites in total (S1 File)
Sediment type:	Predominantly unconsolidated, undisturbed carbonate sediments forming a thin veneer (0.5–3 m thick) overlying limestone pavements ranging from rubble to typically gravelly sand mixed with fine silts and clays. Low TOC content <0.8%. Sediments at deeper sites were typically finer. SSC = Turbidity × range of 1.1 to1.6
Cape Lambert (MS840)	
Project works	Capital dredging project to create an approach area and channel (15.6 m seawater depth), turning basin (10.0 m seawater depth) and berth pocket (20 m seawater depth), and tug harbour extension (6.8 m seawater depth)
Volume dredged	~14 Mm^3
Dredging Period (d)	22 Dec 2010 to 15 Sept 2012 (633 days). Baseline days: Turbidity 13–536 (399) NTU, Light: 0–279 (91) μmol photons m^{-2} s^{-1}.Dredging days: Turbidity 629–699 (685) NTU, Light 0–686 (649) μmol photons $m^{-2}s^{-1}$
Instrumentation:	(1) Wetlabs (ECO-NTU-SB OBS turbidity recorder) every 30 mins. ALEC ALW-CMP loggers. (2) WET Labs ECO-PAR-SB (30 min) ALEC ALW-CMP. Readings every 30 minutes. 15 sites in total (S1 File))
Sediment type:	Unconsolidated predominantly carbonate sediments, composed of medium to coarse sand (70–90%) at a range of 1–5 km from dredging but typically finer sediments (fine sands, silt and clay) closer to the nearshore areas. SSC = A[Turbidity] $e^{B[Turbidity]D}$ +C, where A = 0.670 B = 0.256, C = 0.275 and D = 0.0391

The range in number of seawater quality sample days during baseline (Baseline days) and dredging (Dredging days) are included at each location for turbidity and light data. Values in parentheses represent the median number of sampling days across sites where that seawater quality parameter was measured. MS refers to the Federal Ministerial approval Statement, searchable on the WA EPA website: http://www.epa.wa.gov.au).

doi:10.1371/journal.pone.0137112.t001

baseline periods covering up to 786 days. Seawater quality data for these projects were collected using instruments mounted ~40 cm from the seabed on steel framed *in situ* monitoring platforms. The instruments used and logging and download frequencies for each project varied (see Table 1).

As the primary purpose of this paper was to describe the seawater quality characteristics in the immediate vicinity of dredging activity, we have limited the analysis for each of the projects to those monitoring sites <2 km from the primary area of dredging activity, and those sites that were considered to be un-impacted by the dredging activity (reference sites, see labelled sites, Fig 1). Full details for each site in the present analysis, including total baseline and dredge period sampling days, seawater depths (where available) and distances of the monitoring sites from the main dredging activities are listed in Table 1 and the supplementary data (S1 File).

All seawater quality data provided by the proponents of the various projects were processed similarly to ensure data integrity and remove potentially erroneous values (see below) and time standardised to decimal Julian days, where the start of dredging was used as the origin. This ensures that negative values of Julian day represent the baseline period, and positive values represent days during the dredging program. For all turbidity data, any values <0 NTU were removed, and a smoothing filter was applied where for any value >3 NTU, if the value was more than 2.5× the mean of the preceding and following value, it was replaced with the mean of the two values. This smoothing filter was initially applied to reduce any high single point anomalies that may be due to material or organisms (e.g., fish or algae) passing in front of the sensor at the time the reading was taken. For both the turbidity and light datasets for each location, raw data were plotted as time series and inspected visually for anomalies and any evidence of logger or wiper failure. Suspect data points and/or sections were identified in a data cleaning log which was subsequently used to screen out this data for all analyses. A range of different types of anomalies were removed and included: erratic spikes or peaks representing large changes in turbidity lasting for short periods of time that could not possible be due to natural (or dredge induced) changes in turbidity and/or were not reflected in changes in light data (where this was also available); sections of systematically fluctuating turbidity patterns occurring on the same period as the logger wipers (very likely due to logger error, only removed when these caused extreme fluctuations in turbidity readings); sudden elevations or drops in turbidity readings (occurring suddenly over the time of a single reading, rather than rising across several readings as would be expected by natural turbidity patterns) that indicate an issue with sensor calibration; other sensor 'drift' issues where there was a pattern of increasing turbidity and a sudden drop over the space of a single reading, indicating a sensor drift and re-calibration issue. For the turbidity data from the Burrup Peninsula project there was an issue with data obtained immediately after the commencement of dredging for the HOLD and DPAN sites (Fig 1), where there were clear periods of instrumental 'drift'. Because these sites are very close to the dredging (0.32 and 0.56 km for the HOLD and DPAN sites, respectively) during the relevant period they are of particular value in characterising the near dredge seawater quality conditions. Rather than exclude this data entirely (as was done for other sections of data from the three projects when there were plenty of other representative sites available), these data were instead adjusted assuming linear drift of the sensors across the time period. While this assumption of linear drift might introduce some small error, given the value of this data and the large values of turbidity that occurred during this time, it is unlikely this assumption would impact on the outcomes of the analysis.

For the light measurements, any night-time data collected one hour before predicted sunrise or one hour after predicted sunset, and any values <0 and >2000 μmol photons m^{-2} s^{-1} were removed. Sunrise and sunset estimates were obtained and applied at monthly intervals.

All turbidity data were aggregated for all sites and retained at the finest temporal resolution (10 or 30 min, depending on the logger type and dredging project (Table 1) or aggregated to a daily mean or percentile value as required for various analyses). Light data at the finest temporal resolution were fitted using a Generalised Additive Model (GAM) for each day separately using the mgcv package [28] in R [29]. Days for which insufficient light data were available throughout the full daylight cycle were removed and not included in the analysis. Each fitted daily model was then used to estimate photosynthetically active radiation (PAR, 400–750 nm) values for every second throughout the daylight period, based on monthly sunset and sunrise times. The sum of the per second quantum flux measurements were then added together to calculate the daily light integral (DLI) as mol photons m^{-2} d^{-1}.

Time series and probability profiles

To examine the overall impacts that dredging has on turbidity and irradiance, representative dredge impact and non-impacted (reference) sites were selected across the three projects and used to explore changes in the time series between the baseline and dredging periods. Representative 'near' dredge sites were selected as those closest (<2 km) to the primary dredging activity displaying the longest and most continuous time series throughout the baseline and dredge periods. Similarly, representative 'reference' sites were selected as those within the set of sites considered to be un-impacted by dredging activities due to their greater distance from the dredging activity and displaying the longest and most continuous time series throughout the baseline and dredge periods (<6% of days missing throughout the dredging phase). Although only one or two representative sites are shown here, plots for all 'near' dredge and reference sites are included in the online supplementary information (Figures A, B, C in S2 File).

While characterisation for turbidity was possible across all three dredging programs, analyses based on light data have only been included for the Barrow Island program, as data for light were either sparse or non-existent during the baseline period or during dredging (or both) for the other programs.

Intensity (I), Duration (D), Frequency (F) analysis

Turbidity data were used to carry out an intensity, duration and frequency analysis (IDF, see [30]), at both the daily and hourly temporal scales. The approach expands the recognition that it is suspended sediment concentrations and also duration of exposure that causes effects (see [31,32]). In this analysis the data are first aggregated to the appropriate temporal scale by calculating the maximum hourly or daily turbidity values for each dataset for the baseline and during dredge periods. The intensity threshold is then calculated as the 95th percentile of the baseline period (and compared to the 95th percentile of the dredging period). The duration of events where this 95th percentile baseline threshold is exceeded is then determined, and the 95th percentiles of the duration events are then calculated for the baseline period and compared to the 95th percentile of the dredging period. Finally, the frequency with which the 95th percentile duration events for the baseline state were exceeded was also recorded for the baseline periods and periods during dredging.

Temporal analysis

To examine how the extremes of seawater quality conditions are altered by dredging across a range of time scales, percentile plots of different running mean periods were created for both turbidity and light (where available). Running means of the 10 min or 30 min turbidity/light data were calculated with periods ranging from one hour (for turbidity) or one day (for PAR) to 30 d. Each running time period calculated the average of the previous N_T data points, where

N_T is the number of samples in the T hour mean. For example, for the two hour running mean ($T = 2$), $N_T = 12$ as there are six ten-minute samples per hour. The T hour running mean at a point in time t

$$\bar{x}_T(t) = \frac{1}{N_T}\sum_{i=1}^{N_T} x_i(t) \quad (1)$$

where $\bar{x}_{T)}(t)$ is the mean calculated over the previous T hours of the data from time t-T to time t hours, and $x_i(t)$ are the N_T data points up to and including time t. To avoid biased averages, no $\bar{x}_T$ value was recorded if more than 20% of the data points for any particular running mean time period calculation were missing. Percentile values of the running mean values $\bar{x}_{T)}(t)$ for each running mean period were then calculated. This was done for the pre-dredge and dredge periods.

In R, running means were calculated by converting the data series for each site into an S3 time series object using the zoo function from the zoo library [33] then applying the runmean function from the caTools library [34]. Once running means for each time span were calculated, these were summarised using an average along with various percentile values (50^{th}, 80^{th}, 99^{th} and 100^{th} [maximum] for turbidity and 50^{th}, 20^{th}, 5^{th}, 1^{st} and 0^{th} [minimum] for PAR). These were plotted as a function of the running mean time span and compared for the pre-dredging and dredging periods.

Low light periods

High SSCs frequently cause darkness and also very low light or 'caliginous' periods reducing underwater irradiances to very low daytime similar to 'twilight'. The frequency of these low light periods was examined using four different DLI cut-off values, which are equivalent to 12 h of continuous light at instantaneous levels of 20, 10, 5 and 1 μmol photons m^{-2} s^{-1}. The latter cut-off value is the precision of the light sensors. Equivalent DLI thresholds based on these per second quantum flux thresholds were determined by summing these for every second across the daylight period, and equate to 0.8, 0.4, 0.2 and 0.04 mol photons m^{-2} d^{-1}. Using these thresholds (cut-off values), the total number of days in low light was calculated and normalised per year for each study, for the baseline and dredge periods separately. In addition, the mean number of days in low light per fortnight, as well as the number of consecutive days in low light (summarised as a mean, 80^{th} percentile and maximum) were calculated. For the purposes of calculating continuous days in low light, single missing days of light data were treated as follows: (1) if both the preceding day and following day were defined as low light it was assumed the missing day was also the same; (2) if both the preceding day and following day were defined as 'light', it was assumed the missing day was also defined as 'light'; and, (3) where the preceding day and following day fell into different states the missing day was discarded. This was done to avoid falsely truncating consecutive day calculations where single missing days occurred in the data series. In addition to the proportion of days in low light, the proportion within each day that fell within the low light threshold (i.e. the proportion of the day below the threshold value) was also examined.

Results

Mean turbidity was low across the 100s of days of the baseline and dredging periods for all three of the major dredging projects (Table 2). Highest baseline turbidity values occurred for the Cape Lambert project (4 NTU) with the Barrow Island and Burrup Peninsula projects showing substantially lower levels (1 and 2 NTU respectively, Table 2). Across site means increased only slightly during the dredging to 3 NTU for the Barrow Island project and 5 NTU

Table 2. Mean turbidity and photosynthetically active radiation (PAR) for the Barrow Island, Cape Lambert and Burrup Peninsula dredging programs.

	Turbidity (NTU)		PAR (μmol photons m^{-2} s^{-1})	
Program	**Baseline**	**Dredging**	**Baseline**	**Dredging**
Barrow Island	1 (1–3) N = 18	3 (1–7) N = 18	102 (49–320), N = 18	86 (20–288) N = 18
Cape Lambert	4 (1–10) N = 5	5 (2–9) N = 5		
Burrup Peninsula	2 (0–3) N = 11	5 (1–35) N = 11		

Values are the mean across all sites, with values in parentheses showing the range of within site means at each location. N indicates that number of sites used for each location

doi:10.1371/journal.pone.0137112.t002

for the Cape Lambert and Burrup Peninsula projects (Table 2). Within-site means varied more broadly, with values as high as 7–9 NTU at some sites during dredging at Barrow Island and Cape Lambert (Table 2) and 35 NTU during dredging at one site at Burrup Peninsula (Table 2). Exceptionally high mean values occurred for sites CHC4, DPAN and HOLD for Burrup Peninsula and occurred because these three sites were based on a short data series (~ 3 months in late 2007 and early 2008) collected only during a small window of high dredging activity (see S1 File). For sites surveyed throughout the entire dredging phase in the Burrup Peninsula project, average turbidity values near the dredge site were in the order of 4 NTU, slightly above the precision of the instrumentation (1 NTU).

Time series and probability profiles

Turbidity was variable over time at all three locations, characterised by sudden peaks that occurred occasionally during the baseline period and more frequently throughout the dredging phase for each project (Fig 2A). While the baseline period was more stable (no peaks >50 NTU) during the Barrow Island dredging project (Fig 2A and 2B), peaks of >100 NTU for ~2 days occurred during the baseline of the Cape Lambert project at both impact (Fig 2C) and reference (Fig 2D) locations. These large peaks in turbidity did not appear to be associated with a known cyclonic event (Fig 2C and 2D). The baseline data time series for the Burrup Peninsula project were substantially shorter than for the other two projects but the available data did not tend to show elevated peaks in turbidity (Fig 2E and 2F). Despite variation among the three projects in the baseline turbidity profiles, representative dredge impacted sites clearly show a much greater frequency of high turbidity peaks (>50–100 NTU) in addition to those associated with cyclone activity during the dredging phase compared to the baseline period for all three locations (Fig 2A, 2C and 2E).

Probability density profile plots for the representative impact and reference locations clearly show an upward shift in the turbidity profile during the dredging period relative to baseline, such that there is a decrease in the skewness, but only at impact locations (Fig 2).

Temporal scales analysis

To illustrate how the temporal scale influences the measureable scale of impact that dredging has on the seawater quality, running means analysis was used over multiple time frames from hours to up to 30 d. The full output is presented in the online supporting information (Figs A-D in S2 File) and representative figures are shown here for turbidity (Fig 3).

Running mean profiles show similar patterns across all three projects, with upper percentile values of turbidity (100^{th}, 99^{th} and 95^{th}) generally decreasing as temporal scale is increased

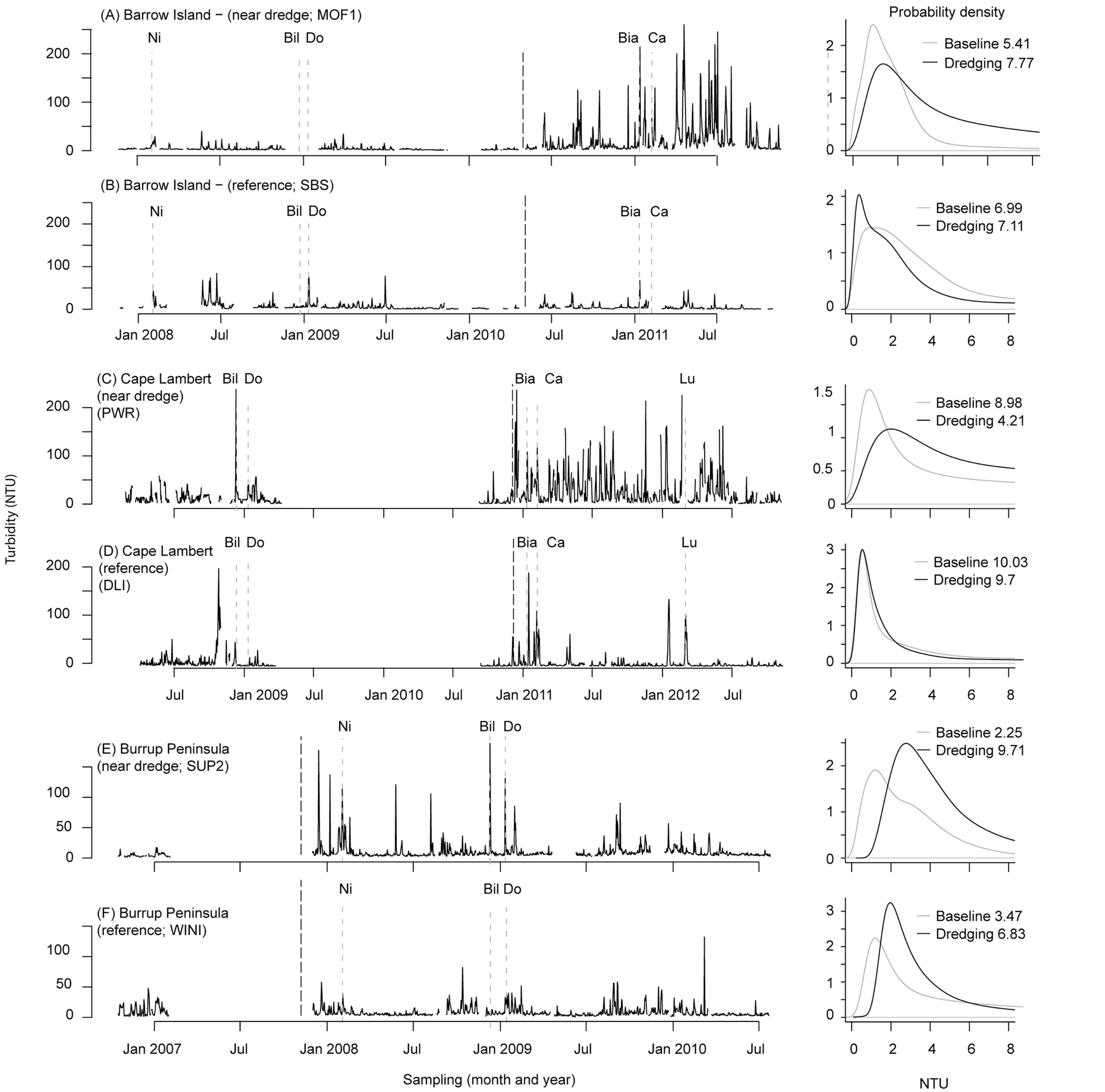


Fig 2. Instantaneous turbidity as maximum daily NTU (left column) and probability density function (far-right panels) at (A) MOF1 (B), SBS during the Barrow Island dredging project, (C) PWR and (D) DLI during the Cape Lambert dredging project, and (E) SUP2 and (F) WINI during the Burrup Peninsula project. LNGI, PWR and SUP2 represent dredge impacted sites whereas SBS, DLI and WINI represent sites un-impacted by dredging (reference sites). The thick solid line on the left hand plots indicates the start of dredging for each project, whereas the dashed lines indicate the timing of cyclone events that may have had the potential to cause sustained periods of very rough seas in this region (Puotinen, pers comm) based on the cyclone size, intensity and proximity to sites (Beeden et al 2015). Annotations under each axis indicate each cyclone event, as follows: Nicholas (N), category 4; Billy (Bil), category 3; Dominic (Do), category 2; Bianca (Bia) category 4; Carlos (Ca), category 3; Lua (Lu) category 4. Cyclone categories indicate the intensity (Australian Ranking Scale) of each cyclone at closest approach to the sites. Time series and probability density function plots for all sites for the three projects can be found in the online supplementary information (Figures, A, B, C in S2 File).

doi:10.1371/journal.pone.0137112.g002

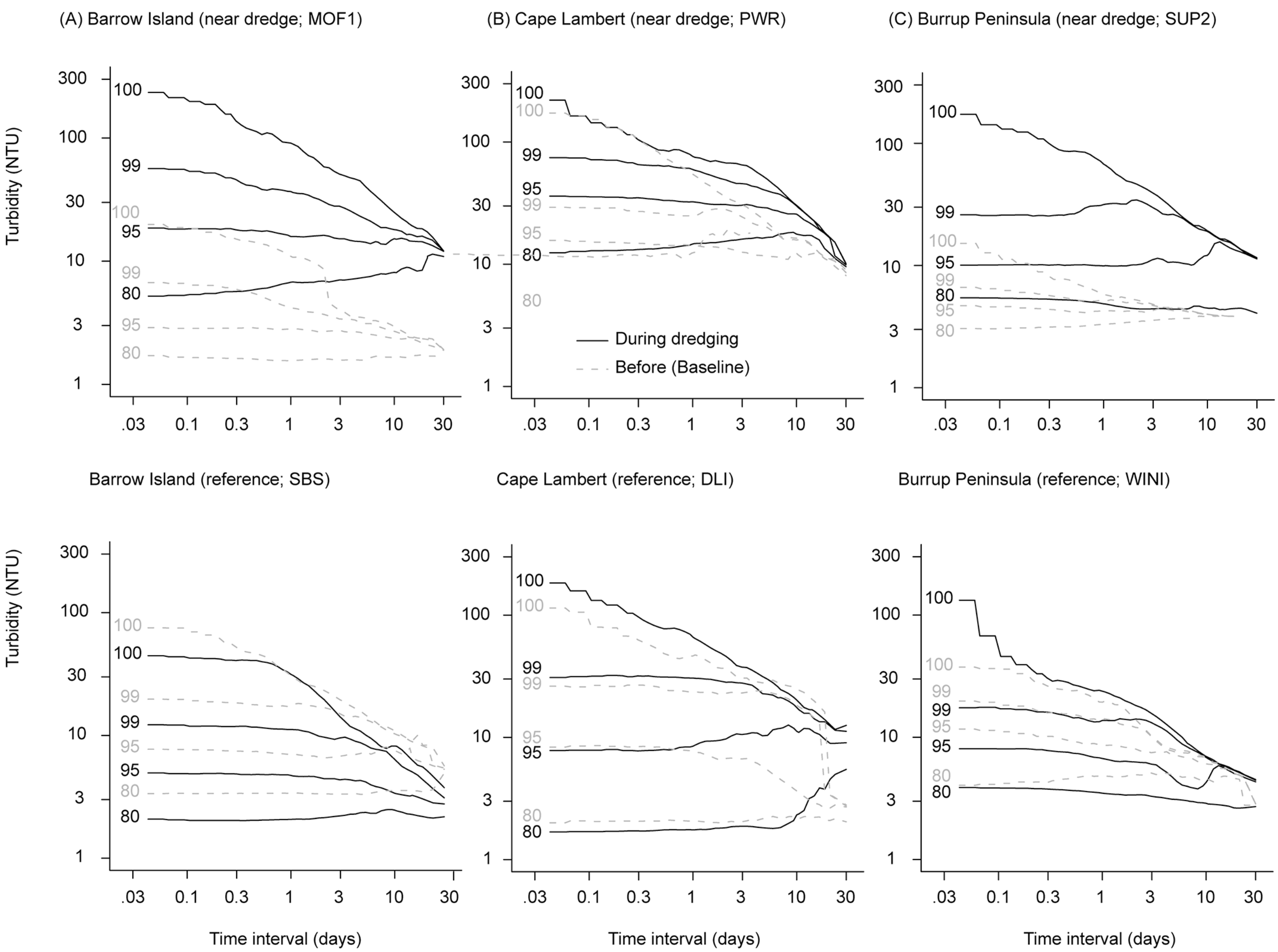


Fig 3. Running means percentile analysis for turbidity (NT U) at sites close to dredging (<2 km) or at reference sites during the Barrow Island, Cape Lambert and Burrup Peninsula dredging projects (see Fig 1). The 100th (maximum), 99th and 95th and 80th percentiles for the running mean turbidity are shown. Percentiles were calculated separately for the baseline period (dashed grey lines) and during dredging (black solid lines).

doi:10.1371/journal.pone.0137112.g003

from hours to weeks (Fig 3). Values for the 80th and 50th were relatively stable across the various time scales examined here (Fig 3).

For the Barrow Island project the SBS reference site located 30 km from the dredging activity (Fig 1) has running mean turbidity values across time frames from hours to weeks that only differed slightly between the baseline period and during the dredging program (i.e. the dotted lines and solid lines largely overlap, Fig 3B). In contrast, at the MOF1 site (located ~0.5 km from the dredging, Fig 1), turbidity levels during the dredging program over one hour, one day and one week time periods were at least an order of magnitude higher than during the baseline period (Fig 3A).

The dramatic shift in seawater quality between the baseline and dredging periods was also seen at the representative sites closest to dredging during the Cape Lambert and Burrup Peninsula projects (Fig 3B and 3C). However, due to occasional periodic peaks in turbidity during the baseline period for the Cape Lambert project, the separation between baseline and dredge periods was slightly less pronounced at this location for the extreme upper percentiles over shorter time frames (Fig 3B).

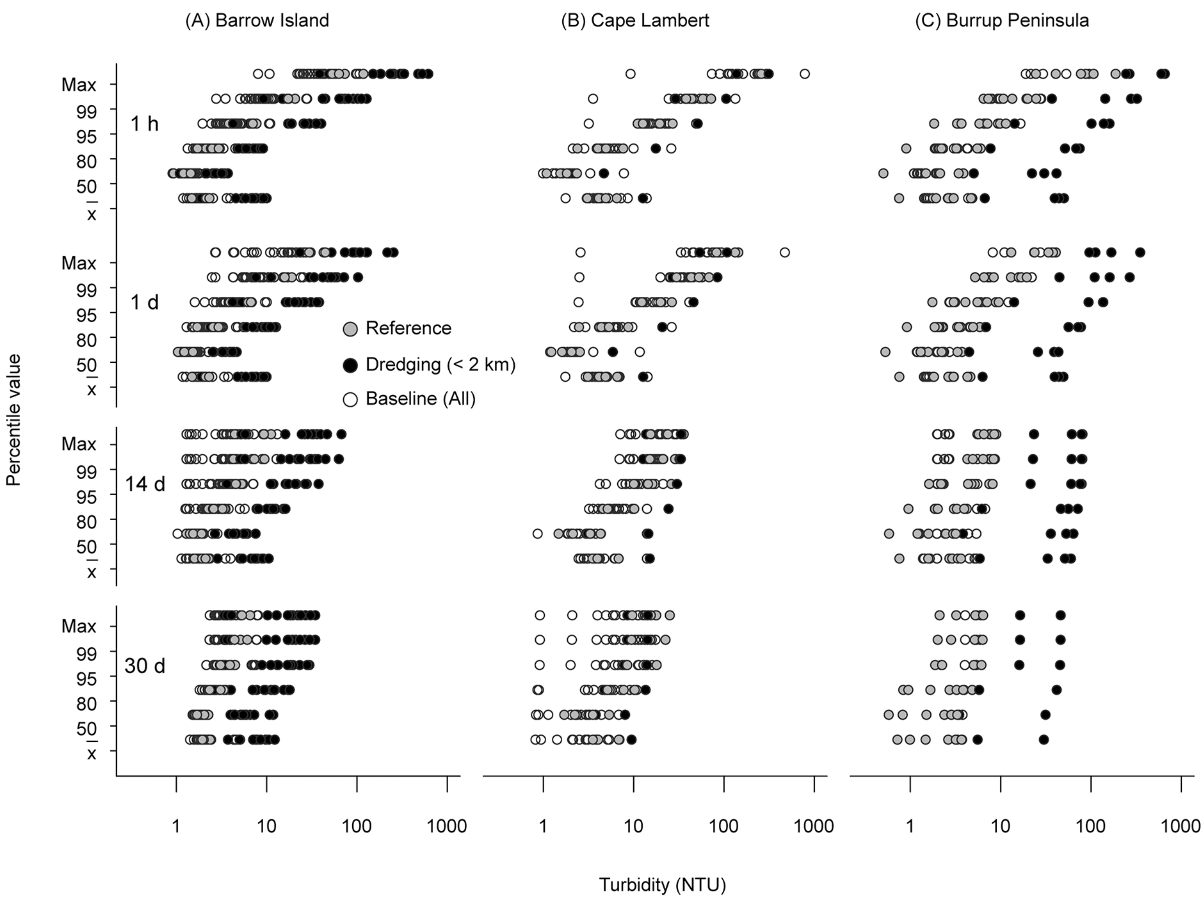


Fig 4. Turbidity (NTU) percentile values for running means calculated on time scales of one hour (h) and 1, 14 and 30 days (d) for all sites at (A) Barrow Island, (B) Cape Lambert and (C) Burrup Peninsula dredging projects. White symbols represent percentiles for the baseline period (pre-dredging period), grey symbols represent reference sites during the dredging period and black symbols represent sites close to (<2 km) the dredging.

doi:10.1371/journal.pone.0137112.g004

Examined collectively across all locations, the upwards shift in running mean turbidity (Fig 4), and downwards shift in available light (see below) at both fine (daily) and coarse (fortnightly, monthly) temporal scales is clearly evident at many near dredge locations for the Barrow Island Project (Fig 3A). Lower percentile values (50^{th}, 80^{th}) tend to show some overlap between dredge impacted sites during dredging and those occurring for reference sites and baseline periods, with values of ~1 NTU dominant across all time frames (Figs 3A and 4A, Table 3). Upper bounds (95^{th} to 100^{th} percentile values) however, show a marked increase for sites near (<2 km) dredging activity, with hourly means maxima of ~300 NTU and 30 d running means of ~30 NTU (Figs 3B and 4B, Table 3).

The overall patterns were similar for the Burrup Peninsula project (Figs 3C and 4C, Table 3), with turbidity values ranging from ~1 NTU for baseline periods and reference sites up to 30 NTU at the monthly scale, and >300 NTU for maximum hourly running means (Fig 3C, Table 3). The results for the Cape Lambert project were mixed, with turbidity values for baseline and reference sites exceeding the near dredge sites in terms of maximum observed values in some cases (Fig 3C, Table 3).

Table 3 includes both median (50^{th} percentile) and mean values of turbidity over time–frames of one hour to 30 d. Data summarised as a mean gave greater values than when summarised via median in all time periods (with the ratio of mean to median usually greater than

Table 3. Turbidity (NTU) percentile values for various running mean time periods for the Barrow Island, Cape Lambert and Burrup Peninsula dredging projects.

	P_{100} (max)	P_{99}	P_{95}	P_{80}	P_{50}	Mean
Barrow Island project Baseline/Reference						
1 h	29, 35, 6–104	7, 8, 2–32	3, 4, 1–13	2, 2, 1–4	1, 1, 1–2	1, 1, 1–3
1 d	12, 14, 2–61	5, 7, 2–28	3, 3, 1–12	2, 2, 1–4	1, 1, 1–2	1, 1, 1–3
14 d	3, 4, 1–18	3, 4, 1–16	2, 3, 1–10	2, 2, 1–4	1, 1, 1–2	1, 1, 1–3
30 d	2, 3, 2–10	2, 3, 2–10	2, 3, 2–10	2, 2, 1–5	1, 1, 1–3	1, 2, 1–3
Barrow Island project Dredging period						
1 h	224, 233, 106–434	49, 51, 24–90	19, 19, 11–28	6, 6, 3–8	2, 3, 2–5	5, 5, 3–7
1 d	67, 77, 33–179	36, 37, 18–72	18, 18, 9–27	7, 7, 4–9	3, 3, 2–6	5, 5, 3–7
14 d	19, 20, 4–47	16, 18, 4–44	12, 13, 4–26	8, 8, 2–11	4, 4, 2–7	5, 5, 2–8
30 d	13, 13, 3–24	12, 13, 3–24	9, 11, 3–21	8, 8, 3–13	4, 5, 3–8	5, 6, 3–9
Cape Lambert project Baseline/Reference						
1 h	154, 149, 7–553	28, 32, 3–94	11, 13, 2–35	4, 5, 1–18	1, 2, 1–5	3, 4, 1–10
1 d	46, 63, 2–333	25, 26, 2–48	10, 12, 2–29	4, 5, 2–19	1, 2, 1–8	3, 3, 1–10
14 d	14, 14, 5–25	13, 13, 5–23	8, 9, 3–18	4, 5, 2–10	2, 2, 1–10	3, 3, 2–10
30 d	7, 7, 1–18	7, 7, 1–16	6, 6, 1–13	4, 4, 1–8	2, 2, 1–5	2, 3, 1–5
Cape Lambert project Dredging period						
1 h	159, 159, 97–220	48, 48, 21–75	23, 23, 9–36	8, 8, 4–12	2, 2, 2–3	6, 6, 3–9
1 d	57, 57, 38–76	39, 39, 19–60	21, 21, 9–32	9, 9, 4–15	3, 3, 2–4	6, 6, 3–9
14 d	17, 17, 10–24	16, 16, 9–23	14, 14, 7–21	10, 10, 4–17	6, 6, 2–10	7, 7, 3–11
30 d	8, 8, 6–10	8, 8, 6–10	8, 8, 6–10	6, 6, 3–10	4, 4, 3–6	5, 5, 3–7
Burrup Peninsula project Baseline/Reference						
1 h	15, 28, 13–132	5, 8, 5–20	3, 4, 1–12	2, 2, 1–4	1, 1, 0–3	1, 2, 1–3
1 d	8, 11, 6–29	5, 7, 4–16	2, 3, 1–9	1, 2, 1–5	1, 1, 0–3	1, 2, 1–3
14 d	2, 3, 1–6	2, 3, 1–6	2, 3, 1–6	1, 2, 1–5	1, 2, 0–4	1, 2, 1–4
30 d	4, 3, 1–5	4, 3, 1–4	3, 3, 1–4	2, 2, 1–3	2, 2, 0–3	2, 2, 1–3
Burrup Peninsula project Dredging period						
1 h	306, 312, 173–463	149, 138, 26–227	85, 73, 10–113	42, 36, 5–53	19, 17, 4–29	30, 25, 5–35
1 d	99, 128, 68–247	95, 103, 32–189	81, 67, 10–96	45, 38, 5–55	23, 20, 3–31	30, 25, 4–35
14 d	49, 43, 16–57	49, 43, 16–57	48, 42, 15–56	36, 32, 4–50	31, 28, 3–45	30, 27, 4–42
30 d	22, 22, 12–33	22, 22, 12–32	22, 22, 11–32	17, 17, 4–29	12, 12, 2–22	13, 13, 4–21

Percentiles were calculated separately for the baseline and reference site data (combined) and for near dredge sites (<2 km) during dredging. Shown are the median, mean and range (min–max) for the 100th (maximum), 99th, 95th, 80th, 50th (median) percentiles and mean for one hour, one day, 14 d and 30 d running mean periods.

doi:10.1371/journal.pone.0137112.t003

one). To further examine the relationship between median and mean, Fig 5 shows the ratio calculated for each day during the Barrow Island project for three reference sites (AHC, BAT, SBS) and three near dredge sites (LNG0, LNG1, MOF1) where there was a known high turbidity peak (>20 NTU, any time during the day). Mean daily turbidity values were over 5 times higher than the median for some days at sites impacted by dredging. For example, mean daily turbidity for LNG0 on day 285 was 8.5 NTU versus a median value of only 1.6 NTU, with the maximum turbidity observed for the day as high as 153.6 NTU (Fig 5C).

Intensity, duration, frequency (IDF) analysis

Based on maximum daily values, the intensity (95th percentile) of turbidity peaks was 11 times greater during the dredging period than the baseline at LNG1 (dredge impacted site) from the

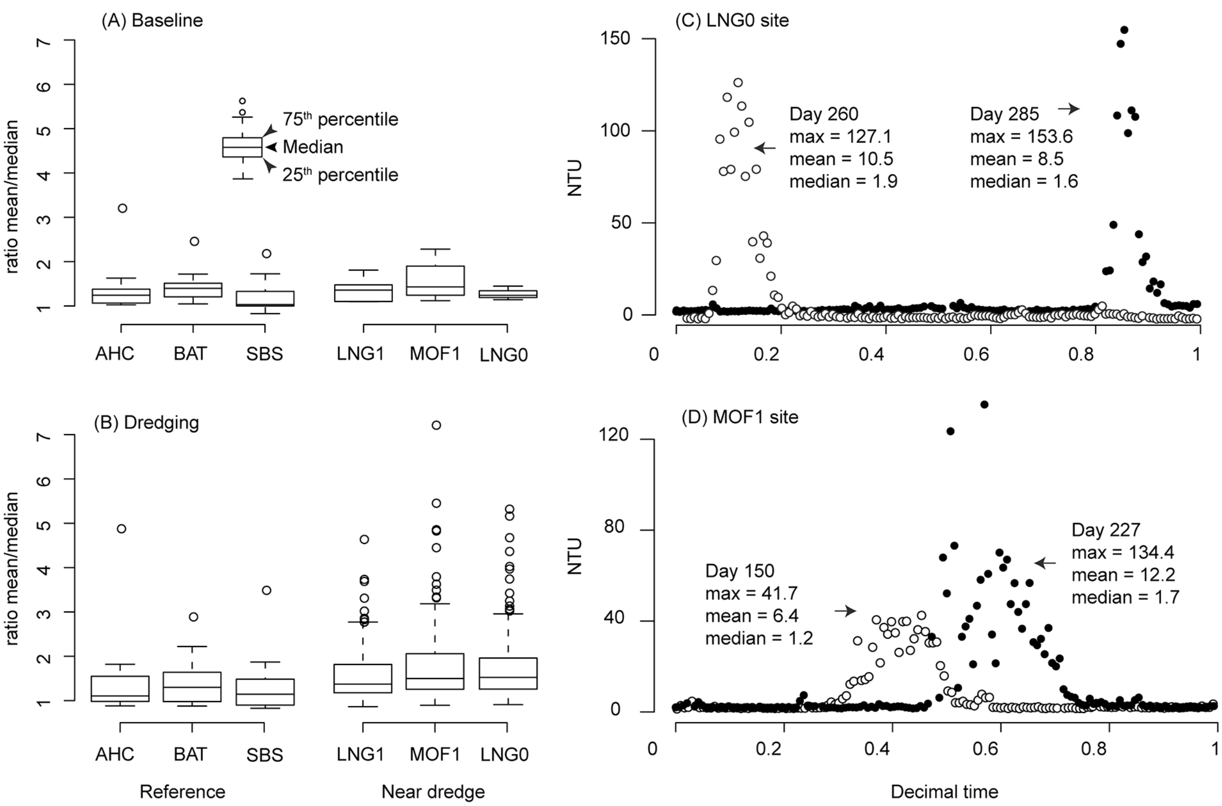


Fig 5. A comparison of mean versus median values as a statistical summary for daily turbidity (NTU) readings for selected near dredge and reference sites at Barrow Island. Boxplots of the ratio of the mean daily value versus the median daily value are shown during (A) the baseline period and (B) the dredging phase. The central bar of the box represents the median value, with the hinges indicating the first and third quartiles, and whiskers extending to the most extreme data point within 1.5 times this interquartile range. Only days where the maximum turbidity reading at any time throughout the day was greater than 20 NTU were included. This ratio was greater than 5 fold for four days from two sites, and the turbidity readings (NTU) of these days are plotted in C (LNG0) and D (MOF1).

doi:10.1371/journal.pone.0137112.g005

Barrow Island project, whereas reference sites (e.g., SBS) showed little change (Table 4). Although less pronounced, there was also an increase in the intensity of turbidity peaks for dredge impacted sites for the Cape Lambert and Burrup Peninsula projects with 2–3-fold increases in intensity (Table 4). In addition to an increase in intensity, both the duration and frequency of turbidity peaks also increased during dredging at dredge impacted sites (Table 4). The upper 95^{th} percentile of the duration of turbidity events ranged from 6.4 to 16 days at the dredging impacted sites during dredging, compared to only 1.9 to 3 days during baseline, representing a 1.8 to 5.3-fold increase (Table 4). The frequency of high turbidity events increased 2.8–3.4-fold across the three projects (Table 4).

Results of the IDF analysis based on maximum hourly values were relatively consistent with those based on daily values, with 7.2, 2.2 and 2-fold increases in intensity; 2.7, 2.3 and 2.8-fold increases in duration; and 13.5, 4.4 and 12.6-fold increases in frequency at dredge impacted locations across the Barrow Island, Cape Lambert and Burrup Peninsula projects respectively. Over these two temporal scales there was little change occurring at representative reference sites, with both scales showing a 0.6–0.9-fold change (Table 4). There were, however, substantial differences in the actual values observed among the two temporal scales (Table 4). Hourly intensity values were significantly more variable and highly left skewed, thus 95% percentiles were much lower (11–41 NTU for hourly values versus 28–99 NTU for daily values), of shorter duration (0.6–0.8 days for hourly values versus 7.2–16.0 days for daily values) and far more frequent than their daily equivalents (34–104 exceedances for hourly values versus 28–34 exceedances for daily values, Table 4).

Twilight periods

Irradiance levels across both the baseline and dredging periods were only consistently available for the Barrow Island project (Table 5). Higher turbidity values resulted in lower underwater light conditions, and a representative time series is shown graphically in Fig 6 for two sites at the same seawater depth (4.5 m) over a period of near uninterrupted sunshine (peaking at 1600 μmol photons m^{-2} s^{-1} at solar noon, Fig 6A). The site closest (~0.5 km) to the dredging experienced a turbidity event which peaked at ~200 NTU on days 3 and 4. Over the 6 days there were frequent low-light periods, and four days in a row where one half to one third of the daylight hours was in darkness. On day 3 of this sequence, instantaneous light levels peaked at only 6 μmol photons m^{-2} s^{-1} and the DLI was only 0.04 mol photons m^{-2} (Fig 6B). Over the same period at the reference site (>30 km away) the peak turbidity was more than one order of magnitude lower, light levels typically exceeded a maximum of ~200 μmol photons m^{-2} s^{-1} each day and the DLIs ranged from 3–9 mol photons m^{-2} (Fig 5C).

DLIs showed substantial drops episodically during the baseline period at both dredged and reference locations (Fig 7A and 7B). Both of these sites were at the same seawater depth

Table 4. Intensity, duration and frequency (IDF) analysis of the seawater quality data at selected dredge-influenced site (Dredg.) and reference site (Ref.) for the Barrow Island, Cape Lambert and Burrup Peninsula dredging programs.

		Barrow Island		Cape Lambert		Burrup Peninsula	
	Period	**Dredging (LNG1)**	**Reference (SBS)**	**Dredging (PWR)**	**Reference (DLI)**	**Dredging (SUP2)**	**Reference (WINI)**
Daily							
	baseline	8	20	38	29	9	29
Intensity (I)	dredging	90	14	99	21	29	25
	change	11.0	0.7	2.6	0.7	3.1	0.9
	baseline	3.0	5.4	3.6	9.2	1.9	2.7
Duration (D)	dredging	16.0	2.0	6.4	6.6	7.2	2.9
	change	5.3	0.4	1.8	0.7	3.9	1.1
	baseline	12	6	8	6	12	12
Frequency (F)	dredging	34	6	28	5	34	9
	change	3.0	1.0	3.4	0.9	2.8	0.7
Hourly							
	baseline	4	10	19	10	6	14
Intensity (I)	dredging	30	7	42	9	11	9
	change	7.2	0.6	2.2	0.9	2.0	0.7
	baseline	0.3	0.8	0.4	0.8	0.2	0.2
Duration (D)	dredging	0.8	0.7	0.8	1.5	0.6	0.3
	change	2.7	1.0	2.3	1.9	2.8	1.4
	baseline	7	4	8	5	6	6
Frequency (F)	dredging	104	2	34	5	77	9
	change	13.5	0.5	4.4	1.0	12.6	1.5

The analysis was carried out separately at daily and hourly temporal scale. Intensity values represent the 95% percentile of turbidity for the site for each period. Duration values represent the 95th percentile of the duration (days) of exceedance events (where exceedance events are defined as an event where the observed value exceeds the 95th percentile (i.e. the intensity threshold) of the baseline state for that site). Frequency represents the number of times the duration of events exceeded the 95th percentile of the duration of exceedance events for the baseline state for that site. Frequency has been normalised per year. 'Change' shows the value for the dredge period as a proportion of the baseline.

doi:10.1371/journal.pone.0137112.t004

Table 5. The photosynthetically active radiation (PAR) daily light integral (DLI, mol photons m^{-2}) percentile values for various running mean time periods for the Barrow Island dredging project.

		Percentile value (DLI, mol photons m^{-2})					
		0th (min)	1st	5th	20th	50th	mean
Baseline/	1 d	0.1, 0.7	0.3, 1	1.1, 1.8	2.8, 3.5	4.3, 5.3	4.2, 5.2
reference		0–6.3	0–8.9	0.2–11	1.1–13	2.2–16	2.5–16
	14 d	1.5, 1.9	1.5, 2	2.1, 2.5	3.1, 3.5	4.2, 4.9	4.2, 4.9
		0.5–12	0.5–13	0.8–14	1.2–14	2.3–17	2.5–17
	30 d	2.1, 2.6	2.3, 2.7	2.4, 2.9	3.2, 3.7	4.3, 5	4.3, 5
		0.7–13	0.8–14	0.9–15	1.4–15	2.1–17	2.5–18
Near dredge	1 d	0, 0	0, 0	0.1, 0.1	0.8, 0.7	2.2, 1.9	2.1, 2.1
		0–0	0–0.1	0–0.5	0.2–1.7	0.7–3.8	2.1, 1–3.8
	14 d	0.3, 0.3	0.3, 0.4	0.5, 0.6	1.1, 1.2	2.3, 2.1	2.2, 2.2
		0.1–0.8	0.1–0.9	0.3–1.2	0.4–2.5	0.9–3.8	1–4
	30 d	0.4, 0.5	0.4, 0.5	0.6, 0.7	1, 1.3	2.4, 2.2	2.1, 2.2
		0.2–1.2	0.3–1.2	0.3–2.2	0.4–2.8	0.9–4.4	1.1–4.3

Percentiles were calculated separately for the baseline and reference site data (combined) and for near dredge sites (<2 km) during dredging. Shown are the median and mean and range across all relevant 0th (minimum), 1st, 5th, 20th and 50th (median) percentiles for the one day, 14 d and 40 d running mean periods.

doi:10.1371/journal.pone.0137112.t005

(~4.5 m). However, both the frequency and intensity of drops in light availability were substantially greater during the dredging phase compared to the baseline, with values below 0.1 mol photons m^{-2} d^{-1} occurring regularly (Fig 7A) as indicated in the running means percentile

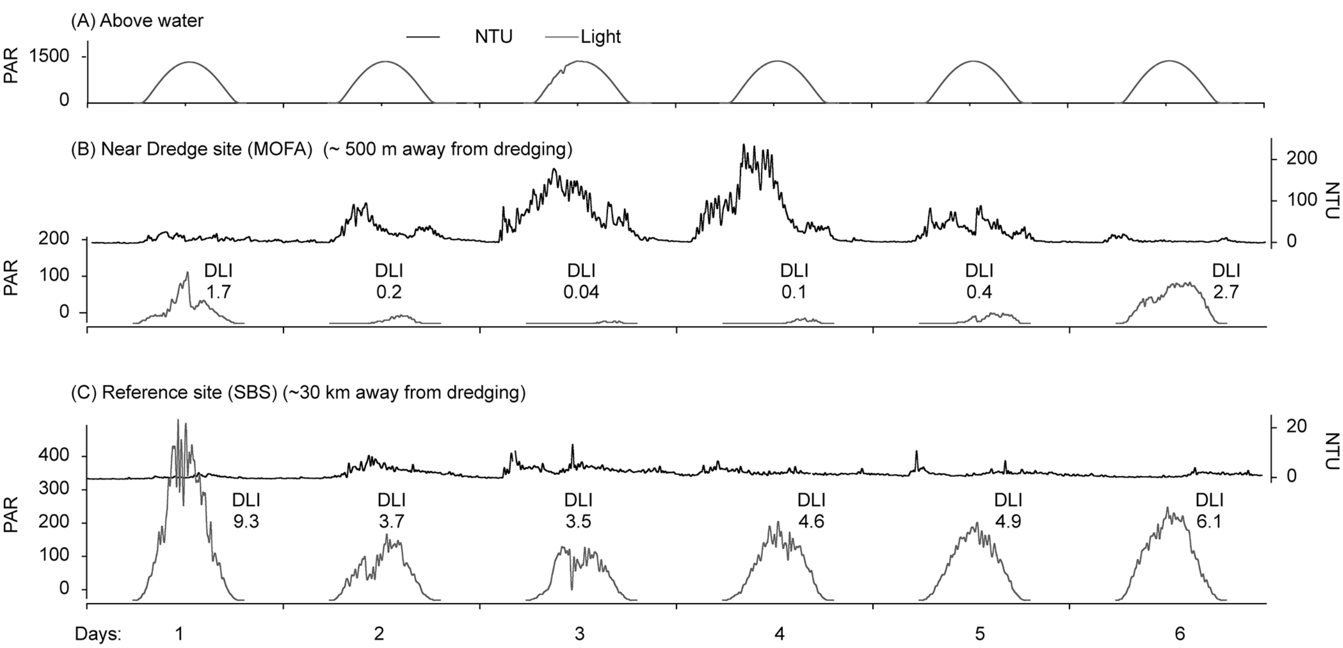


Fig 6. Turbidity (NTU) and PAR (μmol photons m^{-2} s^{-1}) during the Barrow Island dredging project measured every 10 mins over a 6 day period in April 2011 from (A) a terrestrial light sensor located on Barrow Island (B) at 4.5 m depth at a site ~150 m from dredging, and (C) at 4.5 m depth at reference site ~30 km from dredging (see Fig 1). Numbers above the light profiles are the daily light integral (mol photons m^{-2} d^{-1}) (see Material and Methods).

doi:10.1371/journal.pone.0137112.g006

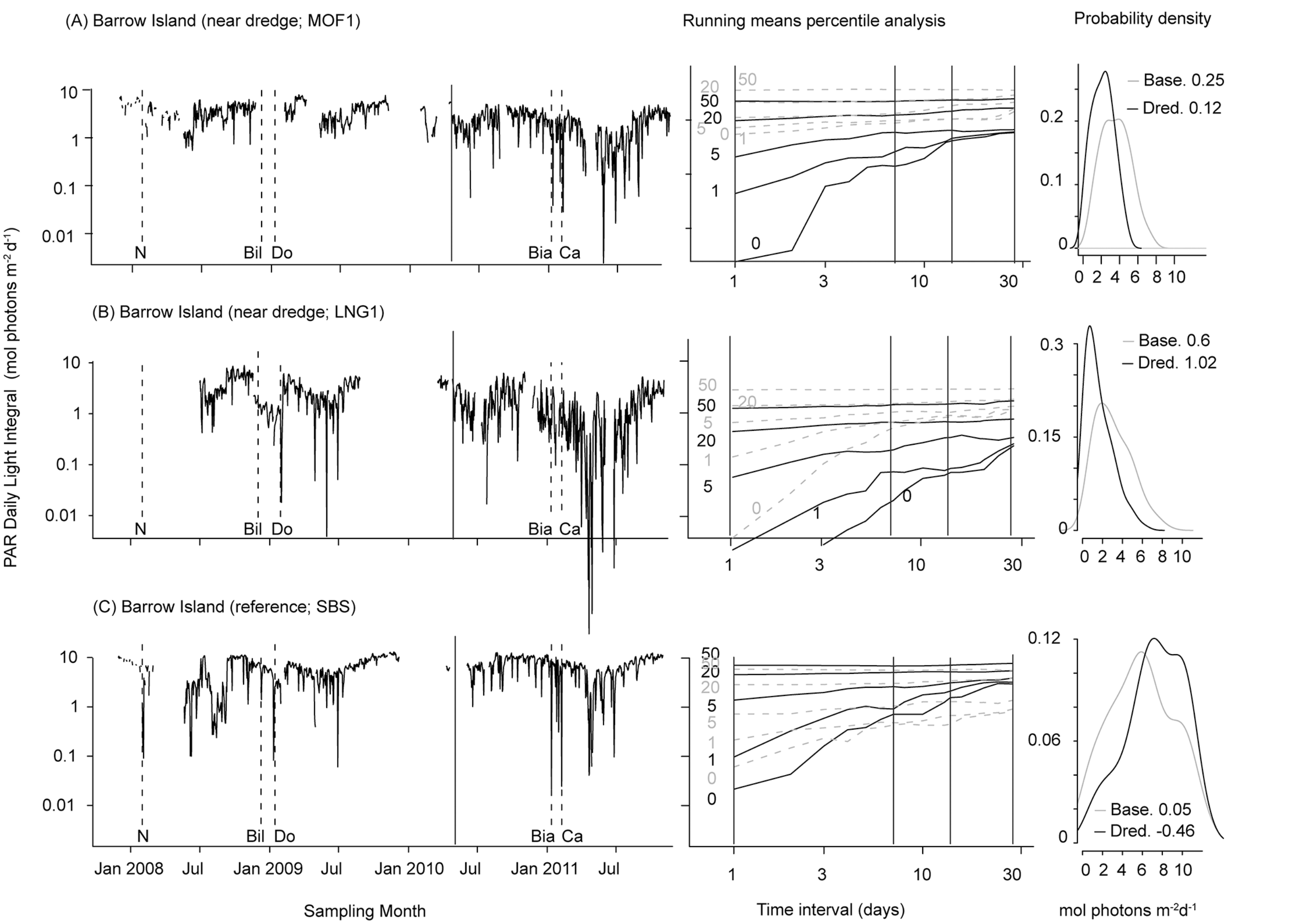


Fig 7. Total daily light integral (mol photons m^{-2} d^{-1}, left panels) and probability density function (right panels) at two dredge impacted sites (MOF1 and LNG1, see Fig 1) and at SBS (reference site) during the Barrow Island project. Seawater depth at MOF1 and SBS were similar (~4.5 m) and at LNG1 was ~9 m. The red line on the left hand plots indicates the start of dredging for each project and dashed lines represent the timing of cyclone events that may have had the potential to cause substantial swell in this region (Puotinen, pers comm). Annotations at the base of the x-axis indicate each cyclone event, as follows: (a) Nicholas, max category 4, min distance 190 km; (b) Dominic, max category 2, min distance 20 km; (c) Bianca, max category 4, min distance 105 km; (d) Carlos, max category 3, minimum distance 0 km. Centre panels show the running means percentile analysis (50th, 20th, 5th, 1st and 0th (minimum)) PAR values, plotted as a function of the running mean time span from 1 to 30 days. Annotations under each axis indicate each cyclone event, as follows: Nicholas (N), category 4 minimum distance 190 km; Billy (Bil), category 3; Dominic (Do), category 2 minimum distance 20 km; Bianca (Bia) category 4, minimum distance 105 km; Carlos (Ca) minimum distance 0 km, category 3; Lua (Lu) category 4. Cyclone categories indicate the intensity (Australian Ranking Scale) of each cyclone at closest approach to the sites.

doi:10.1371/journal.pone.0137112.g007

analyses (centre panels in Fig 7, Table 5). As might be expected the trends resulting from dredging on the probability distribution of light were the inverse of those of NTU, with dredging increasing skewness due to an increasing frequency of low values and increasing kurtosis (Fig 7). Fig 7B shows a similar trend for a site 0.5 km from the dredging (site LNG1, see Fig 1) but where the loggers were located in deeper seawater (9 m). Over the dredging period ~5% of all values were below 0.1 mol photons m^{-2} d^{-1} and the site routinely experienced DLIs <0.04 mol photons m^{-2}.

If low light is defined as an average instantaneous flux of 20 μmol photons m^{-2} s^{-1} (or approximately 1% of surface irradiance) for 12 h (equivalent to 0.8 mol photons m^{-2} d^{-1}), dredge-influenced sites experienced more than 30 consecutive days in very reduced light levels

(Fig 8A). If low light is defined as an average instantaneous flux of 5 μmol photons m^{-2} s^{-1} for 12 (~0.2 mol photons m^{-2} d^{-1}) the worst case (maximum values) for near (<2 km) dredge sites during the dredging period was ~9 consecutive days, with the 80th percentiles reaching 6 days and medians of ~3 days (Fig 8). This contrasts with the worst-case scenarios during baseline and at reference locations, which were ~5, ~4 and ~2 days respectively (maximum, 80th and median, Fig 8).

Expressed as mean number of days per fortnight, dredge impacted sites were subjected to 2–7 (14–50%) days of very low light depending on the light cut-off values used (Fig 8B). Normalised per year, for one of the most light restricted definitions of low light (5 μmol photons m^{-2} s^{-1}), the sites where the seawater quality was worst impacted sites can experience up to 70 days (20%) in effective low light and around 150 days (>40%) if less light restricted cut-off values are considered (data not shown).

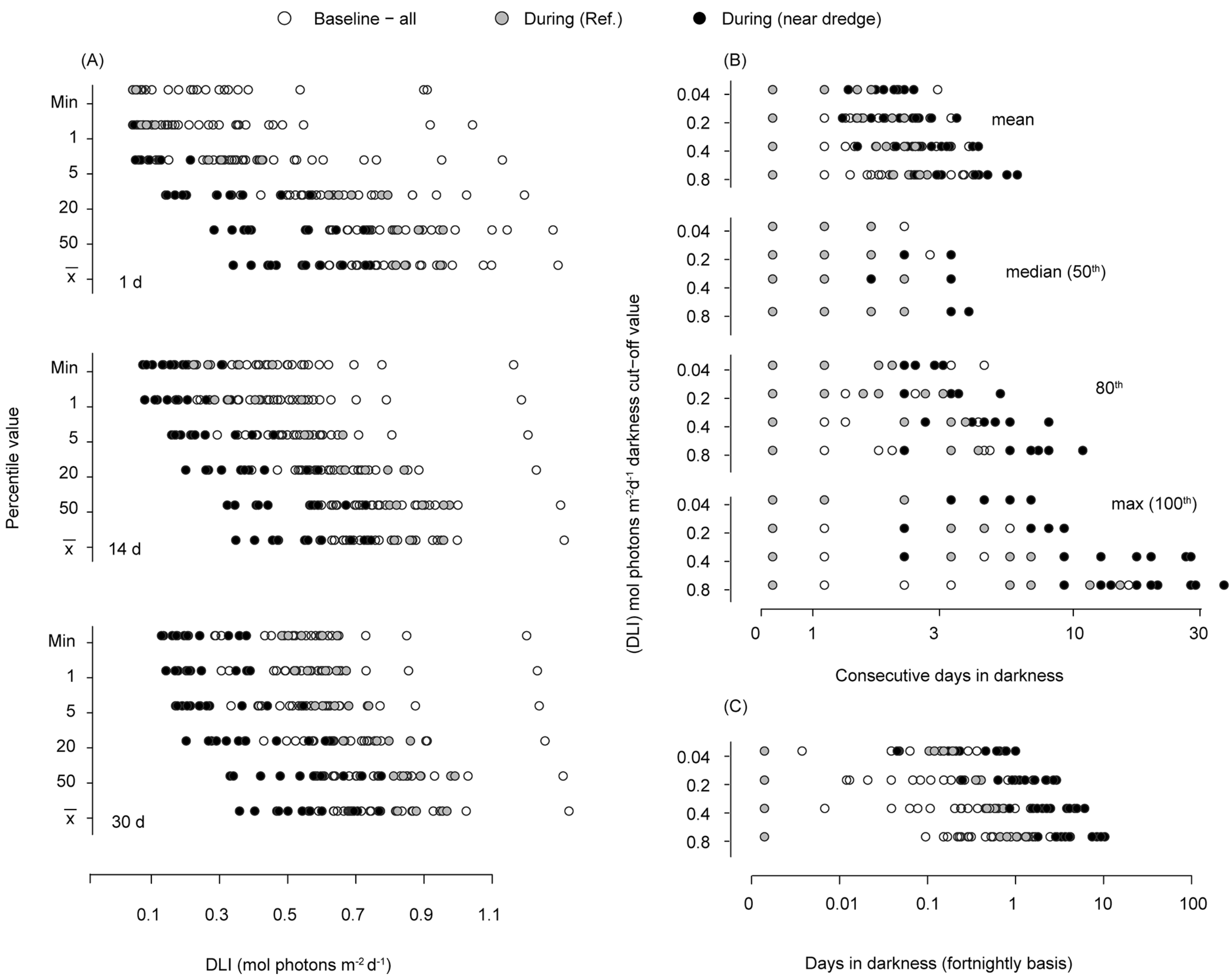


Fig 8. (A) Total photosynthetically active radiation (PAR) daily light integral (DLI, mol photons m^{-2}) percentile values for running means calculated on time scales of 1, 14 and 30 days for all sites for the Barrow Island project. (B) Mean, median, 80th percentile and maximum number of consecutive days in darkness and semi-darkness and (C) and mean fortnightly numbers of days for 4 different semi-darkness cut-off thresholds at all sites for the Barrow Island dredging project (1, 5, 10 and 20 μmol photons m^{-2} s^{-1}; equivalent to DLI values of 0.04, 0.2, 0.4, and 0.8 mol photons m^{-2} d^{-1}). White symbols represent percentiles for the baseline period (pre-dredging period), grey symbols represent reference sites during the dredging period and black symbols represent sites close to (<2 km) the dredging.

doi:10.1371/journal.pone.0137112.g008

Discussion

During the dredging programs turbidity levels were highly variable, sometimes changing 2–3 orders of magnitude over the course of a day. Associated with these high turbidity events PAR levels also exhibit marked changes, frequently dropping to extremely low levels, creating day-time twilight and occasionally periods of darkness even in the shallow (4–5 m) reef environment. Under such highly variable conditions the choice of statistics is very important for summarising over time periods. Daily periods are often used to characterise seawater quality and using median values can miss quite substantial turbidity events if they only occur for a small part of the day period (cf Fig 5). Due to the ephemeral nature of the turbidity events care also needs to be taken when summarising data over longer time periods. For example, over the baseline period of the Barrow Island project, the average turbidity for the sites closest to the dredging was ~1.5 NTU slightly above the resolution of the nephelometers whilst during the dredging period it was 6.1 NTU. This statistic masks the fact that the sites were exposed to plumes for over 300 days during the dredging program ([35] and received maximum hourly average turbidity values sometimes exceeding hundreds of mg L^{-1} (200–400 NTU). These sites were within areas where coral mortality was permitted under regulatory conditions and where many corals suffered whole and/or partial mortality. Clearly the average was much less but the peaks much more, which is important as these peaks can have ecological consequences. Using an estimated turbidity to SSC conversion factor of 1:1.1 to1.6 during the dredging project, these sites received long term average SSCs just under the 10 mg L^{-1} threshold suggested by Rogers (1990) as indicative of reefs not subjected to stresses by humans, and used as a 'rule-of-thumb' for concern [13,36]. The frequently cited threshold value of 10 mg L^{-1} has little meaning without a temporal context i.e. x mg L^{-1} over y days.

Dredging effectively alters the overall probability distributions of fine temporal scale turbidity and light changes, increasing the frequency of extreme values and dampening the probability distribution by increasing the frequency of larger values, decreasing both skewness and kurtosis. When averaged across the entire baseline and dredging phases separately for the three Pilbara dredging projects turbidity values increased by 2–3 fold but when examined by the IDF analysis across baseline and dredging periods, dredging increased the intensity (magnitude) of turbidity peaks by over an order of magnitude, generated peaks that lasted five times longer than the baseline period, and may cause peaks to occur up to three times more frequently.

Temporal scales analysis

The running means analysis of the turbidity data and light (Figs 3 and 6) provides an effective method for viewing seawater quality conditions at multiple different time intervals as well as considering the upper percentile values. Examining these upper values is important as they can have biological consequences ([37]) and the analyses are possible because of the frequent (typically every 10–30 mins) sampling undertaken during the seawater quality monitoring programs which has increased resolution for the upper percentiles and lowered the potential for bias [22]. A recent wavelet analysis of the turbidity data showed clear periodicities of turbidity in the three Pilbara datasets during both the baseline and dredge phases of the studies (Stark, unublished data) peaking semidiurnally associated with tides, diurnally associated with daily sea breezes and sometimes fortnightly associated with spring-neap cycles. The running means analyses were conducted to a period of up to 1 month, a time frame which accounts for the short term acute turbidity events (i.e. hours or a few days) as well and long term (chronic) periods (i.e. days and weeks) and encompasses the periodicities in the data. By then examining these running means periods using a range of percentile values (i.e. P_{100}, P_{99}, P_{95}, P_{80}, or P_{50}) it is possible to describe the impacts that dredging has on seawater quality (relative to the baseline period or appropriate reference sites) simultaneously for both rare (upper percentiles values i.e. $P_{100\text{-}95}$) and common (medium percentile values i.e. P_{80} and P_{50}) turbidity events.

If the running means/percentile analysis is conducted using the baseline (i.e. pre-dredging) data it captures short term turbidity events, effectively characterising the natural turbidity regime at a location. These natural turbidity events are common in the marine environment and usually associated with wind-driven waves in the shallow reef environment [11–14,38]. Conducting the same analyses during the dredging operations (and under the influence of a dredging plume) captures the effect of dredging-related turbidity on top of the natural, background patterns. The analysis shows a clear shift in the running-mean-percentile profiles between baseline and dredging at impacted sites across the dredging programs.

Using the running means/percentile analysis, the P_{100} (i.e. maximum) for a given time interval typically decreased as the averaging period increased. That is, given the transitory nature of turbidity events, seawater quality conditions will usually become better over longer periods as conditions are likely to improve. As the percentile values decreased, the averages across broader time scales became more similar, with the P_{80} values showing relatively consistent values across the whole spectrum of time scales examined. While summary statistics for upper percentile values generally declined with increasing temporal scales, these patterns were not always smooth, and occasionally they increase as the time increment increased. One such inflection point can be seen around 14 days (see Fig 3C), although increases can occur across sites at a range of temporal scales (see Figs A-D in S2 File). This effect is due to the periodicity in turbidity discussed previously (Stark, unublished data), and in this case is certainly the 14.76 d spring-neap cycle [39], where turbidity is naturally higher during spring than neap tides associated with greater current velocities. As the averaging time intervals increases to beyond 2 weeks, it will begin to incorporate a second spring tide sequence and secondary peak, as opposed to only one during the shorter (7 d) time intervals.

Daytime-twilight events

The second prominent and characteristic feature of the seawater quality conditions during the dredging programs were the low light caliginous, or 'daytime twilight' periods. Such conditions are well known, even for tropical environments, associated with wind and wave events [40,41]. Complete darkness was sometimes recorded during the baseline periods but occurred more frequently during the dredging program.

Defining light low as a DLI of 0.8 mol photons m^2, or equivalent to 12 h of 20 μmol photons m^2 s^{-1} or approximately 1% of surface illumination (the delineation between euphotic and dysphotic zones), benthic taxa may experience up to 30 continuous days, or up to 7 days per fortnight of low light conditions when under the influence of dredging plumes. Whilst natural caliginous periods can represent significant challenges to corals, they usually occur naturally over short time periods associated with the passage of storms. Loss of all daytime light can also occur during baseline periods but sometimes over extended periods during dredging. Defining complete darkness as a DLI of 0.04 mol photons m^2 (or equivalent to 12 h of 1 μmol photons m^2 s^1) some sites remained in darkness for >5 consecutive days. Loss of all light for a whole day or loss of light for a significant portion of the day, followed by extreme low light for the remainder of the day (see Fig 5), may present physiological challenges to corals beyond those of a simple energy deficit. In sustained low light periods corals will expel their algal symbionts and this dissociation of the symbiosis causes coral to turn white (cf bleaching). Yonge and Nicholls [42] found that tropical corals will bleach within a few days of being placed in darkness. Kevin and Hudson [43] recorded a much longer-time frame for the temperate coral *Plesiastrea versipora* (Lamarck, 1816), suggesting adaptation to episodic periods of low light as is common in higher latitudes. The dissociation of the symbiosis has profound implications for corals as regaining the algal symbionts to stable-state densities takes several months [44]. Loss of the symbionts will prevent or reduce the ability of corals from regaining an energy deficit autotrophically between turbidity events. Understanding the effects these caliginous periods on the coral-algal symbiosis, and in particular whether full light exclusion as opposed to very low light levels induces bleaching, could be useful in developing light thresholds for dredging programs.

One of the objectives of this analysis was to provide a temporal analysis of seawater quality to allow the design of more realistic experiments examining the effects of sediments on tropical marine organisms (corals, seagrasses, sponges ascidians etc). The running means/percentile analysis described herein has provided a matrix of empirical data of seawater quality (turbidity and light levels) which when expressed as 100th (maximum), 99th, 95th, 80th and 50th (median) percentiles over multiple time frames (hours to weeks) effectively captures the entire range of likely seawater quality conditions associated with dredging in a reefal environment. This provides a reference data set for designing future experiments (see [9]) and also for interpreting the results of previous studies.

Seawater quality thresholds

A useful way of managing dredging programs is seawater quality monitoring i.e. measuring the key hazards or environmental 'pressures', which are capable of having adverse biological effects [2,45]. Given the ephemeral pattern of dredging related turbidity events, thresholds need really to be developed over telescoping time periods, from short term acute events through to longer term chronic time periods an approach that is increasingly adopted in Australia and Singapore. Episodic periods of poor seawater quality are often interspersed with periods of otherwise normal seawater quality, driven by meteorological and hydrological conditions (sea breezes and tidal patterns), and influenced by heterogeneity of the plumes. This may provide benthic communities with opportunities to partially or fully recover depending on the nature of the disturbance and this could be incorporated into thresholds.

This study has concentrated on changes in turbidity and light quantity associated with dredging and yet these are only some of the key cause–effect pathways of risk associated with turbidity generation in shallow tropical marine environments. Changes in light quality, and especially sediment deposition have not been considered here. Deposition rates that exceed the natural clearing ability of corals can result in sediment smothering the tissues [46]. Once this has occurred solute (gas) exchange and light availability will be very limited, and the corals' health will become un-coupled or unrelated to changes in SSC and light in the overlying seawater column (but see [47]). Relating coral health to seawater quality during dredging program requires knowledge of all causes of mortality and especially the potential influence of sediment deposition and incorrect identification of the relevant route(s) of exposure could be very misleading [48].

Dredge material placement sites

Ocean disposal of sediment at dredge material placement sites (spoil grounds) is another potentially significant turbidity-generating event associated with dredging. Plumes can be generated as the sediments are released over the disposal grounds and fine material in the water column can migrate to nearby habitats. In the longer term, this material and any fine material within the disposal site could be subsequently mobilized by storms and dispersed further. The extent to which mobilization and movement from the disposal ground occurs is determined by whether the site is located within a sediment transport pathway with a high or low throughput i.e. is dispersive or retentive site, and in turn dependent on bathymetry and hydrodynamics and coastline features (bays compared to promontories)[49]. Currently the long term fate and effects of ocean disposal is a significant issue on the Great Barrier Reef and the disposal of capital dredge material in the Great Barrier Reef Marine Park has recently been banned ([49]). In two of the three case studies described here there was no monitoring around the dredge material placement sites but some monitoring occurred at the Barrow Island sites with sensors placed ~1 km north and south of the 9 km^2 spoil ground. Turbidity associated with sediment disposal at the placement sites was quite low as compared to extraction at the site of dredging (see **S1 File and** Fig B in S2 File) and consistent with Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image analysis of the dredge plume boundaries during the Barrow Island project [35].

In conclusion, the data from the recent large-scale capital projects in Australia's Pilbara region have produced very detailed information on the changes that can occur in seawater quality during dredging in coral reef environments. Characteristic features are the highly variable and transitory nature of the turbidity events and the pronounced increase in the intensity, duration and frequency of turbidity compared to natural background events. Associated with the turbidity are profound changes in submarine light fields, with frequent and often extended low light caliginous or 'twilight' periods and sometimes loss of all light. The choice of summary statistic and analysis periods is very important for describing such highly variable data as median values or longer term averaging periods can hide significant events which could have ecological consequences. The broad spatial and temporal coverage together with the statistical approaches and methods of analysis used here have provided information that is important for contextualising seawater quality information in future dredging programs. The same information can be used in manipulative studies examining the effects of dredging on tropical marine organisms using environmentally realistic and relevant exposure conditions. Collectively this information could contribute to the development of seawater quality thresholds for dredging projects and ultimately improve the ability to predict and manage the impact of future projects.

Supporting Information

S1 File. Sampling and site information for all seawater quality monitoring sites. Detailed site information, including depth below LAT and distance (km) from dredging activity (where relevant) during the three Pilbara (Western Australia) dredging projects. The number of valid sample days for NTU and light are shown for the baseline and dredging periods, as are the mean values at NTU and light (μmol photons m^{-2} s^{-1}) across all samples for each period. (DOCX)

S2 File. Maximum instantaneous daily turbidity (NTU) or light (μmol photons m^{-2} s^{-1}) during the baseline period (before dredging) or during the dredging program (left), probability density curves (mid) and running mean quantile plot (right) for the Burrup Peninsula project (Figure A), Barrow Island project (Figure B and D) and Cape Lambert project (Figure C). Running mean quantile plots show the 100^{th} (maximum), 99^{th} and 95^{th} and 80^{th} percentile of running periods from 1 h to 21 d before (dashed lines) and during (solid lines) the dredging program. Data are only shown for near dredge sites (<2 km) and those site considered reference sites. Vertical red lines on the left-hand time series plots show cyclone events that may impact sites. Time series, probability density, and running means for all sites during the Burrup Peninsula Project (Figure A), Barrow Island project (Figure B), and Cape Lambert Project (Figure C). Fig. A. Burrup Peninsula project. NTU data. Time series, probability density, and running means for all sites. Fig. B. Barrow Island project. NTU data. Time series, probability density, and running means for all sites. Fig. C. Cape Lambert project. NTU data.

Time series, probability density, and running means for all sites. Fig. D. Barrow Island project. Light data. Time series, probability density, and running means for all sites.
(DOCX)

Acknowledgments

We thank M. Puotinen for providing information on cyclone activity and an anonymous reviewer for extensive comments to an earlier version of the manuscript.

Author Contributions

Conceived and designed the experiments: RJ RF CS PR. Analyzed the data: RJ RF CS PR. Contributed reagents/materials/analysis tools: RJ RF CS PR. Wrote the paper: RJ RF CS PR.

References

1. Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62: 185–202.
2. Foster T, Corcoran E, Erftemeijer P, Fletcher C, Peirs K, et al. (2010) Dredging and port construction around coral reefs. PIANC Environmental Commission, Report No 108.
3. Fabricius KE (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50: 125–146. PMID: 15737355
4. Erftemeijer PL, Riegl B, Hoeksema BW, Todd PA (2012) Environmental impacts of dredging and other sediment disturbances on corals: a review. Marine Pollution Bulletin 64: 1737–1765. doi: 10.1016/j.marpolbul.2012.05.008 PMID: 22682583
5. Bak RPM (1978) Lethal and sublethal effects of dredging on reef coral. Marine Pollution Bulletin 9: 14–16.
6. Johannes RE (1970) How to kill a coral reef. Marine Pollution Bulletin 1: 186–187.
7. Stoddart J, Anstee S (2004) Water quality, plume modelling and tracking before and during dredging in Mermaid Sound, Dampier, Western Australia. In: Stoddart JA, Stoddart SE, editors. Corals of the Dampier Harbour: their survival and reproduction during the dredging programs of 2004: MScience Pty Ltd, University of Western Australia, Perth, Western Australia. pp. 13–33.
8. Trimarchi S, Keane J (2007) Port of Hay Point Apron Areas and Departure Path Capital Dredging Project. Environmental Review, EcoPorts Monograph Series No. 24, Ports Corporation of Queensland, Brisbane.
9. Norris RH, Webb JA, Nichols SJ, Stewardson MJ, Harrison ET (2011) Analyzing cause and effect in environmental assessments: using weighted evidence from the literature. Freshwater Science 31: 5–21.
10. Macdonald RK, Ridd PV, Whinney JC, Larcombe P, Neil DT (2013) Towards environmental management of water turbidity within open coastal waters of the Great Barrier Reef. Marine Pollution Bulletin 74: 82–94. doi: 10.1016/j.marpolbul.2013.07.026 PMID: 23948091
11. Jing L, Ridd PV (1996) Wave-current bottom shear stresses and sediment resuspension in Cleveland Bay, Australia. Coastal Engineering 29: 169–186.
12. Larcombe P, Costen A, Woolfe KJ (2001) The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology 48: 811–835.
13. Ogston AS, Storlazzi CD, Field ME, Presto MK (2004) Sediment resuspension and transport patterns on a fringing reef flat, Molokai, Hawaii. Coral Reefs 23: 559–569.
14. Verspecht F, Pattiaratchi C (2010) On the significance of wind event frequency for particulate resuspension and light attenuation in coastal waters. Continental Shelf Research 30: 1971–1982.
15. Fabricius K, Logan M, Weeks S, Brodie J (2014) The effects of river run-off on water clarity across the central Great Barrier Reef. Marine Pollution Bulletin 84: 191–200. doi: 10.1016/j.marpolbul.2014.05.012 PMID: 24863415
16. Fabricius KE, De'ath G, Humphrey C, Zagorskis I, Schaffelke B (2013) Intra-annual variation in turbidity in response to terrestrial runoff on near-shore coral reefs of the Great Barrier Reef. Estuarine, Coastal and Shelf Science 116: 57–65.

17. Thompson A, Schroeder T, Brando VE, Schaffelke B (2014) Coral community responses to declining water quality: Whitsunday Islands, Great Barrier Reef, Australia. Coral Reefs: 1–16.
18. Larcombe P, Ridd P, Prytz A, Wilson B (1995) Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14: 163–171.
19. Orpin A, Ridd P, Thomas S, Anthony K, Marshall P, et al. (2004) Natural turbidity variability and weather forecasts in risk management of anthropogenic sediment discharge near sensitive environments. Marine Pollution Bulletin 49: 602–612. PMID: 15476839
20. Cooper TF, Ridd PV, Ulstrup KE, Humphrey C, Slivkoff M, et al. (2008) Temporal dynamics in coral bioindicators for water quality on coastal coral reefs of the Great Barrier Reef. Marine and Freshwater Research 59: 703–716.
21. Orpin AR, Ridd PV (2012) Exposure of inshore corals to suspended sediments due to wave-resuspension and river plumes in the central Great Barrier Reef: A reappraisal. Continental Shelf Research 47: 55–67.
22. Falkenberg LJ, Styan CA (2014) Too much data is never enough: A review of the mismatch between scales of water quality data collection and reporting from recent marine dredging programmes. Ecological Indicators 45: 529–537.
23. Zimmermann NE, Yoccoz NG, Edwards TC, Meier ES, Thuiller W, et al. (2009) Climatic extremes improve predictions of spatial patterns of tree species. Proceedings of the National Academy of Sciences of the United States of America 106: 19723–19728. doi: 10.1073/pnas.0901643106 PMID: 19897732
24. Gaines SD, Denny MW (1993) The Largest, Smallest, Highest, Lowest, Longest, and Shortest: Extremes in Ecology. Ecology 74: 1677–1692.
25. Hanley JR (2011) Environmental monitoring programs on recent capital dredging projects in the Pilbara (2003–10): a review. Australian Petroleum Production & Exploration Association (APPEA) 51 273–294.
26. EPA (2011) Environmental Assessment Guidleine for Marine Dredging Programs EAG7. Environmental Protection Authority (EPA), Perth, Western Australia. pp. 36.
27. Davies-Colley R, Smith D (2001) Turbidity, suspended sediment and water quality: a review. Journal of the American Water Works Association 37: 1085–1101.
28. Wood SN (2006) Generalized Additive Models: an introduction with R. Boca Raton, FL: CRC Press. 410 p.
29. R Core Team (2014) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available: http://www.R-project.org/.
30. McArthur C, Ferry R, Proni J (2002) Development of guidelines for dredged material disposal based on abioytic determinants of coral reef community structure. Proceedings of the Third Specialty Conference on Dredging and Dredged Material Disposal Coasts, Oceans, Ports, and Rivers Institute (COPRI) of ASCE. Orlando, FL USA. 1–15.
31. Newcombe CP, MacDonald DD (1991) Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11: 72–82.
32. Wilber DH, Clarke DG (2001) Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. North American Journal of Fisheries Management 21: 855–875.
33. Zeileis A, Grothendieck G (2005) zoo: S3 Infrastructure for Regular and Irregular Time Series. Journal of Statistical Software 14: 1–27.
34. Tuszynski J (2013) caTools: Tools: moving window statistics, GIF, Base64, ROC AUC, etc. R package version 116. Available: http://CRANR-projectorg/package = caTools.
35. Evans RD, Murray KL, Field SN, Moore JA, Shedrawi G, et al. (2012) Digitise this! A quick and easy remote sensing method to monitor the daily extent of dredge plumes. PLoS ONE 7: e51668. doi: 10.1371/journal.pone.0051668 PMID: 23240055
36. Ogston AS, Field ME (2010) Predictions of turbidity due to enhanced sediment resuspension resulting from sea-level rise on a fringing coral reef: evidence from Molokai, Hawaii. Journal of Coastal Research 26: 1027–1037.
37. De'ath G, Fabricius K (2008) Water quality of the Great Barrier Reef: distributions, effects on reef biota and trigger values for the protection of ecosystem health: Great Barrier Reef Marine Park Authority.
38. Lawrence D, Dagg MJ, Liu H, Cummings SR, Ortner PB, et al. (2004) Wind events and benthic-pelagic coupling in a shallow subtropical bay in Florida. Marine Ecology Progress Series 266: 1–13.
39. Kvale EP (2006) The origin of neap–spring tidal cycles. Marine Geology 235: 5–18.

40. Anthony K, Larcombe P (2000) Coral reefs in turbid waters: sediment-induced stresses in corals and likely mechanisms of adaptation. Proceedings of the 9th International Coral Reef Symposium Bali, Indonesia 1: 239–244.

41. Jones RJ (2008) Coral bleaching, bleaching-induced mortality, and the adaptive significance of the bleaching response. Marine Biology 154: 65–80.

42. Yonge CM, Nicholls A (1931) Studies on the physiology of corals. V The effects of starvation in light and in darkness on the relationship between corals and zooxanthellae. Great Barrier Reef Expedition 1928–29, Scientific Reports British Museum (Natural History) London (UK) 13–57 British Museum 1.

43. Kevin KM, Hudson RCL (1979) The rôle of zooxanthellae in the hermatypic coral Plesiastrea urvillei (Milne Edwards and Haime) From cold waters. Journal of Experimental Marine Biology and Ecology 36: 157–170.

44. Jones RJ, Yellowlees DY (1997) Algal (= zooxanthellae) regulation and control in hard corals. Philosophical Transactions of the Royal Society of London Series B: Biological Science 352: 457–468.

45. CEDA (2015) Environmental monitoring procedures. Information paper. Central Dredging Association (CEDA) Delft The Netherlands (http://www.dredging.org/media/): 23 pp.

46. Stafford-Smith M, Ormond R (1992) Sediment-rejection mechanisms of 42 species of Australian scleractinian corals. Marine & Freshwater Research 43: 683–705.

47. Junjie RK, Browne NK, Erftemeijer PLA, Todd PA (2014) Impacts of Sediments on Coral Energetics: Partitioning the Effects of Turbidity and Settling Particles. PLoS ONE 9: e107195. doi: 10.1371/journal.pone.0107195 PMID: 25197883

48. Harris CA, Scott AP, Johnson AC, Panter GH, Sheahan D, et al. (2014) Principles of Sound Ecotoxicology. Environmental Science & Technology 48: 3100–3111.

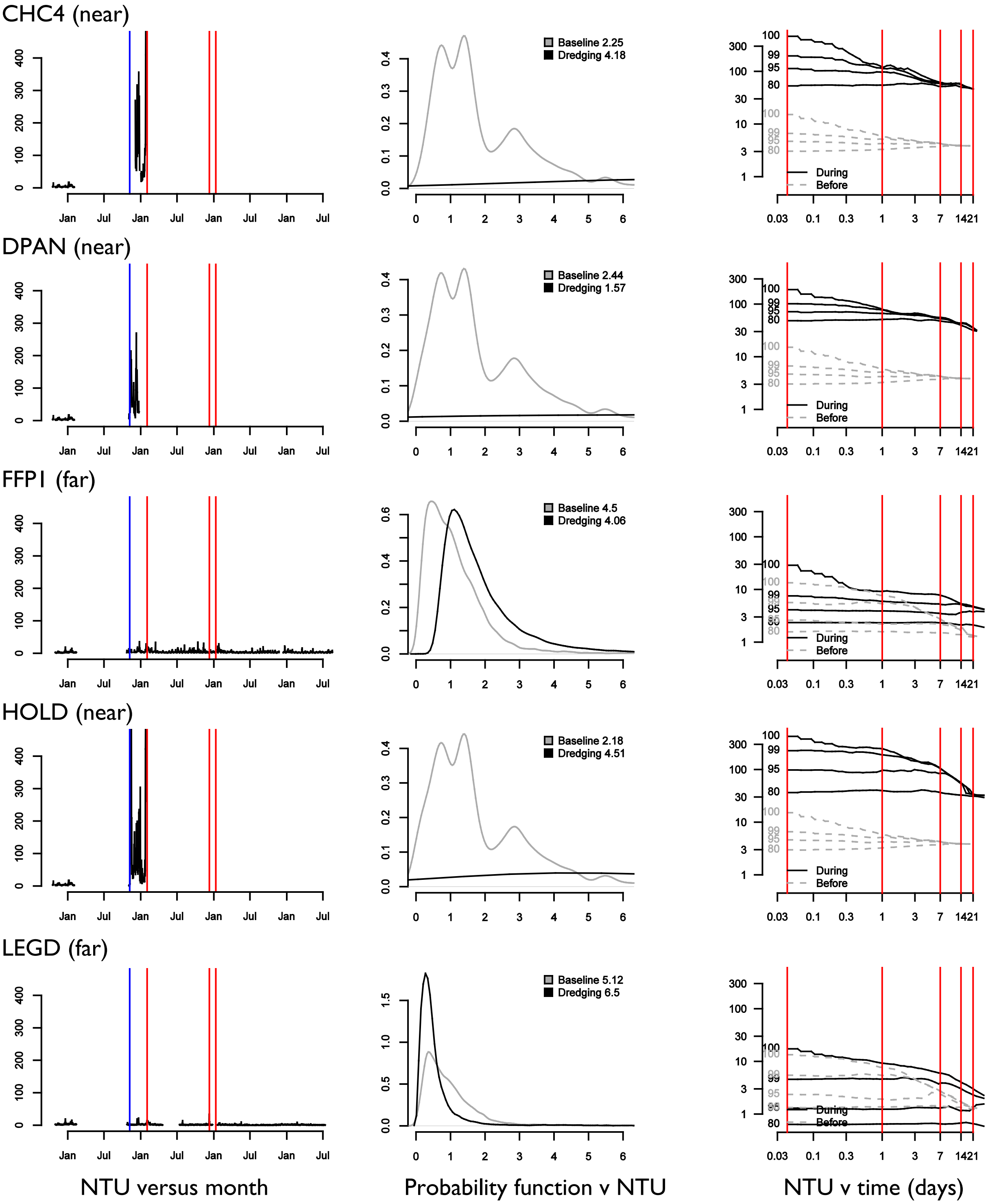
49. McCook L, Schaffelke B, Apte A, Brinkman R, Brodie J, et al. (2015) Synthesis of current knowledge of the biophysical impacts of dredging and disposal on the Great Barrier Reef: report of an independent panel of experts. Great Barrier Reef Marine Park Authority, Townsville.

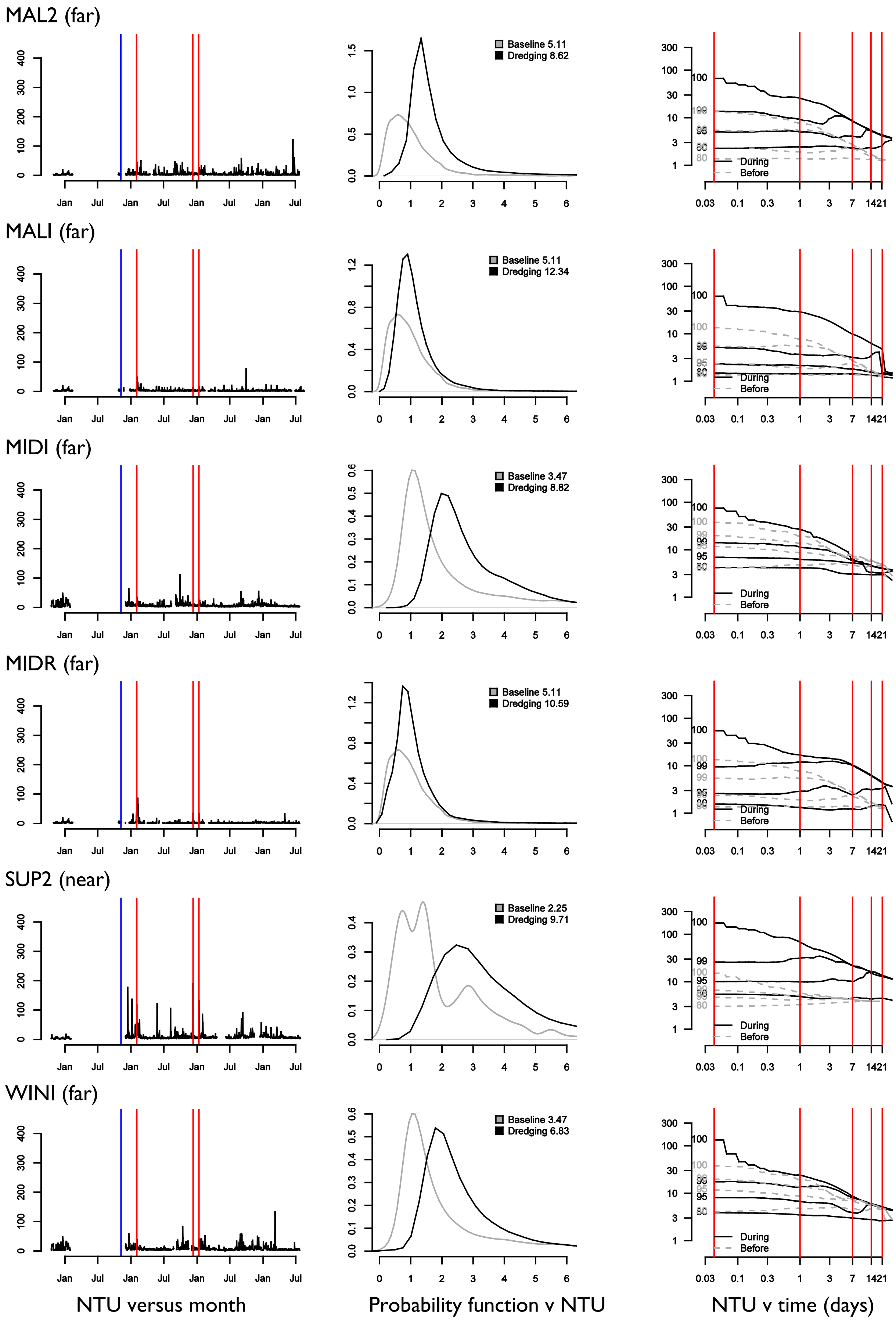
Site information			Number of days sampled				Mean NTU and PAR			
			Baseline		Dredging		Baseline		Dredging	
Site	Dist.	Dep.	NTU	Light	NTU	Light	NTU	Light	NTU	Light
Burrup Peninsula (MS757)										
Near										
CHC4	0.4	2.0	96	114	49		1.9	27.3	35.4	
DPAN	0.6		5	4	47	82	1.5	33.8	31.3	13.2
HOLD	0.3		5	4	83	82	0.1	141.9	28.2	
SUP2	1.8	2.0			866				4.5	
Far										
FFP1	13.8	2.5	16		984		1.8		2.0	
FFP2	14.8									
INTI	11.8									
LEGD	28.6	9.0	11		871		0.4		0.6	
MAL2	13.7				902				2.1	
MALI	9.9	3.5			923				1.3	
MIDI	12.0	3.0			933				3.3	
MIDR	15.9	4.0			860				1.3	
WINI	16.5	1.5	106	115	907		3.1	72.7	3.2	
WLI1	14.6									
Barrow Island (MS800)										
Near										
LNG0	0.2	9.0	457	476	479	482	1.2	60.6	6.1	29.7
LNG1	0.5	10.0	629	450	481	477	1.3	60.4	5.3	32.8
LNG2	1.0	7.0	632	636	510	442	1.0	76.3	3.8	50.9
LNGA	0.3	10.0	117	113	488	471	1.3	51.7	6.5	19.7
LNGB	0.7	8.5	94	115	501	481	2.1	57.9	5.5	30.5
LNGC	1.4	8.5	249	241	486	425	1.0	59.1	4.8	24.5
LOW	1.9	3.0	692	75	459		1.4	180.0	1.4	
LOW1	1.6	8.0	226	173	449	524	1.1	78.3	1.3	79.6
MOF1	0.8	7.0	678	562	505	512	1.3	69.8	5.0	42.9
MOF3	1.5	6.0	657	549	487	488	1.4	95.4	3.2	76.2
MOFA	0.6	6.0	144	137	471	455	1.8	65.2	7.1	61.5
MOFB	1.0	6.0	130	211	521	488	1.5	71.9	4.1	43.6
MOFC	0.7	6.0	121	154	460	472	2.1	71.6	6.6	44.7
Far										
AHC	32.8	8.5	668	612	500	548	1.6	68.7	1.3	95.5
REFN	28.0	4.5	91	93	370	426	0.8	64.8	1.5	103.9
REFS	23.6	4.5	146	144	374	428	2.2	136.9	1.5	137.9
SBS	30.0	4.5	599	605	454	502	2.6	116.1	1.6	138.4
Spoil										
LONE	0.7-5.0	8.5	706	735	485	532	1.0	49.0	1.5	64.1
DSGS	0.7-5.0	14	125	100	387	484	0.7	51.6	1.7	59.2
Cape Lambert (MS 848)										
Near										
BTR	1.8	12.0	467	85	646	649	2.5	239.9	2.8	144.0
PWR	1.2	6.0	399	91	629	686	3.7	438.2	8.9	225.6
Far										

DLI	17.7	9.0	425	279	675	609	2.1	200.0	2.1	218.0
DOI	35.4	7.0	13	12	686	607	1.2	335.3	2.9	251.6
HAT	13.9	4.0	389	136	661	649	3.1	252.1	4.6	230.7
SMSB	5.6	4.0	481	91	698	592	3.6	402.9	5.3	201.6

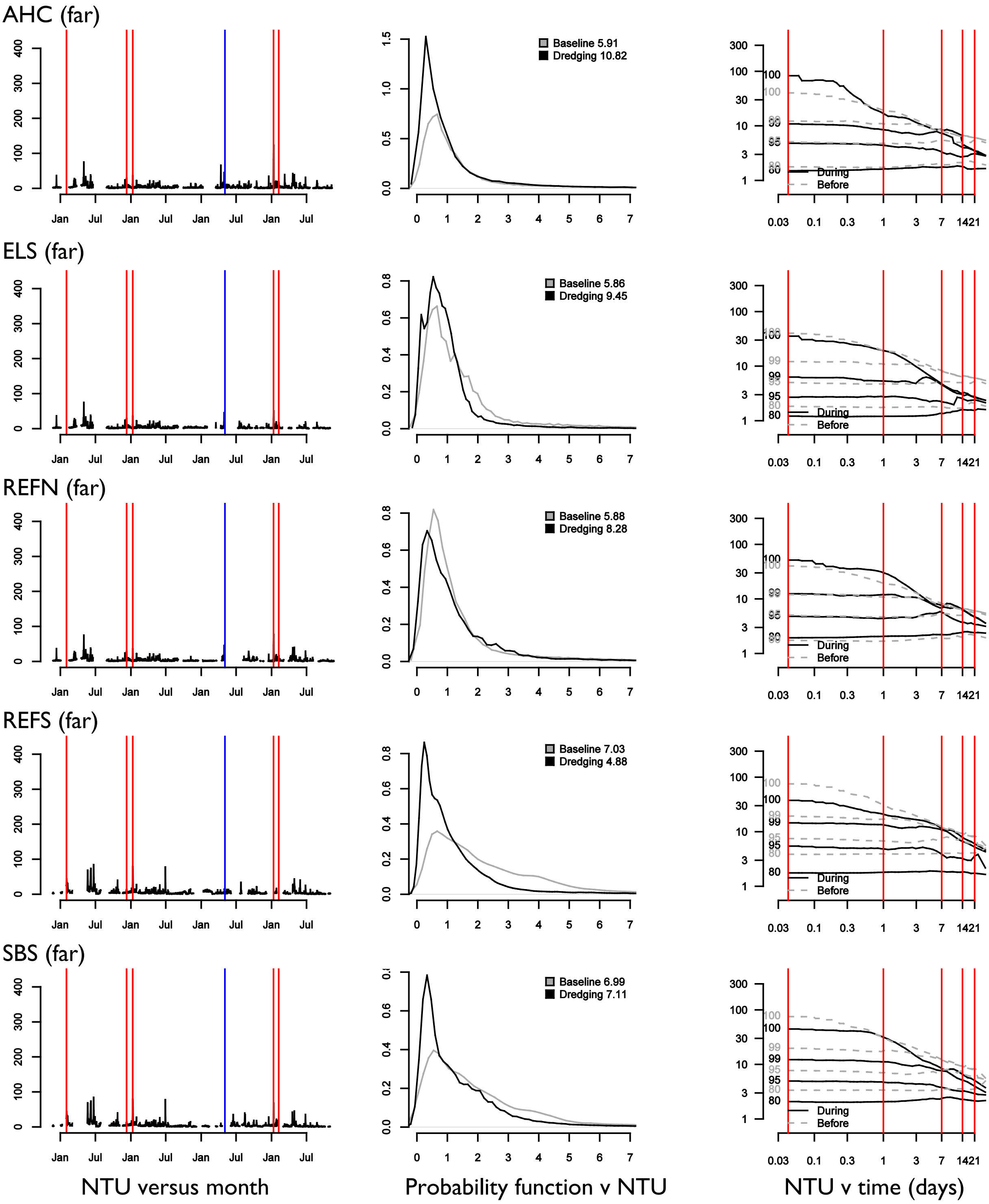
Data from a total of 83 sites were collated from the three major Pilbara dredging programs (32 sites from the Burrup Peninsula project, 36 sites from the Barrow Island project and 15 sites from the Cape Lambert project). Although there were 83 sites in total, for the purpose of the present analysis data was only used for sites that were in the immediate vicinity of dredging activity (near dredge, <2 km away) and those sites that were deemed appropriate reference sites for each project according to their approvals documents (far sites). Data collected at each site varied, as did the sampling effort during both baseline and dredging periods. For the Barrow Island project, two sites were situated near to the spoil ground (between 0.7 and 5.0 km, depending on which part of the spoil ground is used).

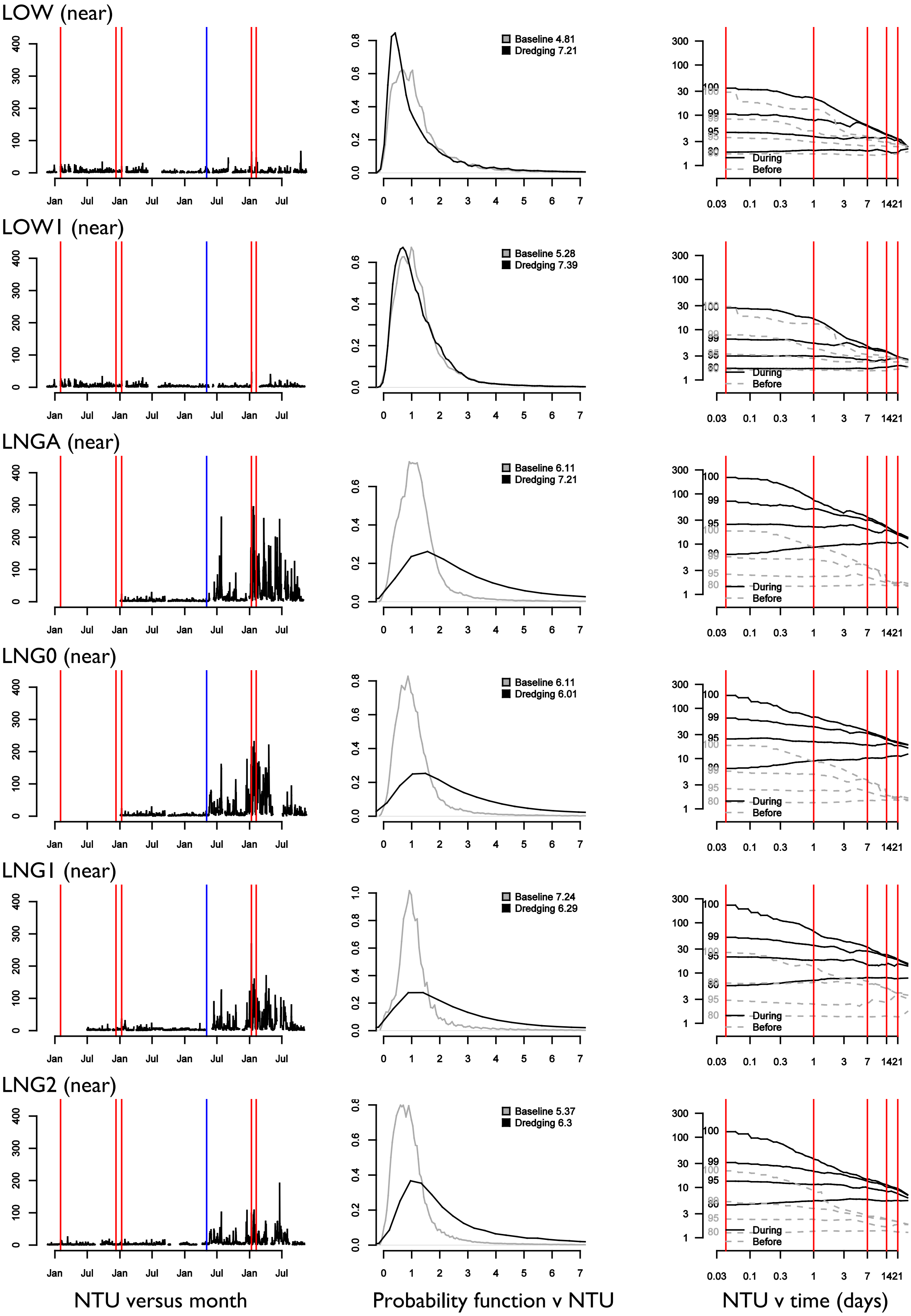
S2 Fig. A. Burrup Peninsula project.



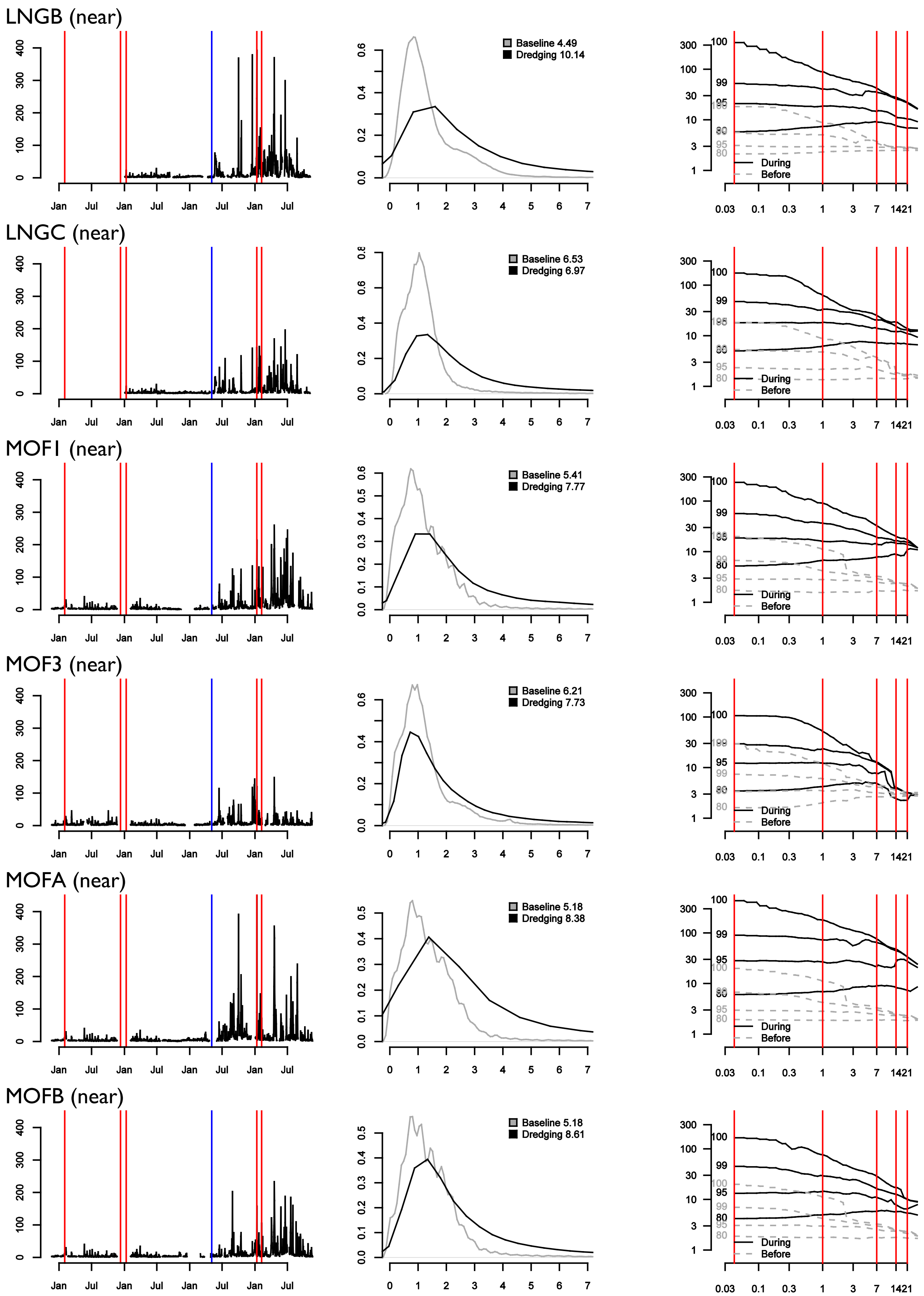

MAL2 (far)
Baseline 5.11
Dredging 8.62
MALI (far)
Baseline 5.11
Dredging 12.34
MIDI (far)
Baseline 3.47
Dredging 8.82
MIDR (far)
Baseline 5.11
Dredging 10.59
SUP2 (near)
Baseline 2.25
Dredging 9.71
WINI (far)
Baseline 3.47
Dredging 6.83
During
Before
Jan Jul Jan Jul Jan Jul Jan Jul
0.03 0.1 0.3 1 3 7 14 21
NTU versus month
Probability function v NTU
NTU v time (days)

S2 Fig. B. Barrow Island Project





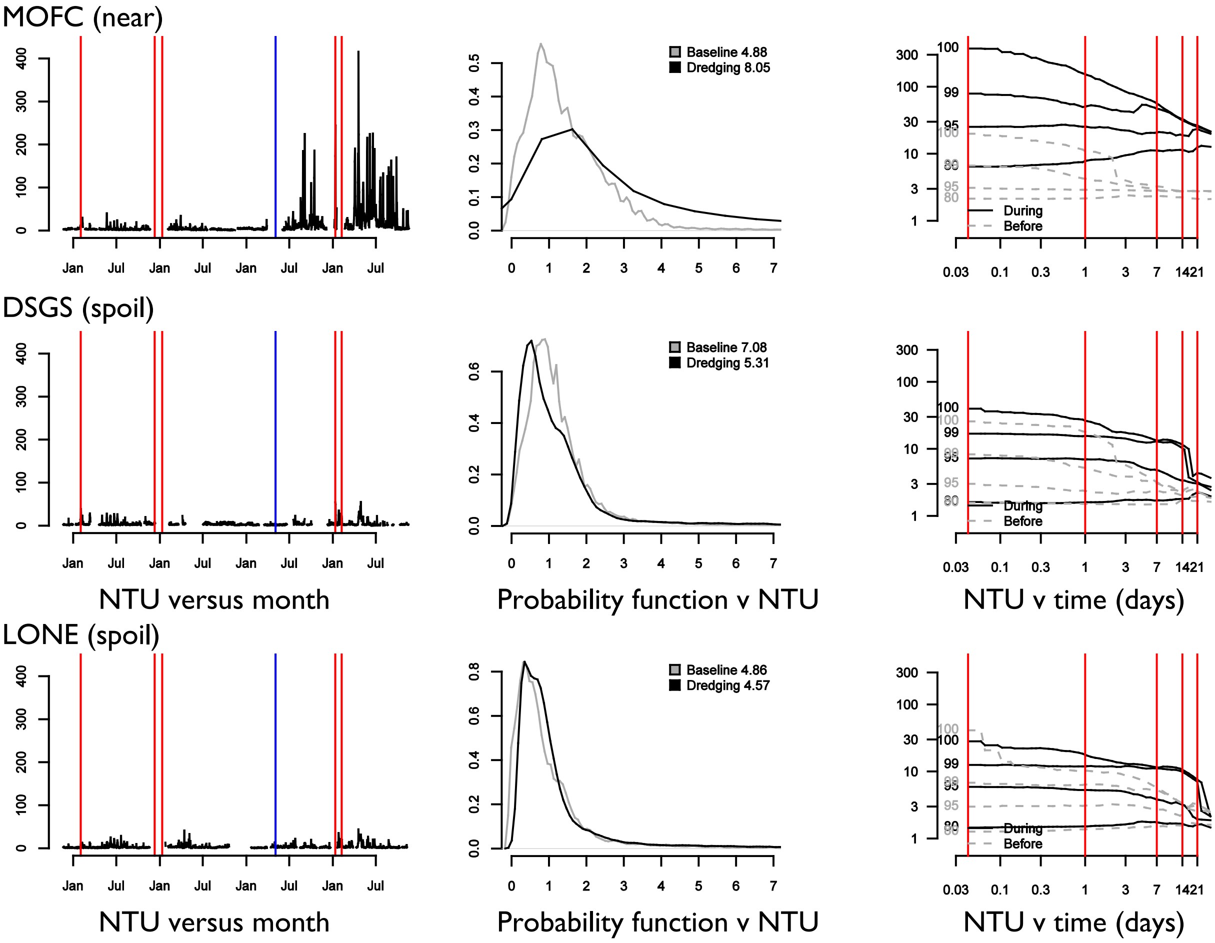
LOW (near)
Baseline 4.81
Dredging 7.21
LOW1 (near)
Baseline 5.28
Dredging 7.39
LNGA (near)
Baseline 6.11
Dredging 7.21
LNG0 (near)
Baseline 6.11
Dredging 6.01
LNG1 (near)
Baseline 7.24
Dredging 6.29
LNG2 (near)
Baseline 5.37
Dredging 6.3
During
Before
Jan Jul Jan Jul Jan Jul Jan Jul
0.03 0.1 0.3 1 3 7 1421
NTU versus month
Probability function v NTU
NTU v time (days)



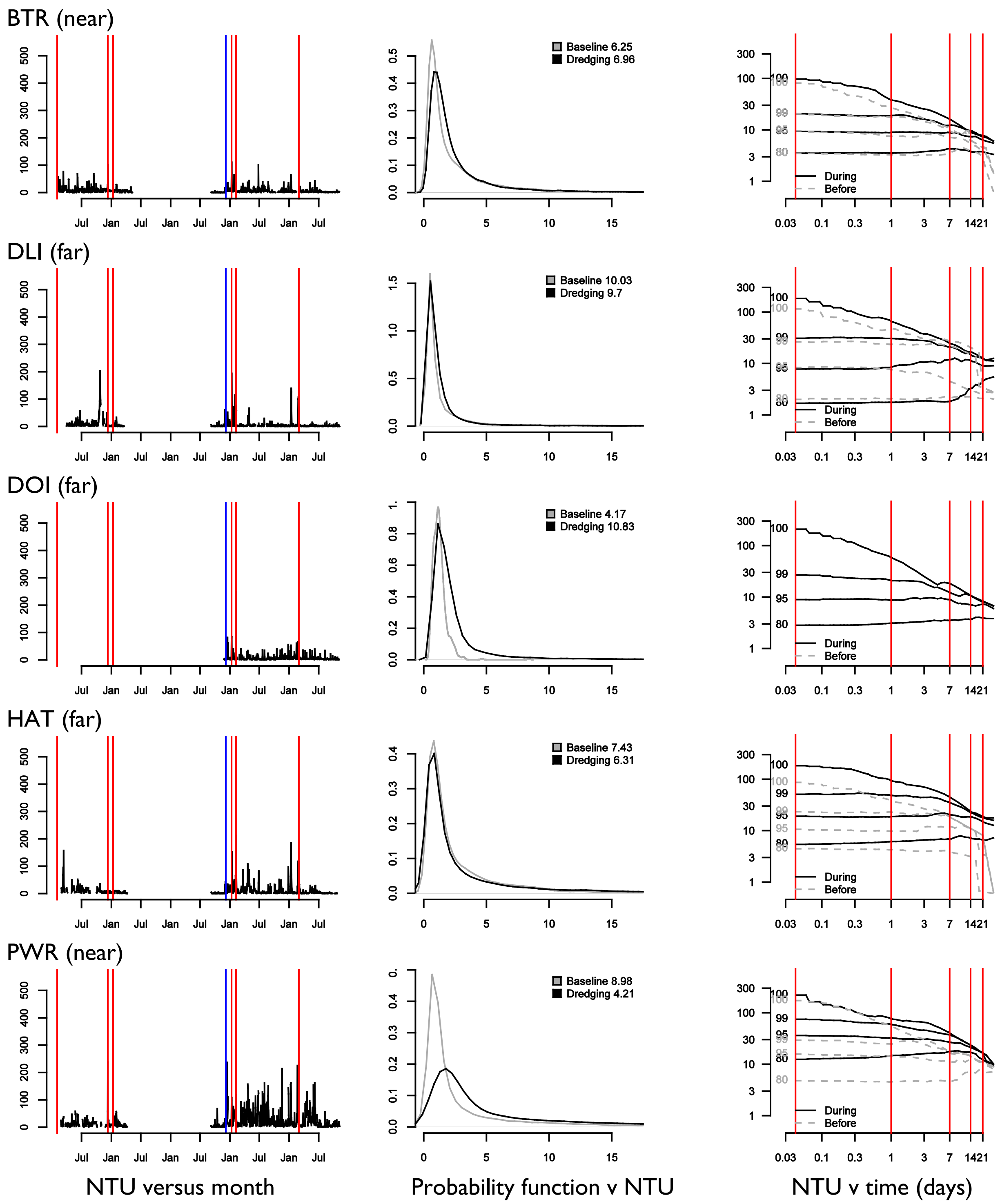
NTU versus month

Probability function v NTU

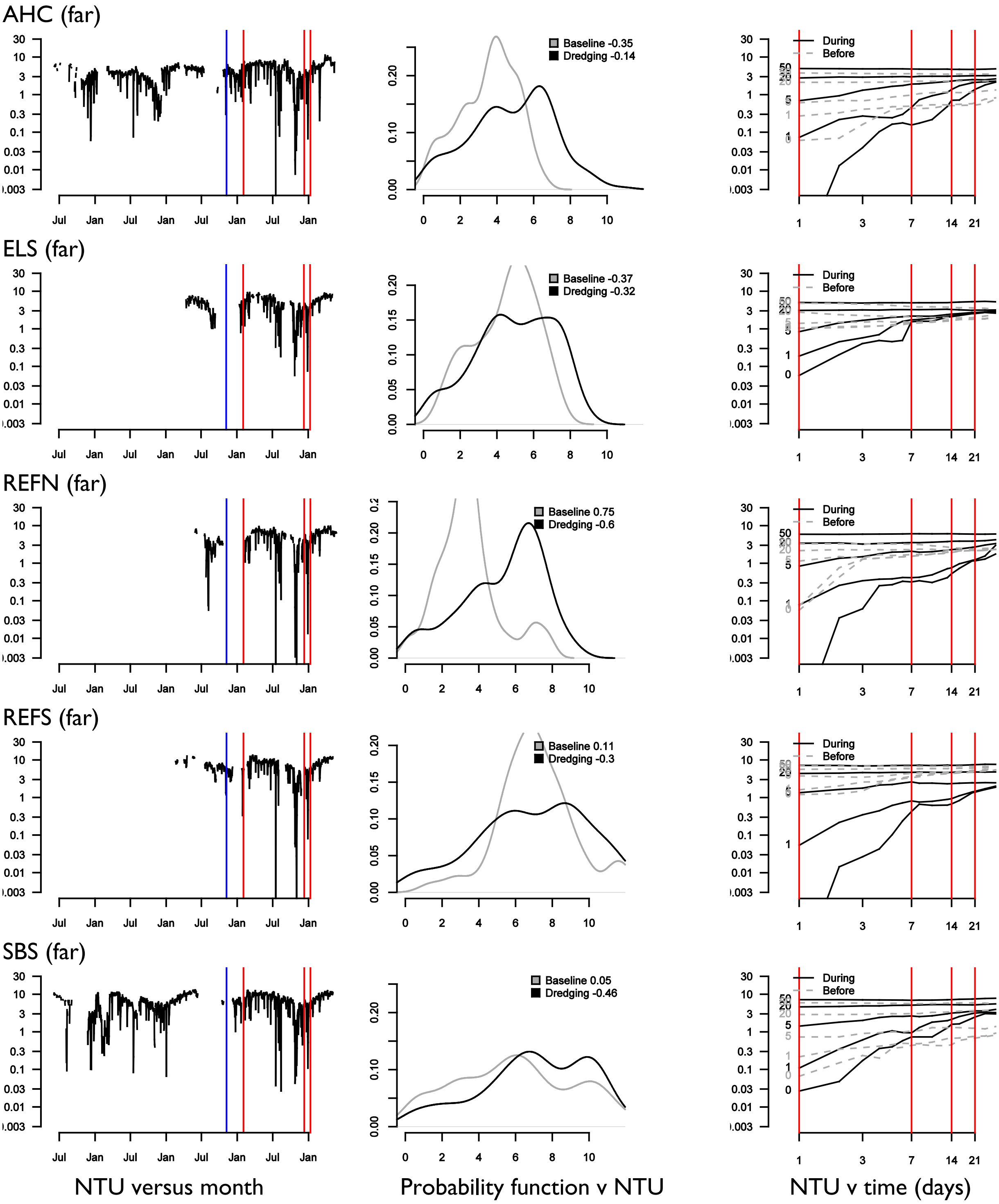
NTU v time (days)

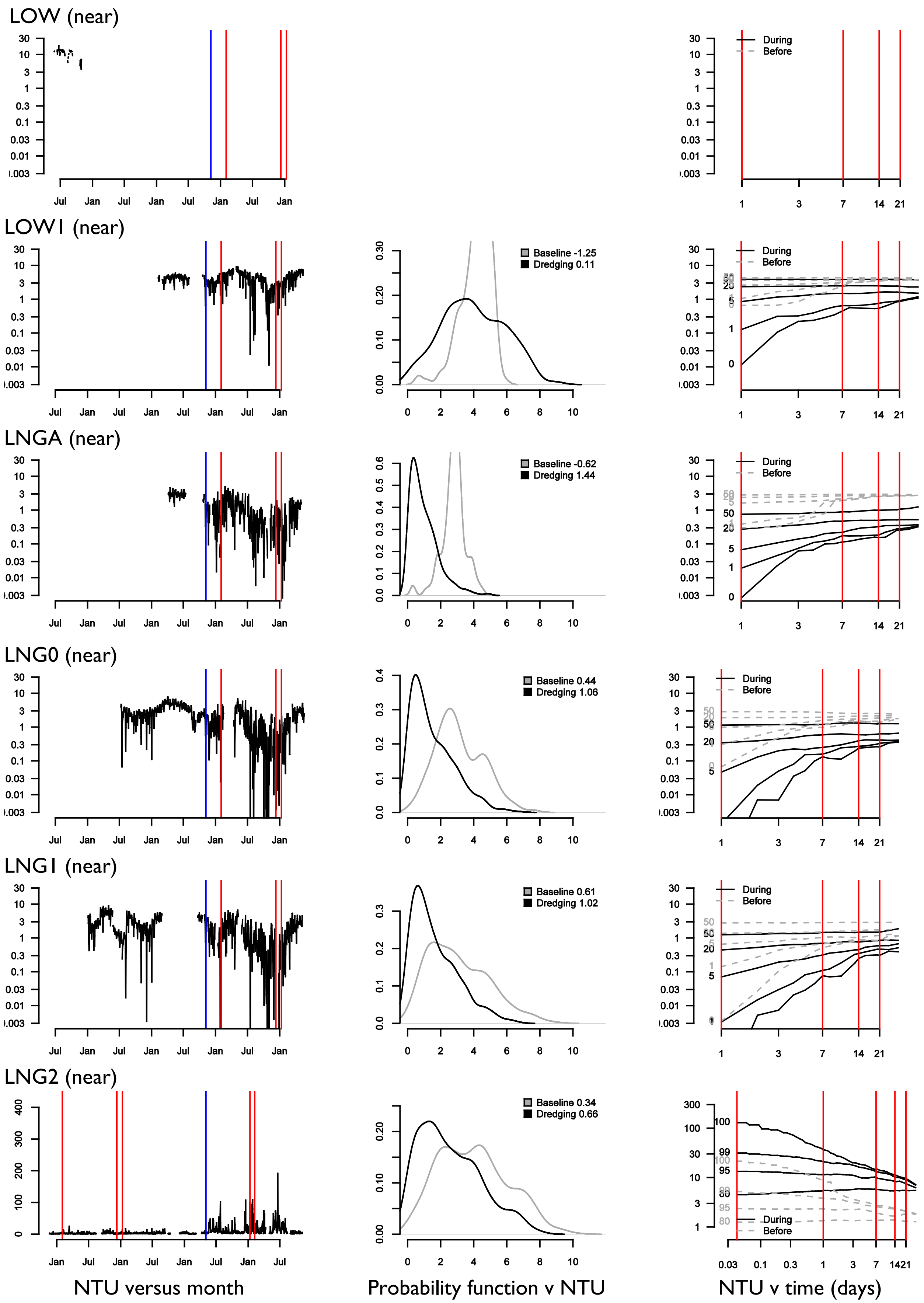

MOFC (near)
Baseline 4.88
Dredging 8.05
During
Before
DSGS (spoil)
Baseline 7.08
Dredging 5.31
During
Before
NTU versus month
Probability function v NTU
NTU v time (days)
LONE (spoil)
Baseline 4.86
Dredging 4.57
During
Before
NTU versus month
Probability function v NTU
NTU v time (days)

S2 Fig C. Cape Lambert project.

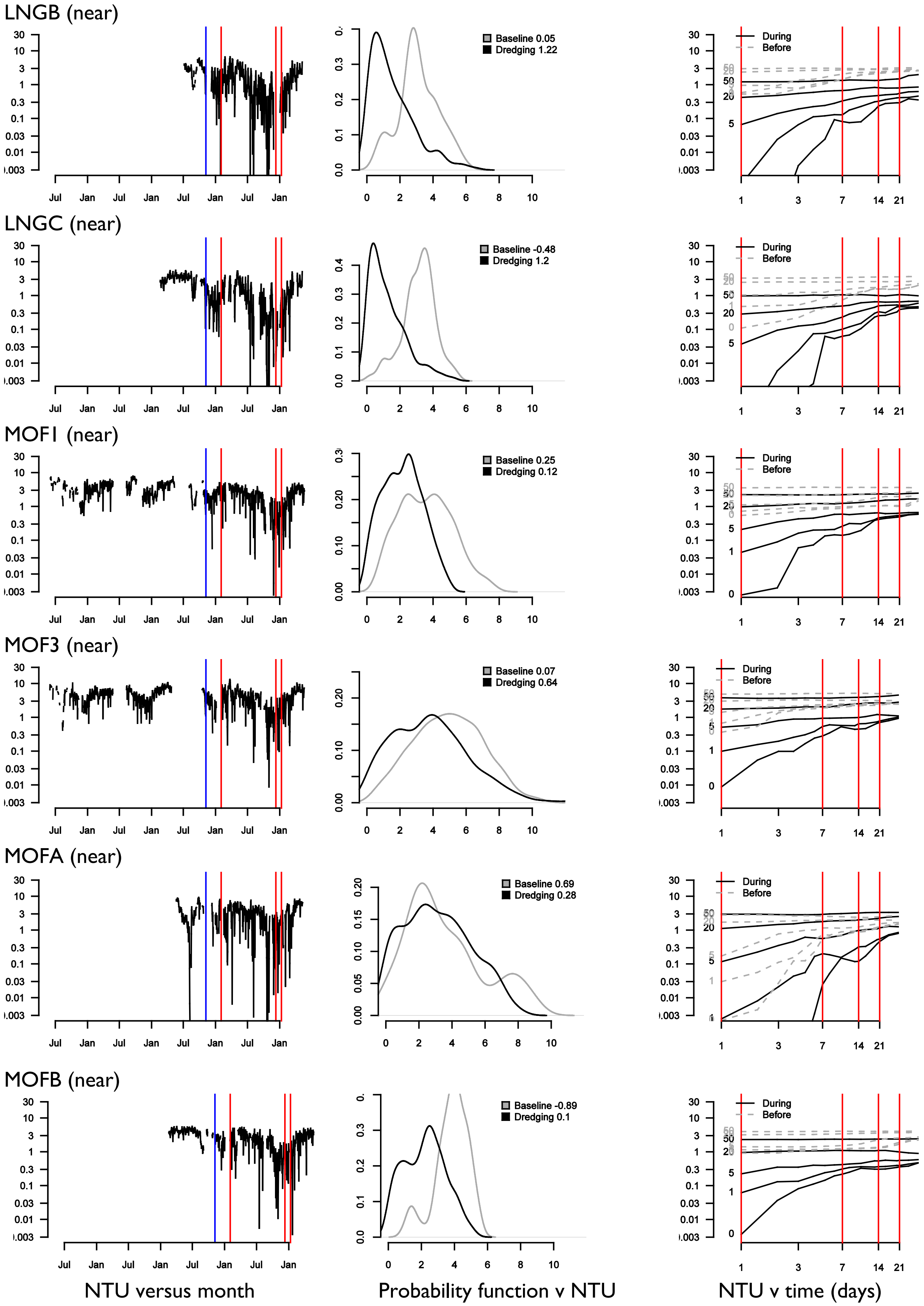


S2 Fig D. Barrow Island project.

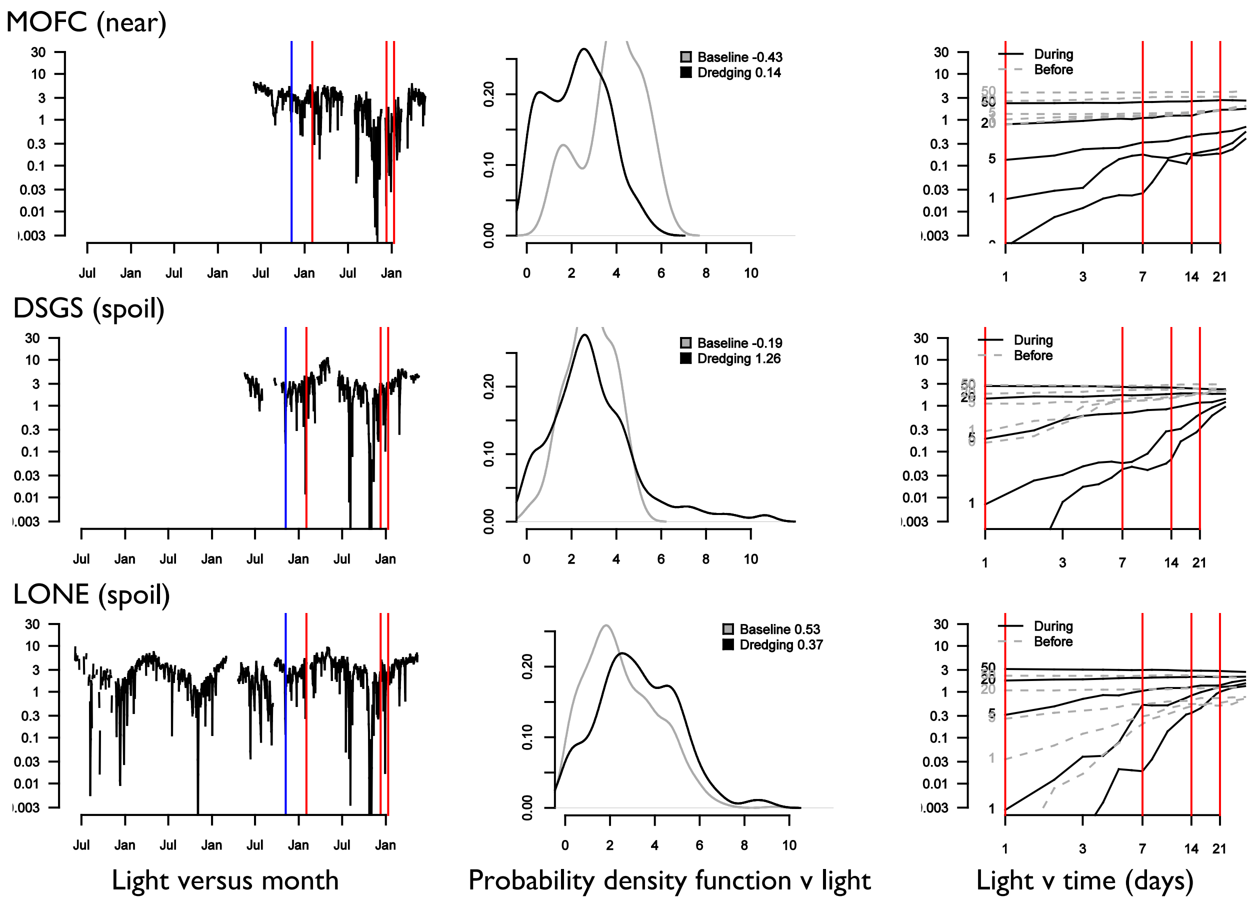




LOW (near)
During
Before
LOW1 (near)
Baseline -1.25
Dredging 0.11
During
Before
LNGA (near)
Baseline -0.62
Dredging 1.44
During
Before
LNG0 (near)
Baseline 0.44
Dredging 1.06
During
Before
LNG1 (near)
Baseline 0.61
Dredging 1.02
During
Before
LNG2 (near)
Baseline 0.34
Dredging 0.66
During
Before
NTU versus month
Probability function v NTU
NTU v time (days)



LNGB (near)
Baseline 0.05
Dredging 1.22
LNGC (near)
Baseline -0.48
Dredging 1.2
MOF1 (near)
Baseline 0.25
Dredging 0.12
MOF3 (near)
Baseline 0.07
Dredging 0.64
MOFA (near)
Baseline 0.69
Dredging 0.28
MOFB (near)
Baseline -0.89
Dredging 0.1
During
Before
NTU versus month
Probability function v NTU
NTU v time (days)



MOFC (near)
DSGS (spoil)
LONE (spoil)
Baseline -0.43
Dredging 0.14
Baseline -0.19
Dredging 1.26
Baseline 0.53
Dredging 0.37
During
Before
Jul
Jan
Light versus month
Probability density function v light
Light v time (days)

RESEARCH ARTICLE

Spatial Patterns in Water Quality Changes during Dredging in Tropical Environments

Rebecca Fisher[1,2,3]*, **Clair Stark**[2,4], **Peter Ridd**[2,4], **Ross Jones**[1,2,3]

1 Australian Institute of Marine Science, Perth, Western Australia, Australia, **2** Western Australian Marine Science Institution, Perth, Western Australia, Australia, **3** Oceans Institute, University of Western Australia, Perth, Western Australia, Australia, **4** School of Engineering and Physical Sciences, James Cook University, Townsville, Queensland, Australia

* r.fisher@aims.gov.au

Abstract

Dredging poses a potential risk to tropical ecosystems, especially in turbidity-sensitive environments such as coral reefs, filter feeding communities and seagrasses. There is little detailed observational time-series data on the spatial effects of dredging on turbidity and light and defining likely footprints is a fundamental task for impact prediction, the EIA process, and for designing monitoring projects when dredging is underway. It is also important for public perception of risks associated with dredging. Using an extensive collection of *in situ* water quality data (73 sites) from three recent large scale capital dredging programs in Australia, and which included extensive pre-dredging baseline data, we describe relationships with distance from dredging for a range of water quality metrics. Using a criterion to define a zone of potential impact of where the water quality value exceeds the 80th percentile of the baseline value for turbidity-based metrics or the 20th percentile for the light based metrics, effects were observed predominantly up to three km from dredging, but in one instance up to nearly 20 km. This upper (~20 km) limit was unusual and caused by a local oceanographic feature of consistent unidirectional flow during the project. Water quality loggers were located along the principal axis of this flow (from 200 m to 30 km) and provided the opportunity to develop a matrix of exposure based on running means calculated across multiple time periods (from hours to one month) and distance from the dredging, and summarized across a broad range of percentile values. This information can be used to more formally develop water quality thresholds for benthic organisms, such as corals, filter-feeders (e.g. sponges) and seagrasses in future laboratory- and field-based studies using environmentally realistic and relevant exposure scenarios, that may be used to further refine distance based analyses of impact, potentially further reducing the size of the dredging footprint.

Citation: Fisher R, Stark C, Ridd P, Jones R (2015) Spatial Patterns in Water Quality Changes during Dredging in Tropical Environments. PLoS ONE 10 (12): e0143309. doi:10.1371/journal.pone.0143309

Editor: Silvia Mazzuca, Università della Calabria, ITALY

Received: June 30, 2015

Accepted: November 3, 2015

Published: December 2, 2015

Data Availability Statement: There are very detailed tables and Figures in the manuscript and in the supporting information files containing all the relevant data. A metadata record is available from the Australian Institute of Marine Science at: http://data.aims.gov.au/metadataviewer/faces/view.xhtml?uuid = a884e0ab-1a82-4871-8f39-18c20ab4c9fb.

Funding: This project was funded by the Western Australian Marine Science Institution as part of the WAMSI Dredging Science Node, and made possible through investment from Chevron Australia, Woodside Energy Limited, BHP Billiton as environmental offsets and by co-investment from the WAMSI Joint Venture partners. This research was also enabled by data provided by Woodside Energy Ltd, Rio Tinto Iron Ore and Chevron. The commercial investors and data providers had no role in the data analysis, data interpretation, the decision to publish or in the preparation of the manuscript.

Competing Interests: The authors have the following interests. This project was funded by the Western Australian Marine Science Institution as part of the WAMSI Dredging Science Node and was made possible through investment from Chevron Australia, Woodside Energy Limited, BHP Billiton as environmental offsets and co-investment from the WAMSI Joint Venture partners. This research was enabled by data and information provided by Woodside Energy Ltd, Rio Tinto Iron Ore and Chevron Australia. There are no patents, products in development or marketed products to declare. This does not alter the authors' adherence to all the PLOS ONE policies on sharing data and materials, as detailed online in the guide for authors.

Introduction

Dredging and dredge material (spoil) disposal releases sediments into the water column, creating turbid plumes that can drift onto nearby marine habitats [1]. The elevated suspended sediment concentrations and the eventual settlement of the sediments can have a range of negative effects on benthic filter and suspension feeding organisms [1–7]. By altering the characteristics of underwater light, the increased turbidity can also have marked effects on primary producers. This is of particular significance for habitat-forming groups such as corals and seagrasses, as their loss would also result in loss of the habitat-associated biodiversity [8,9]. There are many examples of dredging programs that have had widespread environmental effects on these communities [10–13] and dredging programs usually require active management when underway to minimize environmental harm [14–18].

Despite the well-known effects of dredging there have been surprisingly few peer reviewed studies of water quality conditions associated with dredging in tropical environments. Published studies include [19–21] and a number of publically available technical reports and higher level summaries of individual projects [15,22,23]. Suspended sediment concentrations in the hoppers of trailing suction hopper dredges (TSHDs, considered the workhorse of the dredging fleet (see [24])), can reach tens of grams L^{-1}, but typically undergo an initial rapid 10–100 fold dilution when overflowing to the receiving water [25–29]. Suspended sediments in the associated plumes decrease with both time [28,30,31] and distance from dredging, as lateral dispersion, mixing with ambient water and settling at the seabed occurs (see for example [26,29,32]).

The lateral movement of dredging plumes, and diminution in space and time, is especially important for impact prediction purposes and the Environmental Impact Assessment (EIA) process. Environmental policy for dredging, in Australia at least, is based on this principle, with dredging proponents required to manage projects according to a spatially-based zonation scheme identifying areas which could be exposed to plumes (referred to as a 'zone of influence') and where effects (i.e. mortality) of underlying communities could occur [17,33]. Although highly site and project specific, some dredging plumes can travel up to 70 km [34] and a basic task is to quantify the intensity, frequency and duration of pressure fields (see [35] for a definition of the term pressure field) with respect to distance from the dredging activities and ultimately understand any possible effects on the local ecology.

In addition to the EIA process, establishing an evidence-based footprint of the scale of potential impacts is becoming increasingly important for public perception [29]. Effects on water quality associated with the operations of TSHDs in the UK marine aggregate industry has recently been reviewed, and effects typically occurred from a few hundred metres to up three km from the point of dredging [29]. This three km limit is useful as a broad limit of potential impact, but TSHDs in the aggregate industry are generally smaller than those used in maintenance and capital dredging for channel widening and deepening, and tend to produce less fines because of the coarser nature of the material being dredged.

Recently several large water quality data sets have become available from a sequence of major capital dredging campaigns in the Pilbara region of tropical Western Australia (WA [18]). Three of the larger projects involved dredging and subsequent marine disposal of ~34 Mm^3 or ~60 Mt tonnes of sediment (using a conversion factor of 1.7 g/cm^3 see [36]). For comparative purposes the UK marine aggregate industry extracts on average 20 Mt tonnes of sediment annually. The Australian state and federal regulatory conditions for the Australian projects (see Ministerial approval statements MS757, MS800, MS840 searchable on the WA EPA website) required detailed baseline, surveillance and compliance water quality and biological monitoring programs (for a discussion of these terms see [35]). The water quality monitoring included measurements of turbidity and light levels on sub-hourly time scales at multiple reference and potential impact sites. Measurements were also made at different distances from the dredging, over extended periods (>1 year) and in many cases included extended pre-dredging baseline periods. This has provided water quality data where the detailed effects of dredging can be assessed with respect to distance from the turbidity-generating events as well as allowing the changes to be placed within the context of natural background turbidity events associated with wind and waves [37–40].

Analyses of the temporal characteristics of the water quality from the Pilbara datasets close to the dredging have already highlighted the variable nature of the plumes with fluctuations of turbidity of 2–3 orders of magnitude over the course of a day [21]. Dredging was found to change the overall probability distribution of turbidity values, increasing the frequency of extreme values and altering the intensity, duration and frequency of the turbidity events over background levels. There were marked changes in photosynthetically active radiation (PAR) in the shallow reef environment associated with the turbidity, including frequent daytime 'twilight' periods and occasionally periods of complete darkness. However, a more common feature was extended periods (i.e. days to weeks) of low light. The choice of summary statistics used (mean versus median etc), as well as the temporal scale examined (hours, days, weeks etc) was found to be very important for interpreting the data. Upper percentile values (e.g. 99^{th}, 95^{th}) of water quality parameters were highly elevated over short periods, but converged to values only slightly above baseline states over longer periods (weeks to months).

In this study we further analyse the Pilbara datasets using similar statistical summary techniques, but this time examine the spatial characteristics of the data. The information has provided a first order approximation of the distance where any dredging related effects become indistinguishable from natural variation. The information has also provided a matrix of data that can be used to design future manipulative experiments on the effects of dredging pressure on tropical marine organisms using environmentally realistic/relevant exposure scenarios.

Methods

Study sites

All necessary permits for deploying the instrumentation were sought from the relevant state authority, the Western Australia Department of Environment and Conservation. The field studies did not involve endangered or protected species. Water quality data was collected at 32 sites for the Burrup Peninsula Project, 26 sites during the Barrow Island project, and 15 sites during the Cape Lambert project (Fig 1). Full details for each site sampled, including total baseline and dredge period sampling days, water depth (where available) and distances of the monitoring sites from the main dredging activities are listed in S1 Table and [21]. All three projects had sites spanning distances of up to ~30 km from the location of dredging activities.

While the three projects were relatively near to each other, spanning a total distance of <250 km, they did occur in slightly different marine settings and therefore represent a range of coral reef environments; with Barrow Island representing an offshore 'clear water' environment, Cape Lambert an exposed nearshore cape or headland, and Burrup Peninsula an enclosed inshore turbid reef environment. Sediment characteristics varied somewhat among the three projects, although all three were generally characterised by unconsolidated carbonate sediments, ranging in grain size from gravel to fine silts [21]. Both the Cape Lambert and Burrup Peninsula projects tended to have finer sediments grain sizes at inshore sites closer to the dredging areas.

All water quality data was processed similarly to ensure data integrity and to remove potentially erroneous values. Full details of the data processing and cleaning steps can be found in [21]. Briefly, all turbidity data was aggregated for all sites and retained at the finest temporal

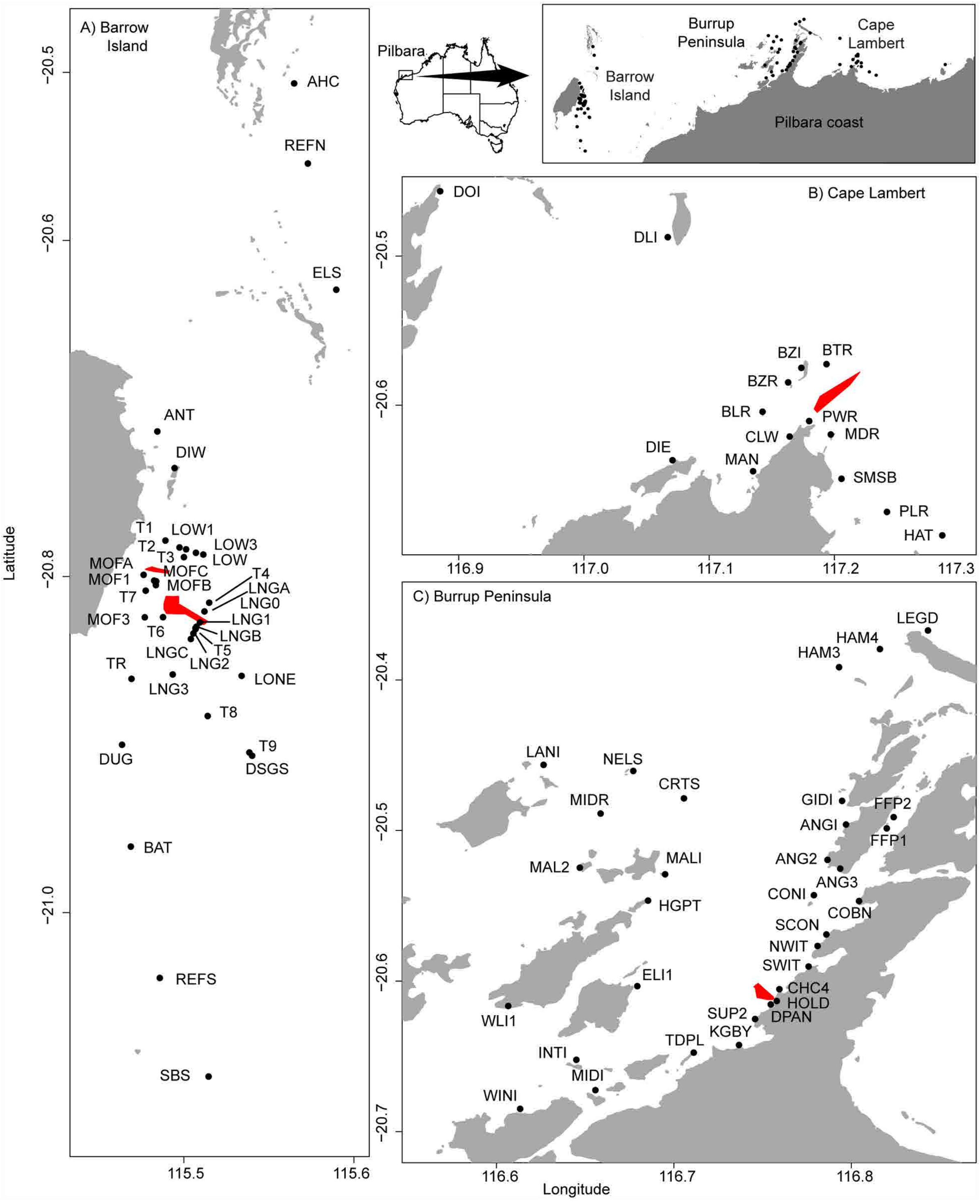


Fig 1. Water quality monitoring sites for three capital dredging projects in the Pilbara region (Western Australia). Shown are sites for the Barrow Island, Burrup Peninsula and Cape Lambert dredging projects (see Ministerial approval statements MS757, MS800, MS840 searchable on the WA EPA website). Polygons in red show the primary location(s) of dredging activity, including: the materials offloading facility (MOF) and the LNG jetty access channel and turning basin for (A) the Barrow Island project (B) the Cape Lambert project and (C) the Burrup Peninsula project. Maps were constructed in R using the package rgdal [41] based on the GA 2004 coastline dataset [42], and arranged using gridBase [43], with additional edits carried out using Adobe Illustrator [44].

doi:10.1371/journal.pone.0143309.g001

resolution (10 or 30 min, depending on the logger type and project) or aggregated to a daily mean or percentile value as required for the various analyses. Light data at the finest temporal resolution were fitted using a Generalised Additive Model (GAM) for each day separately using the mgcv package [45] in R [46]. Days for which insufficient light data were available throughout the full light cycle were removed and not included in the analysis. Each fitted daily model was then used to estimate photosynthetically active radiation (400–750 nm, PAR) values for every second throughout the daylight period, based on monthly sunset and sunrise times. The sum of the per second quantum flux measurements were then added together to calculate the daily light integral (DLI) as mol photons m^{-2}.

Turbidity (NTU) and light (PAR as DLI) data were summarised using a range of methods that represent different water quality hazard metrics that might have a negative impact on surrounding benthic communities such as coral reefs. For all three dredging projects we examined a range of turbidity metrics, including: mean, median, 80th percentile, 95th percentile and maximum daily turbidity values, and running 7 and 14 day mean, median and 80th percentile turbidity values. Running mean and percentile values were calculated using the runmean and runquantile functions from the caTools package in R [47]. In addition, several light based metrics were examined for the Barrow Island project where sufficient light data were available across both dredging and baseline periods, including: mean DLI, 7 and 14 day running mean DLI; the mean portion of the day <5, 10, 15 and 20 μmol photons $m^{-2}s^{-1}$ (equivalent to 0.2, 0.4, 0.6 and 0.8 mol photons m^{-2} assuming 12 h per day of light at those irradiance levels); and the total number of days (per year) < 1, 12 and 46 μmol photons $m^{-2}s^{-1}$ (equivalent to ~ 0, 0.5 and 2 DLI). Running means (or percentiles) of the 10 or 30 min turbidity data were calculated using the 7 and 14 day running time periods by converting the data series for each site into an S3 time series object using the zoo function from the zoo library [48] then applying the runmean or runquantile function from the caTools library [47].

Spatial patterns in turbidity & light

A generalised additive mixed modelling (GAMM [49]) approach was used to examine spatial variation and the effect of distance from dredging on the calculated turbidity and light summary metrics. Distances from dredge activities were calculated using the ArcGis 10.2 Esri software [50], and represent the nearest distance to shape file features representing the channels for the Burrup Peninsula and the Cape Lambert projects, and MOF and LNG footprints for the Barrow Island project (Fig 1). At Barrow Island, four sites (DSGS, LONE, T8 and T9) were near the spoil disposal area (<3 km) and were not included in statistical analyses of distance from dredging. For simplicity, analyses were carried out for all three dredging projects separately, as preliminary examination indicated there would be slightly different directional effects among the three projects which would lead to high order interactions if they were analysed together. Broad-scale distance decay relationships were initially examined for all three studies across a range of time scales (hourly, daily, and fortnightly running means for NTU; daily weekly and fortnightly running means for DLI) based on either the 80th (for NTU) or 20th (for DLI) percentile values for each site during the pre-dredging and dredging phases. Formal statistical analyses were undertaken at a finer temporal scale to more closely examine spatial patterns in distance decay relationships. For the detailed distance analysis, data were summarized as 95th percentiles, quarterly for each year of data from both the pre-dredging and dredging phases for each site. Quarterly summaries were used in these analyses because they allowed a reasonable level of temporal variation to be included whilst avoiding issues associated with serial autocorrelation inherent in shorter summaries [51]. While there are time series analysis methods available to account for such autocorrelation in models [52], an analysis at the daily level was also prohibited by the large amount of data and available computing power. Quarterly summaries were based on a 95th percentile (i.e. the near worst case scenario during that quarter at that site). This upper percentile value was used in preference to a median, as this better identifies times and sites when and where high turbidity events occurred, as median values can miss important turbidity events associated with dredging (see [21]). Quarterly summaries were only used where at least three weeks of valid data were available.

For all turbidity based metrics, only distance from dredging was included as a continuous variable in the models. For the light based metrics depth was included as an additional continuous variable to account for the effects of attenuation through the water column [53,54]. Where depth was included in the best model (see below), the relationships with distance were plotted after effectively removing any depth effects. Continuous variables (distance and depth) were fitted as smoothers using cubic regression splines via the gamm4 function in the package gamm4 [49]. To ensure monotonic relationships with distance and depth (when included), and to more generally avoid over-fitting smoothers, the k parameter (basis dimension, see [45]) in the smoother argument was set at 4. Both site and yearly quarter were included as independent random effects.

The factors considered included a treatment effect (during baseline/during dredging) and two spatial directional variables (N/S and E/W) representing either North or South, or East versus West of the primary dredging activity. Two-way interactions between each of the directional variables and the baseline versus dredging treatment variables were also included, such that an effect during dredging for only one direction could be accommodated. The factor variables were included as an offset term (moving the overall relationship up or down), or as a 'by' argument to the gam smooths (see [45]), representing an interaction between the distance from dredge effect and each factor (a different smooth is fitted for each level of the factor). The full (most complex model fitted) included the three way interaction between distance, dredging treatment and either one of the directional variables, and was thus:

$$R \sim \mathrm{s(Dep)} + \mathrm{s(Di)} * \mathrm{Dr} * \mathrm{NS} + \mathrm{Dr} * \mathrm{NS} + \mathrm{Dr} + \mathrm{NS} + (1|\mathrm{Site}) + (1|\mathrm{quarter})$$

Where: *R* represents the particular response metric being examined (light or turbidity based); s(Dep) represents the smoothing function applied to depth (only included for light based metrics); s(Di) represents the smoothing function applied to distance from dredging; NS represents the fixed factor delineating North versus South of the dredging location (inter-changeable with EW, which delineates East from West of the dredging location); (1|Site) signifies inclusion of a random site effect; and (1|quarter) signifies inclusion of a random quarterly effect. Due to limited baseline data at some sites for the Burrup Peninsula project, the full three way interaction was not included, with all baseline combined and only the during dredging data delineated into spatial levels.

A full subsets analysis approach was used, where all possible models are compared (including an intercept only 'null' model) using the model selection statistic AICc [55], with the model having fewest parameters within 2 AICc units of that with the lowest AICc value selected as the 'best' or most parsimonious model [56].

Once the optimal model structure was determined using GAMM the equivalent parametric power decay model was fitted using the nls function from the stats package in R [46,57,58]. For those models where there was evidence of an effect of distance from the dredge site, the distance at which the fitted curve (which essentially represents the median value) falls below the 80th percentile of the baseline value was calculated. This test of distance of effect is effectively the P_{50}–P_{80} approach of the ANZECC/ARMCANZ guidelines [59] which is used to define water quality changes that may result in a 'measurable perturbation' [59]. These distances of effect were calculated separately for each level of any factors identified as important in the most likely model (e.g. north versus south), and used to compare the relative distances at which the effects of dredging are observed.

Detailed plume analysis at Barrow Island

The dredge plume at Barrow Island was unusual in that it moved predominantly in a southward direction [60]. With a large number of water quality monitoring sites regularly spaced along the principal axis of flow, and at increasing distance from a fairly focal point of dredging, this provided an ideal opportunity to examine the spatial structure of dredge plumes in much finer detail. High resolution satellite imagery during the baseline period (23rd November 2008) and during dredging (24 July 2010 & 29 August 2010) were also analysed to examine the relationship between visually apparent plumes and real time water quality. Images from were sourced either from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) Advanced Visible and Near Infrared Radiometer (AVNIR-2) and the Landsat 5 Thermal Mapper. In addition, we examined the cumulative probability function of turbidity (NTU) and light (DLI) and how these change with distance from dredging using the series of sites south of the primary dredging activity at Barrow Island.

Results

Broad-scale patterns of distance decay

Scatterplots of a range of turbidity (all projects) and light based metrics (Barrow Island only) of water quality clearly indicated a strong power-decay effect with distance from dredging for all three projects, which was absent during the baseline phase (Figs 2 & 3). Distances from dredging effects were apparent in the 80th percentile values observed across sites during the dredging phase for a range of temporal scales, from 1 h to 2 week running mean turbidity values, with no such spatial patterns apparent prior to dredging (Fig 2). The 80th percentiles values for turbidity decayed rapidly with increasing distance from dredging across all studies, with half-distance values (the distances at which turbidity values fell to half of those observed at 200 m of dredging) from just over 1 km for the Barrow Island project (Fig 2A, 2B and 2C), 400 m for Burrup Peninsula project (Fig 2D and 2E) and up to 2 km for the Cape Lambert project (Fig 2H, 2I and 2J). Similar relationships with distance from dredging were also observed for light related water quality metrics at Barrow Island, with DLI values increasing rapidly with increasing distance (Fig 3A, 3B and 3C), and the number of observed days at various darkness-cut off levels declining rapidly with distance (Fig 3D, 3E and 3F). Near dredging some sites can experience over 20 days per year where the DLI is near 0 mol photos m^{-2}, over 120 days per year where DLI values are less than 0.5 mol photos m^{-2} and upwards of 340 days per year where DLI levels are less than 2 mol photos m^{-2} (Fig 3).

Detailed statistical analysis incorporating spatial and temporal variability indicated that for the Barrow Island project there was strong evidence of an effect of distance from dredging for all the water quality metrics examined including those based on turbidity (Fig 4, Table 1A) and light (Fig 4, Table 1B, see also S1 Table). Relationships with distance were relatively strong, with 36 to 55% of the variance explained by the best model fit (Table 1). Most of the turbidity-based water quality metrics showed a significant three-way interaction effect between baseline/dredging, North/South and distance (Table 1), with no discernible relationship with distance occurring for the baseline data, a very sharp relationship occurring for sites north of the dredging site, and a strong but more gradual relationship occurring for the southern sites during the dredging period (Fig 4, Table 1, S1 File). Effects of an impact on water quality were evident at

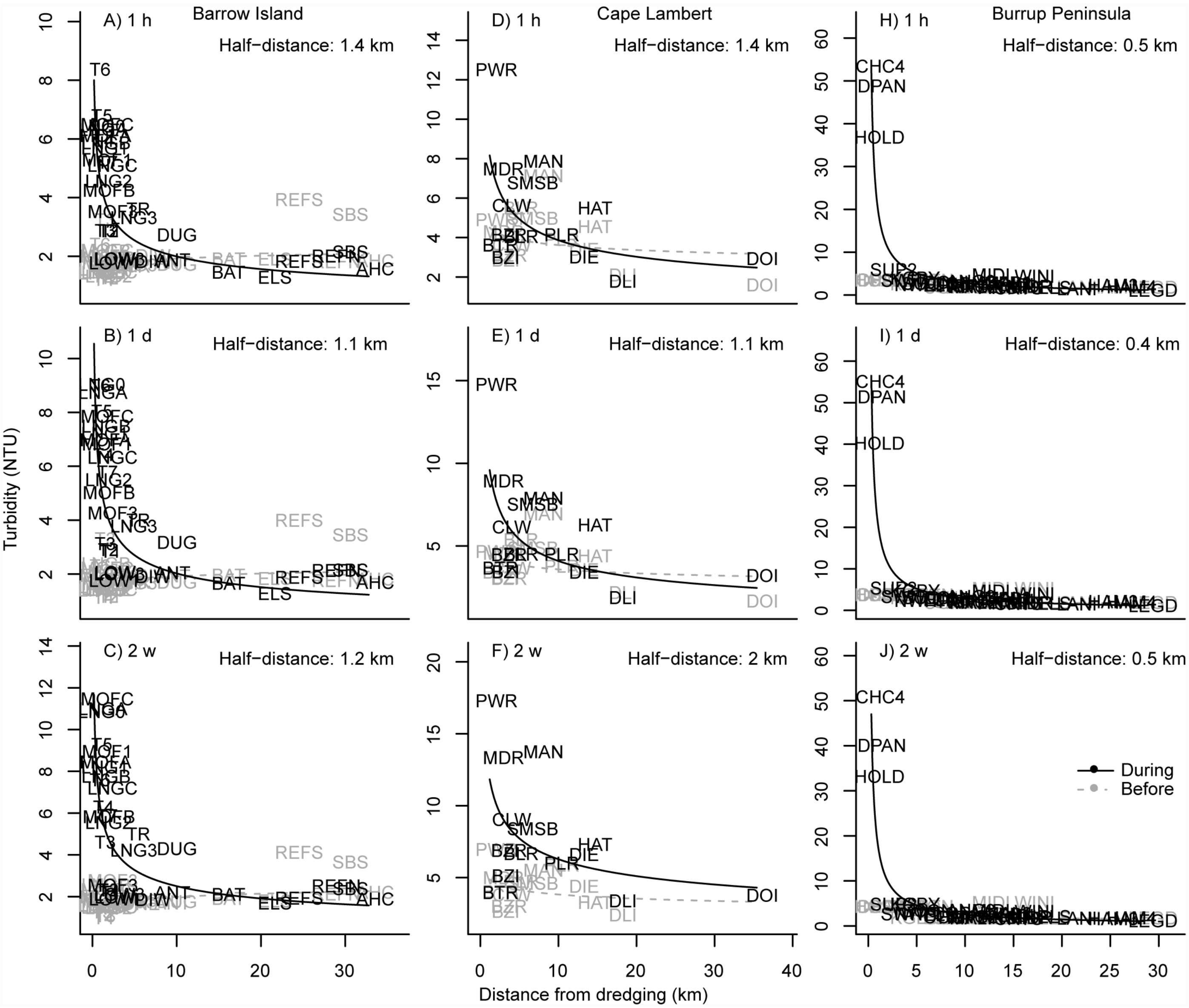


Fig 2. Distance decay relationships based on turbidity (80th percentile NTU) across the three different dredging programs (Barrow Island, Cape Lambert and Burrup Peninsula). Shown are decay relationships based on the 80th percentile value for each site for the hourly (panels A, D, H), daily (panels B, E, I) and fortnightly (panels C, F, J) running means. Half distance values represent that distance at which each turbidity metric decays to half of the predicted value at 200 m from the dredging activity.

doi:10.1371/journal.pone.0143309.g002

distances of up to only 2.1 km for the Northern sites at Barrow Island, whereas the Southern sites appeared to show evidence of an effect of distances of up to 20 km (Fig 4, Table 1, S1 File).

Distances from dredging relationships were much weaker for the Cape Lambert and Burrup Peninsula projects (Fig 5, Table 2, S1 File). For the Cape Lambert project, R^2 values were exceptionally low (<16% of the variance explained across all metrics) and the best fit models tended to delineate patterns in space rather than an effect of distance to dredging (Fig 5, Table 2A). Baseline data was sparse for the Burrup Peninsula project, as was data at sites very close to the primary dredging activity (S1 Table). What data there is available indicates a potential East/West interaction during the dredging period, with highly elevated turbidity close to the dredge

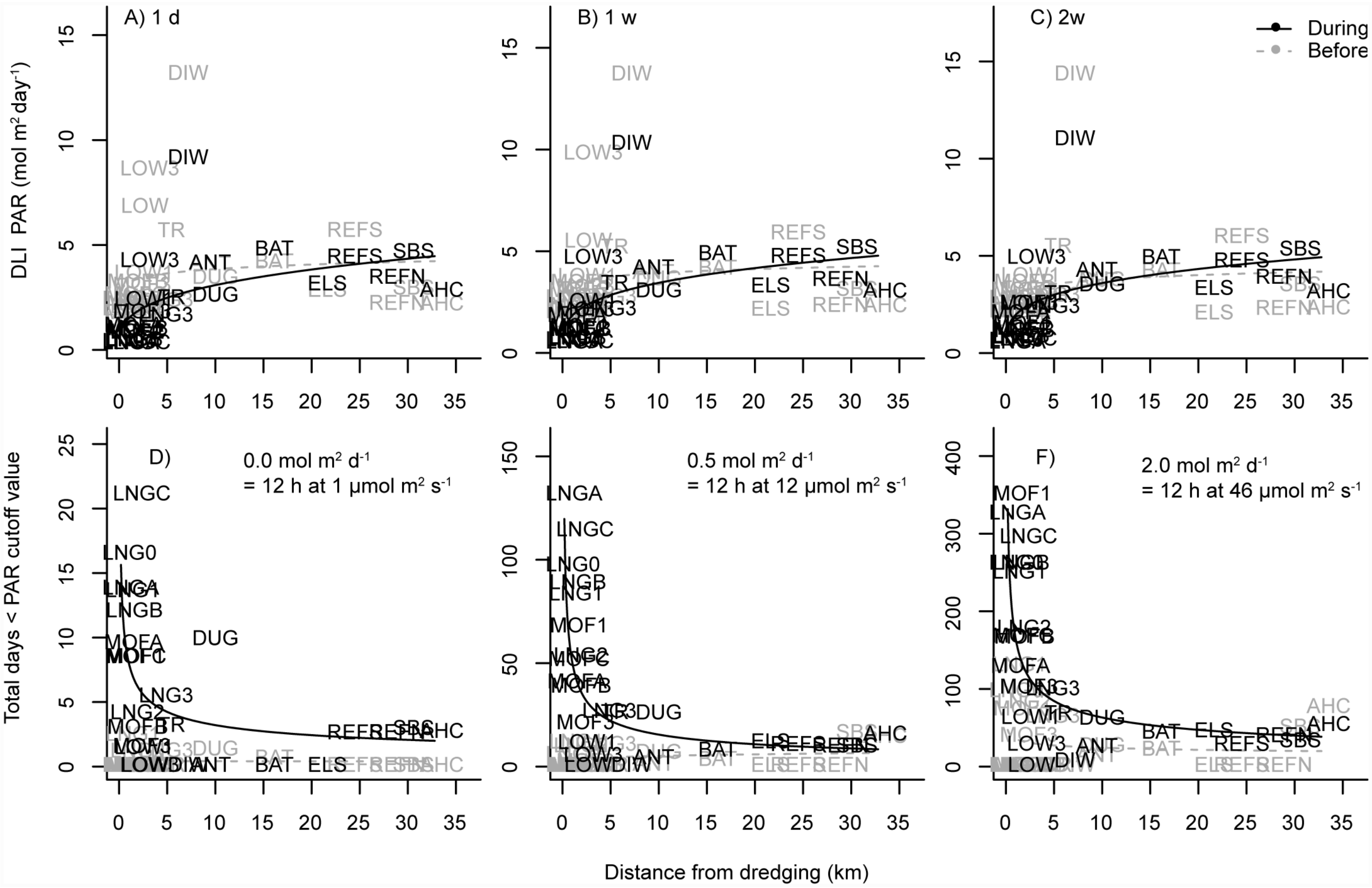


Fig 3. Distance decay relationships based on light for the Barrow Island dredging program. Shown are distance relationships based on the 20th percentile of the daily light integral (DLI) value for 1 day (A), 1 week (B) and 2 week running means (C); and the total number of days in near-darkness (normalised to 1 year) for DLI threshold values of ~0 mol m^{-2} photons (D), 0.5 mol m^{-2} photons (E) and 2.0 mol m^{-2} photons (F).

doi:10.1371/journal.pone.0143309.g003

activity for the Western sites, although this relationship is driven by a single point (CHC4, early in 2008). Estimated distances of impact for Burrup Peninsula ranged from 2.1 to 6.0 km, depending on the metric examined (Fig 5, Table 2).

Detailed plume analysis at Barrow Island

The predominantly southerly movement of the dredge plume during the dredging project at Barrow Island, as well as the overall temporal variability in plume extent, can be seen through the sequential time series of the turbidity data across the sites from the north of Barrow Island (the AHC, REFN, ELS, ANT, and LOW sites), through the region of high dredging activity (the MOF and LNG sites) and down through the southern sites (the TR, DUG, BAT, REFS and SBS sites; Fig 6). The time series shows some periods where the turbidity is relatively widespread across many sites, extending to both northern and southern control sites. This is likely to be associated with storm events such as the one occurring in late February associated with tropical cyclone Carlos. At other times the turbidity events are highly contracted, impacting only those sites close to the dredging, and are clearly the result of dredging plumes (Fig 6)

The satellite imagery shows that during the dredging period there were clearly visible plumes which generally travelled in a southerly direction, (Fig 7B & 7C). In the July 2010

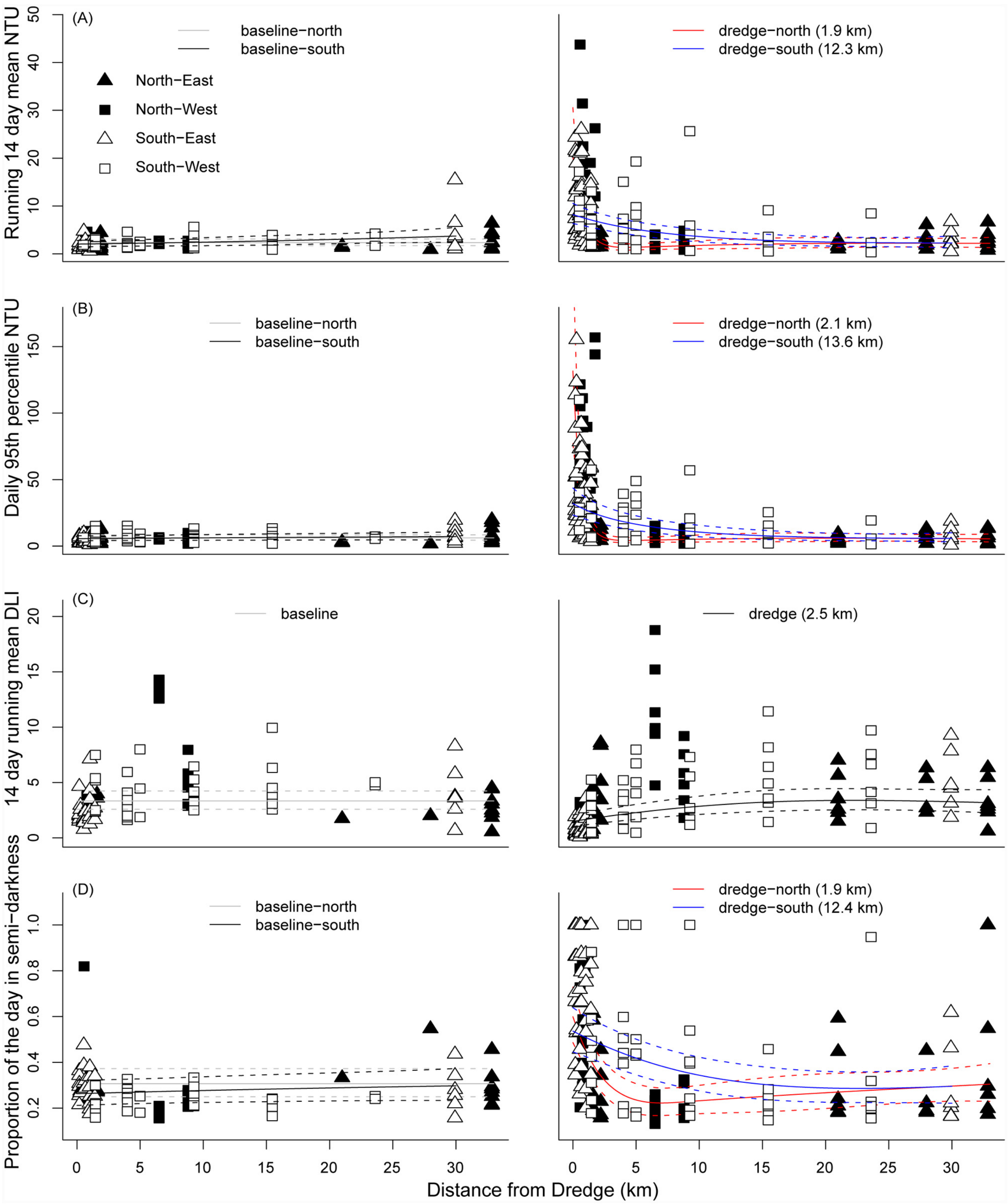


Fig 4. Distance decay relationships for four representative water quality metrics during the Barrow Island project. Shown are: (A) Daily 95th percentile of turbidity, (B) running 14 day mean turbidity, (C) running 14 day mean DLI and (D) proportion of the day below 0.2 DLI. Fitted curves represent fitted best fit Generalised Additive Mixed Models ± 95% confidence. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

doi:10.1371/journal.pone.0143309.g004

Table 1. Distance from the dredging activity relationships for the Barrow Island project. Shown are results for 11 turbidity (NTU) and 6 light based water quality metrics. The notation of P_{80} and P_{95} represents the 80th and 95th percentiles. Shown are the 'best' model as selected by AICc (see methods for more details), R^2 values, along with estimated distance of effects and power decay functions (Equation; in the form $a*d^{-b}$, where d is distance from the primary dredging activity), divided into spatial components (N-S—North or South, E—W–East or West) where required according to the best model. The distance of effect values represent the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Notation for the 'best' model are as follows: NS—a North versus South factor; EW—an East versus West fixed factor; Dr—a factor delineating the pre-dredge versus during dredging; Di—a continuous predictor representing the distance from dredging; Dep—a continuous predictor representing the depth of sites; ":" indicates an interaction among the predictors.

Metric	Best Model	R^2	Distance (km)	Equation
Turbidity (NTU)				
Mean daily	NS:Dr+Di:NS:Dr	0.46	1.9(N); 15.6(S)	$11.8d^{-1.42}$(N); $12.6d^{-0.22}$(S)
Running 7 d mean	NS:Dr+Di:NS:Dr	0.48	1.9(N); 15.9(S)	$10.3d^{-1.54}$(N); $10.8d^{-0.23}$(S)
Running 14 d mean	NS:Dr+Di:NS:Dr	0.48	1.9(N); 13.2(S)	$8.2d^{-1.32}$(N); $8.6d^{-0.23}$(S)
Running 7 d median	NS:Dr+Di:NS:Dr	0.44	2.0(N); 12.4(S)	$8.6^{-1.47}$(N); $9.1d^{-0.26}$(S)
Running 14 d median	NS:Dr+Di:NS:Dr	0.47	2.1(N); 10.5(S)	$5.8d^{-0.88}$(N); $6.9d^{-0.26}$(S)
Running 7 d P_{80}	NS:Dr+Di:NS:Dr	0.44	1.8(N); 16.5(S)	$15.0d^{-1.64}$(N); $15.6d^{-0.22}$(S)
Running 14 d P_{80}	NS:Dr+Di:NS:Dr	0.47	1.9(N); 13.3(S)	$11.7d^{-1.39}$(N); $12.5d^{-0.25}$(S)
Median daily	NS:Dr+Di:NS:Dr	0.36	1.6(N); 19.6(S)	$7.3d^{-1.64}$(N); $9.0d^{-0.12}$(S)
Daily P_{80}	NS:Dr+Di:NS:Dr	0.46	1.8(N); 15.5(S)	$17.3d^{-1.70}$(N); $19.1d^{-0.24}$(S)
Daily P_{95}	NS:Dr+Di:NS:Dr	0.53	2.1(N); 13.6(S)	$37.4d^{-1.12}$(N); $33.2d^{-0.35}$(S)
Daily maximum	EW:Dr+Di:EW:Dr	0.55	1.9(E); 8.8(W)	$44.4d^{-0.52}$(E); $63.3d^{-0.54}$(W)
Light (DLI)				
Mean	Dep+Dr+Di:Dr	0.40	4.6	$1.35d^{0.28}$
7 d running mean	Dep+Dr+Di:Dr	0.48	3.3	$2.02d^{0.26}$
14 d running mean	Dep+Dr+Di:Dr	0.49	2.6	$2.35d^{0.25}$
Proportion d <5	Dep+ NS:Dr+Di:NS:Dr	0.44	1.9(N); 12.6(S)	$0.50d^{-0.25}$(N); $0.59d^{-0.18}$(S)
Proportion d <10	Dep+NS:Dr+Di:NS:Dr	0.46	1.6(N); 13.3(S)	$0.59^{-0.23}$(N); $0.69d^{-0.16}$(S)
Proportion d <15	Dep+NS:Dr+Di:NS:Dr	0.45	1.6(N); 12.6(S)	$0.64d^{-0.20}$(N); $0.74d^{-0.15}$(S)
Proportion d <20	Dep+NS:Dr+Di:NS:Dr	0.44	1.5(N); 11.6(S)	$0.68d^{-0.17}$(N); $0.79d^{-0.13}$(S)

doi:10.1371/journal.pone.0143309.t001

image, the plume was relatively widespread and well mixed, with clear evidence of high suspended sediment concentrations near the primary dredging activity as well as at sites as far away as DUG (~9 km, with mean of 9.4 NTU), followed by LNG3 (mean of 7.1 NTU) and LNG1 (mean of 4.3 NTU; Fig 7B & 7E). In the August 2010 image the plume was highly spatially complex, and despite being readily apparent on satellite imagery, resulted in only marginal increases in turbidity across the sites (Fig 7F).

The relatively systematic decline in water quality impacts from dredging across these southern sites at Barrow Island can be seen clearly in daily time series data for both turbidity and light across the southern transect of sites at Barrow Island; with very high peaks in turbidity (Fig 8A) and associated declines in light evident throughout the dredging period (Fig 8B). There was a clear shift across this southern transect in terms of the cumulative probability distribution curves for both turbidity (Fig 8C) and light (Fig 8D), with dredging causing a positive shift in turbidity (Fig 8C) and a negative shift in light (Fig 8D) across the full range of probabilities.

The high turbidity during the dredging period resulted in sites close to the dredging activity having DLI levels of <2 mol photons m^{-2} for up to 80% of the time, with values of less than 4 mol photons m^{-2} being relatively commonplace (Fig 8D). There is a clear seasonal pattern in light levels following annual changes in daylight hours, with the low light conditions associated with high turbidity being most pronounced during the already lower light winter months (Fig 8C). Importantly, even for a strongly directionally biased plume such as that seen in the Barrow

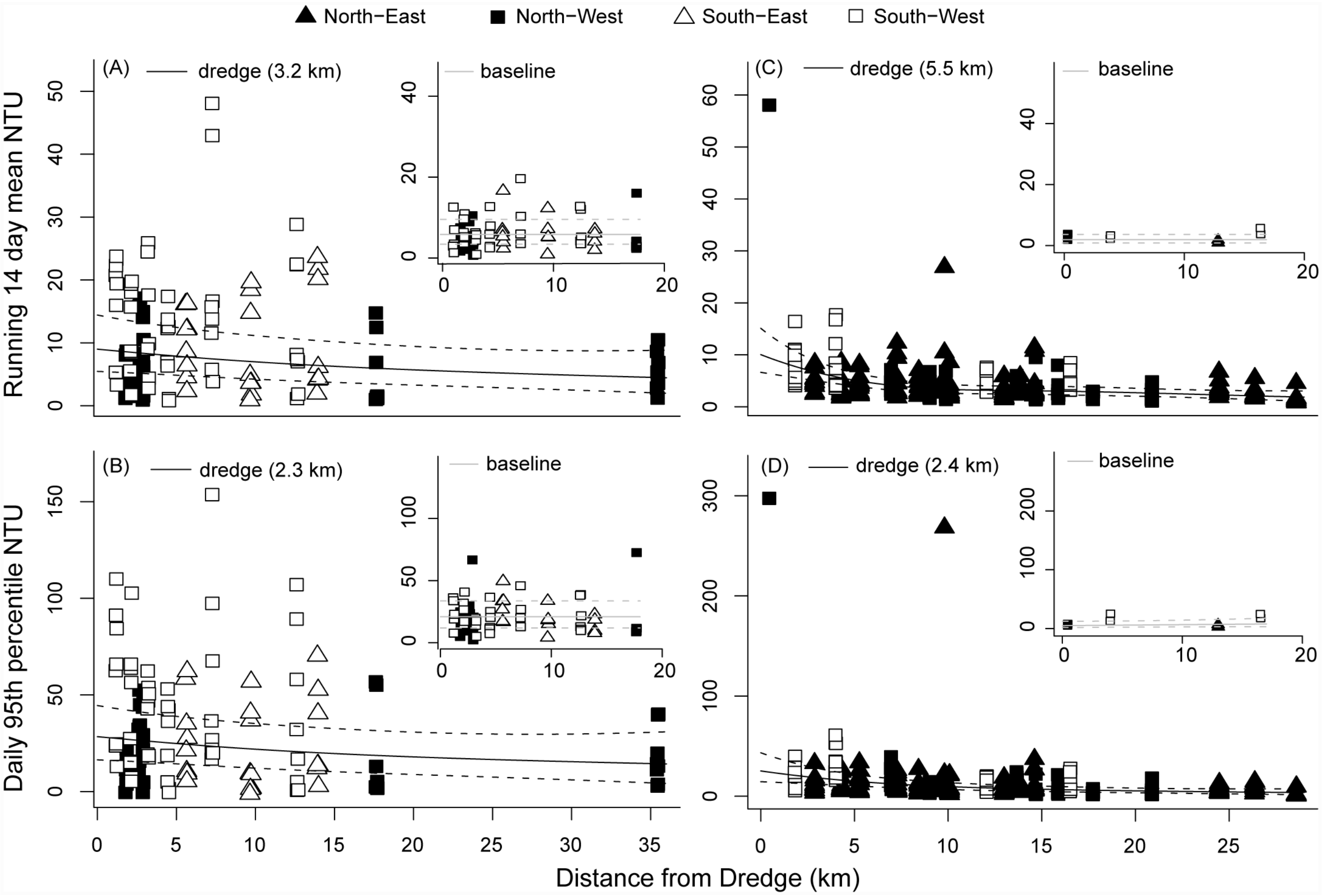


Fig 5. Distance decay relationships for the Cape lambert and Burrup Peninsula dredging projects. Shown are the running 14 day mean turbidity (NTU, A) and daily 95th percentile of turbidity (B) at Cape Lambert, and the running 14 day mean turbidity (C) and daily 95th percentile of turbidity (D) at Burrup Peninsula. Fitted curves represent fitted best fit Generalised Additive Mixed Models ± 95% confidence bounds. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible).

doi:10.1371/journal.pone.0143309.g005

Island project, the effects of dredging appear to decline relatively rapidly with distance, with impacts becoming minimal at distances of around 5 km, and completely indistinguishable from baseline at distances of ~15–20 km (Fig 8).

Discussion

This is one of the first published studies to examine in detail the spatial impacts of large scale capital dredging operations in a tropical, coral reef setting. Overall there was strong evidence of a relationship with distance from dredging with all the water quality metrics examined, particularly for the dredging program at Barrow Island. The impacts of dredging followed a steep power-law decay relationship, with sites near dredging experiencing much greater changes to water quality than the more distant ones, supporting the use of spatial zoning to manage dredging projects [17,33]. The study has also provided valuable information of water quality conditions during large scale capital dredging operations, allowing the design of future studies on the

Table 2. Distance from the primary dredging activity relationships. Shown are results for 11 turbidity (NTU) based water quality metrics for the Cape Lambert (A) and Burrup peninsula (B) projects. The notation of P_{80} and P_{95} represents the 80th and 95th percentiles. Shown are the 'best' model as selected by AICc (see methods for more details), R^2 values, along with estimated distance of effects (Distance) and power decay functions (Equation; in the form a.d-b, where d is distance from the primary dredging activity), divided into spatial components where required according to the best model. The distance of effect values represent the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Notation for the 'best model' are as follows: NS—a North versus South factor; EW—an East versus West fixed factor; Dr—a factor delineating the pre-dredge versus during dredging; Di—a continuous predictor representing the distance from dredging; Dep—a continuous predictor representing site depth; ":" indicates an interaction among the predictors.

Turbidity Metric (NTU)	Best Model	R^2	Distance (km)	Equation
(A) Cape Lambert—turbidity				
Mean daily	NS	0.09		$20.4d^{-0.13}$
Running 7 d mean	NS+EW	0.10		$15.6d^{-0.11}$
Running 14 d mean	NS+EW	0.10	2.3	$12.4d^{-0.11}$
Running 7 d median	NS+EW	0.12		$13.7d^{-0.13}$
Running 14 d median	NS	0.09		$9.6d^{-0.12}$
Running 7 d P_{80}	NS+EW	0.09		$25.9d^{-0.10}$
Running 14 d P_{80}	EW+NS:Dr	0.16	2.7	$19.0d^{-0.09}$
Median daily	NS	0.10		$17.9d^{-0.12}$
Daily P_{80}	NS	0.08	0.5	$28.5d^{-0.14}$
Daily *p*95	NS+EW	0.09	2.3	$44.6d^{-0.16}$
Daily maximum	NS:Dr	0.09	2.0	$58.4d^{-0.16}$
(B) Burrup Peninsula				
Mean daily	EW:Dr+Di:EW:Dr	0.21	5.0 (W)	$8.8d^{-0.27}$ (W)
Running 7 d mean	Di+NS	0.26	5.1	$24.0d^{-0.88}$
Running 14 d mean	Dr+Di:Dr	0.21	5.5	$21.5d^{-0.97}$
Running 7 d median	Di+NS	0.28	4.5	$23.5d^{-1.07}$
Running 14 d median	EW:Dr+Di:EW:Dr	0.29	4.7 (W)	$4.6d^{-0.27}$(E); $19.2d^{-1.15}$(W)
Running 7 d P_{80}	Di+NS	0.21	6.0	$32.6d^{-0.81}$
Running 14 d P_{80}	Di+NS	0.23	5.5	$26.6d^{-0.90}$
Median daily	EW:Dr+Di:EW:Dr	0.20	4.1 (W)	$7.1d^{-0.28}$(E); $24.1d^{-1.07}$ (W)
Daily P_{80}	EW:Dr+Di:EW:Dr	0.19	3.9 (W)	$11.8d^{-0.28}$ (W)
Daily P_{95}	Dr+Di:Dr	0.19	2.1	$95.2d^{-1.25}$
Daily maximum	Dr+Di:Dr	0.18	2.6	$139.6d^{-1.30}$

doi:10.1371/journal.pone.0143309.t002

effects of turbidity on tropical species using environmental relevant or realistic exposure scenarios (see [61]).

How far dredging plumes can travel has important implications for the EIA process and compliance water quality and biological monitoring programs. Recently Evans et al. (2012) visually interpreted MODIS images to map the dredge plume boundaries in the shallow, clear water environment of the Barrow Island project. Their analyses showed that occasionally sediment plumes could be observed over 30 km away from the dredging activities. Such observations define a 'zone of influence' i.e. areas where changes in turbidity can occur, but are not necessarily associated with detectable impacts on the benthic biota. Aerial and satellite images are able to detect very small quantities of suspended material if the turbid water is juxtaposed to clear oceanic water. The blue light scattering from the oceanic water can contrast very strongly with the integrated scattering of sediment and organic material over the water column due to subtle changes in ocean colour. During the EIA process, zones of influence are often predicted (by modelling) and the primary reason is so that authorities can be made aware beforehand of potential social issues such as plumes impacting swimming beaches or marine recreational areas. However, at the outer limits of the zone suspended sediment concentrations

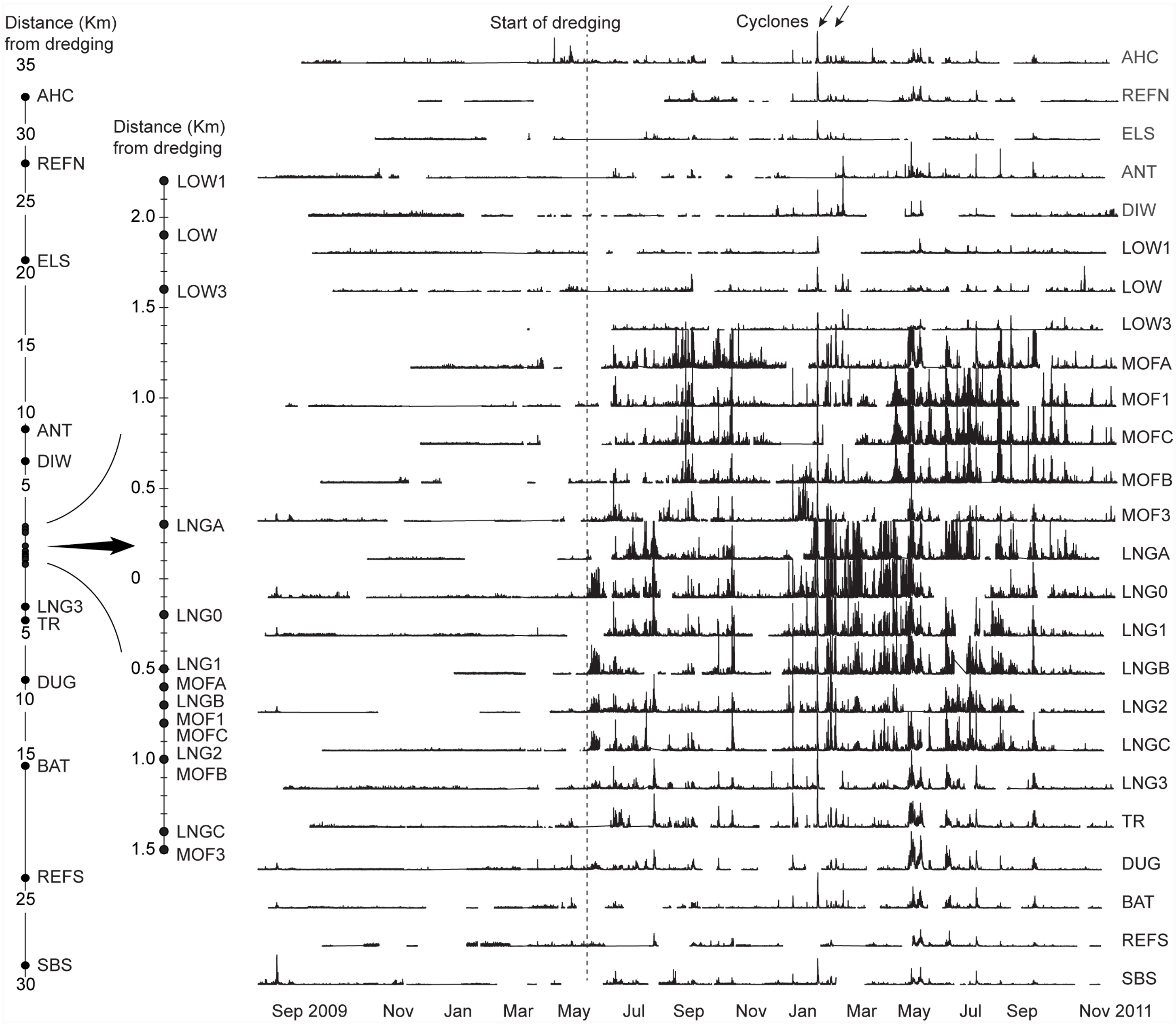


Fig 6. Turbidity time series for the Barrow Island project. Shown are turbidity (NTU) measured every 10 mins from September 2009 to November 2011 at 25 water quality monitoring sites located from ~30 km north to ~30 km south of the main dredging areas (see Fig 1 for sites names and details). Gaps in the data represent occasional failure of the loggers. Each figure is scaled identically from 0–100 NTU. Occasionally readings exceed 100 NTU (see [21] and S1 Table contains full, non-truncated summary statistics).

doi:10.1371/journal.pone.0143309.g006

are, by definition, at the limits of the detection techniques, and are likely to be very low and within the range of turbidity naturally experienced during wind and wave events. It is questionable whether such weak plumes will exert any significant biological effects; An unintended consequence, however, could be a public misconception of the scale of potential deleterious effects (for further discussion of the issue see [29]).

For the purpose of defining the extent of the plume footprint in this study, we used a criterion where the value of the fitted curve (representing a median) intersects the 80th percentile

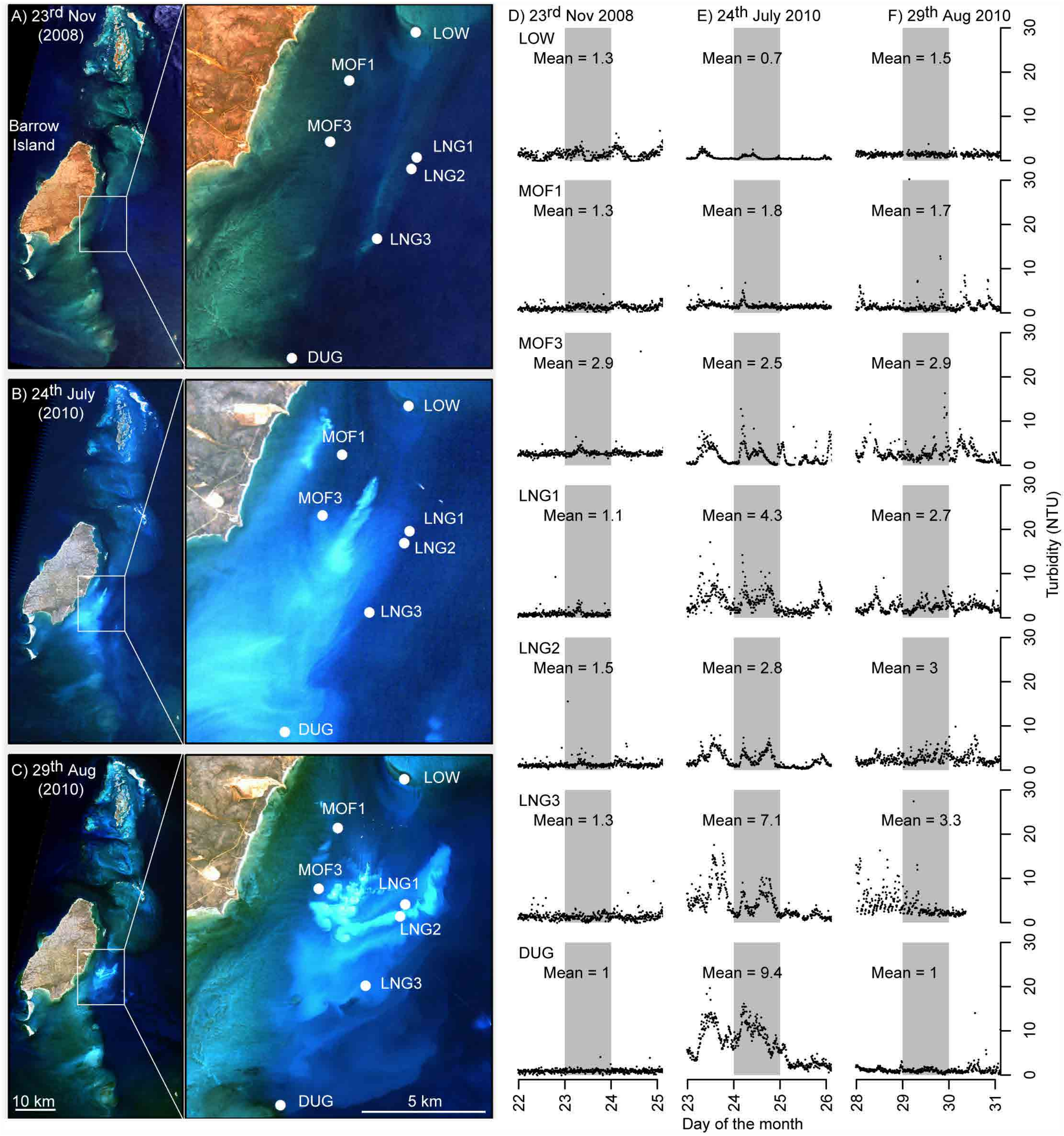


Fig 7. A comparison of satellite images and turbidity. Images are shown for three periods during the Barrow Island dredging program, taken on: (A) 23rd of November 2008 (baseline phase), (B) 24th of July 2010 (dredging phase), and (C) 29th August 2010 (dredging phase). Images from (A) and (C) were sourced from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) satellite. image (10 m pixel resolution). The image in (B) was sourced from the Landsat 5 Thermal Mapper (Path/Rows 114/74-75) 30 m resolution (courtesy of the U.S. Geological Survey)(see also Fig 1 for sites names). Turbidity data (NTU) are shown for the three days surrounding the image date for each image (D, E and F), including all sites for which there were data across all three periods. The grey shaded area indicates the data for the specific date of each image.

doi:10.1371/journal.pone.0143309.g007

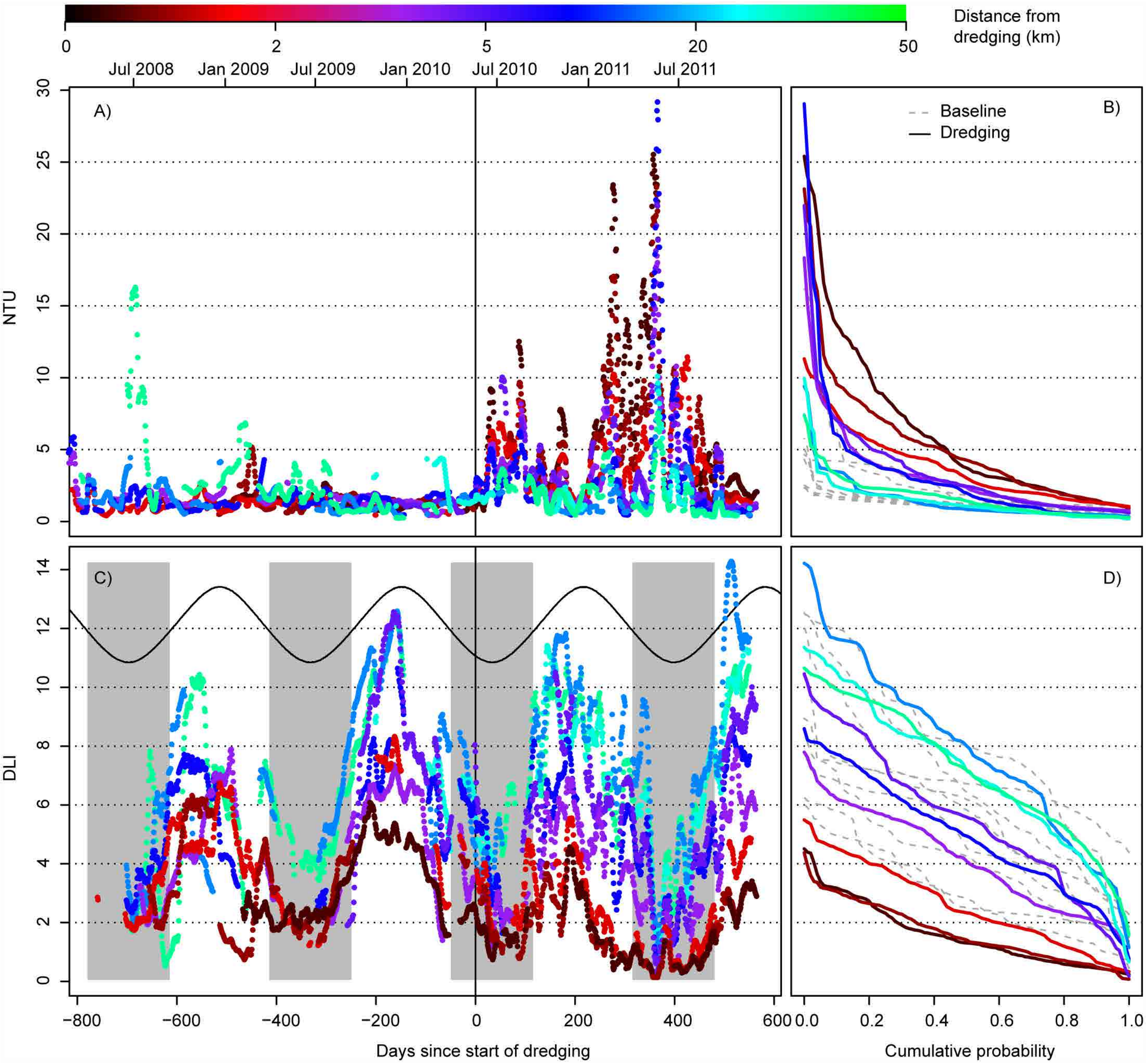


Fig 8. Daily time series and cumulative probability plots. Shown are running 14 day mean turbidity (NTU; A and C) and light (DLI; B and D), with a colour ramp indicating relative distance from dredging activity. Only sites south of the LNG dredging activity (see Fig 4) are included to aid figure clarity. Grey panels indicate the six shortest-day months of the year, based on sun-rise and sun-set data in the region.

doi:10.1371/journal.pone.0143309.g008

(P_{80}) of the baseline value for turbidity (or the 20th percentile for the light data). This comparison procedure (P_{50}–P_{80}) has its origins in the Australia and New Zealand water quality guidelines for fresh and marine waters [59]. The basis is somewhat arbitrary but also pragmatic and associated with a notion of the developers that a median value at an impact site above the 80th percentile of a reference site represents a 'measurable perturbation', and thus worth investigating [59]. The approach is nevertheless useful as it links water quality with the possibility of ecological change and is also based on a relative change rather than an absolute value [62]. In this study the P_{50}–P_{80} approach was compared to pre-dredging baseline period (as opposed to comparing to control of reference sites) and impacts of dredging on water quality appear to extend distances of ~3 km from the dredging, although in one instance extended as far as 15–20 km. The larger estimate for potential distances of measurable effect occurred during the Barrow Island project, where local oceanographic features produced an unusual pattern of a near unidirectional flow southwards over the duration of the project, with minimal days of northward movement. This pattern resulted in the significant three-way interaction between the baseline-versus-dredging periods, distance from dredging, and a north versus south characterisation of sites. The outcome of interaction was that there was a slower decline of water quality with distance south of the primary dredging area (P_{50}–P_{80} distances of 8.8–19.6 km), with a correspondingly much faster decline in the north (P_{50}–P_{80} distance of 1.5–2.1 km).

Overall the strength of the relationship with distance from dredging was much weaker for the Cape Lambert and Burrup Peninsula projects. The general dredging activity may have been less concentrated given the length of the shipping channels. Both locations are also nearer the mainland and likely to show stronger underlying onshore-offshore gradients in water quality that may have masked patterns associated with dredging. Also, there were much fewer water quality monitoring sites close to the dredging activities in the projects because the regulatory conditions at the time were most concerned with establishing that water quality and ecological change did not occur at more distant sites, than showing effects did occur close to dredging where habitat loss was allowed. This policy direction has recently changed (see [17]).

The spatial analysis carried out here are based on a range of metrics that capture site level summaries across time using a range of temporal scales (hours, days, weeks) and summary metrics (e.g. means, percentiles). However, it is important to remember that such metrics do not necessarily capture the realised *in-situ* water quality conditions across all sites at instantaneous time-scales. While the distance from dredging activity plots may seem relatively consistent once potential effects of overall plume direction are taken into account, the reality is that at any given time turbidity plumes appear to be highly spatially heterogeneous as clearly shown in the satellite images (Fig 7B & 7C). A peak in turbidity occurring at one location may not be evident at sites only a few hundred metres away. High levels of variation among sites within regions appears to be a consistent feature of turbidity data [63]. Fine scale spatial structure in turbidity raises two issues with respect to dredging management and monitoring that have not yet been thoroughly addressed. First is the issue of whether previously adopted water quality monitoring designs are spatially sufficient, or should more effort be made to establish more optimal designs (e.g. spatially hierarchical and/or stratified sampling [64] or grid sampling [65]) that may be better suited to demonstrating dredging impacts. While power analysis [66–68], principles of optimal sampling design [64,69–71] and before-after-control-impact assessment [72,73], as well as cost benefit analysis [74] are widespread in ecology, such principles are not often applied to water quality sampling. Second is the issue that if there is poor temporal correlation in water quality readings among sites even at relatively small spatial scales, monitoring protocols and threshold values based on the use of comparisons to control or reference sites may be of limited value unless extreme care is taken to ensure they adequately represent the impact locations [39].

The focus of this study has been the spatial effects from the excavation itself (including spillage from drags heads and hopper overflow). However, disposal of sediments at offshore dredge material placement sites (spoil grounds) is also a significant turbidity-generating activity associated with dredging. Preliminary analyses were carried out to attempt to examine patterns in turbidity with distance from spoil disposal sites across the three studies, and no strong relationships were revealed. Admittedly, however, none of the three projects had a sampling design that was spatially designed for looking at effects of distance from the placement sites, rendering the conclusion of such analyses relatively weak. The effect of the disposal at Barrow Island can be seen in the satellite images in Fig 7B & 7C (bottom left hand corner of enlarged panels), and generally appears relatively minor compared to the turbidity generated at the point of excavation. For the Barrow Island project the spoil disposal site was situated to the south east of the dredging activities and may in fact partially account for some of the southerly extent of the Barrow Island dredge plume. In this context the distance analysis reported here potentially represents the total effect of the whole dredge operation (both excavation and disposal), with anything over ~15–20 km not affected.

Water Quality thresholds for reef biota

The P_{50}–P_{80} approach of ANZECC/ARMCANZ to estimate distances of detectable effects is recommended where information on biological responses is absent, and is considered to be reasonably conservative. Other statistical criteria based on water quality could be used, that might yield substantially different estimated distances. For example, it could be defined as the distance at which the predicted (best fit value, representing a mean or median) crosses the upper 95th percentile value of the baseline state. Such a definition would likely yield shorter distances of potential impact than currently reported here.

What is really needed to define the distance of effects are water quality thresholds which relate changes in the physical parameters (light reduction, total suspended sediment, sediment deposition) to biological responses (sublethal and lethal) of the underlying organisms. Such thresholds are not yet available for reef biota such as coral, seagrasses and filter feeders and require laboratory and/or manipulative field based studies and subsequent verification before being used. The spatial analyses described here and the temporal analyses described in Jones et al. [21] have however provided some insights into the problems that need to be addressed when developing such thresholds, and especially how to incorporate exposure across varying temporal scales. For example, during the Barrow Island project, >50% of the daily light integrals were very low (i.e. <1.5 mol photons m^{-2}) at sites within a few hundred metres of the dredging, as opposed to 3–8 mol photons m^{-2} during the baseline period. Clearly light was affected by dredging but it is very significant for the underlying communities whether these low light values occur at once or intermittently. Theoretically, an intermittent pattern could afford the opportunity for primary producers such as corals to recover energy deficits between the low light periods. This has already been suggested as a mechanism for how corals survive natural resuspension events ([9,75]). Simple inspection of the data shows many low light days occurred in a near continuous block in the winter period, where a combination of low seasonal light availability and more intense turbidity generating events resulted in a 6 month period of DLIs <1 mol photons m^{2}. The pattern suggests one possible management practice could be timing maintenance and/or short-term capital dredging programs to avoid seasonal lows in light availability if light is considered a key pressure parameter (i.e. dredging near seagrass beds). However the data also suggests that analyses of water quality data using the whole dredging or baseline periods using cumulative probability plots (see Fig 8) although instructive for characterizing effects on a broad scale, is much too coarse for threshold development.

The recent study of the temporal patterns of changes in water quality close to dredging indicated that dredging changes the overall probability distribution of turbidity values and the upper/lower percentile values (e.g. 99th, 95th for NTU or 1st 5th for light) were highly elevated/lowered over short periods, but converged to values close to the baseline states over longer periods (weeks to months) [21]. The running means calculated across multiple time periods (from hours to a month), summarized across a broad range of percentiles values [21], and expressed in terms of distance from the dredging activities (this study) has provided a matrix of environmentally realistic exposure conditions that can be used to explore lethal and sub-lethal water quality thresholds in future laboratory- and field-based manipulative studies (see online S1 Table). This could ultimately lead to a more accurate definition of the potential ecological footprint of plumes from dredging projects than the P_{50}–P_{80} approach used here or other statistical approaches.

The three projects described here spanned a range of environmental settings including an offshore, 'clear water' environment (Barrow Island), an exposed nearshore cape or headland (Cape Lambert), and an enclosed inshore turbid reef environment (Mermaid Sound, Burrup Peninsula). Nevertheless, the patterns of turbidity generation will be highly site and project specific and will vary with production rates (volumes dredged) and dredge types (cutter suction dredge versus back hoe or TSHD) and methodology used (overflow etc). Other factors include the nature of the sediments being dredged and the oceanographic conditions such as tidal and current strengths and wind- and wave-induced resuspension associated with seabreezes. For the upper (15–20 Km) bound identified for the Barrow Island project, it should be recognized that was a very large scale capital dredging operation (8 Mm^3) with multiple dredges working 24 a day, in a clear water environment, and with the unusual oceanographic feature of unidirectional flow. As such, we consider that the southerly extension of the plume represents an upper bound on the distances at which dredging might be expected to cause 'measurable perturbations' as defined by the P_{50}–P_{80} approach.

Supporting Information

S1 File. Detailed results. Full subsets best model output (Tables A-C) and plotted best model fits (Figures A-D) for all variables examined statistically for distance decay relationships for each of the three dredging projects in the Pilbara.
(PDF)

S1 Table. Detailed summary data. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period or for during the duration of the dredging program.
(PDF)

Acknowledgments

We thank industry for making this data available for scientific research and M. Poutinen for providing information on cyclone activity.

Author Contributions

Conceived and designed the experiments: RF RJ CS PR. Analyzed the data: RF RJ CS. Wrote the paper: RF RJ PR CS.

References

1. Bray RN (2008) Environmental aspects of dredging. CRC Press.; Bray RN, editor.
2. Johnston JSA (1981) Estuarine dredge and fill activities: a review of impacts. Environmental Management 5: 427–440.
3. Newell R, Seiderer L, Hitchcock D (1998) The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. Oceanography and Marine Biology: An Annual Review 36: 127–178.
4. Clarke A, Lidgard S (2000) Spatial patterns of diversity in the sea: bryozoan species richness in the North Atlantic. Journal of Animal Ecology 69: 799–814.

5. Thrush SF, Dayton PK (2002) Disturbance to marine benthic habitats by trawling and dredging: implications for marine biodiversity. Annual Review of Ecology and Systematics 2002: 449–473.
6. Morton J (1977) Ecological effects of dredging and dredge spoil disposal: A literature review. US Fish and Wildlife Service Technical Papers 94: 1–33.
7. Jones R, Ricardo GF, Negri AP (2015) Effects of sediments on the reproductive cycle of corals. Marine Pollution Bulletin doi: 10.1016/j.marpolbul.2015.08.021
8. Kleypas JA, McManus JW, Meñez LA (1999) Environmental limits to coral reef development: where do we draw the line? American Zoologist 39: 146–159.
9. Anthony KR, Fabricius KE (2000) Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity. Journal of experimental marine biology and ecology 252: 221–253. PMID: 10967335
10. Bak RPM (1978) Lethal and sublethal effects of dredging on reef coral. Marine Pollution Bulletin 9: 14–16.
11. Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62: 185–202.
12. Erftemeijer PL, Lewis RRR (2006) Environmental impacts of dredging on seagrasses: A review. Marine Pollution Bulletin 52: 1553–1572. PMID: 17078974
13. Erftemeijer PLA, Riegl B, Hoeksema BW, Todd PA (2012) Environmental impacts of dredging and other sediment disturbances on corals: A review. Marine Pollution Bulletin 64: 1737–1765. doi: 10.1016/j.marpolbul.2012.05.008 PMID: 22682583
14. Doorn-Groen SM, Foster T (2007) Environmental monitoring and management of reclamations works close to sensitive habitats. Terra et Aqua 108: 3.
15. Trimarchi S, Keane J (2007) Port of Hay Point Apron Areas and Departure Path Capital Dredging Project. Environmental Review, EcoPorts Monograph Series 24.
16. Foster T, Corcoran E, Erftemeijer P, Fletcher C, Peirs K, Dolmans C, et al. (2010) Dredging and port construction around coral reefs. PIANC Environmental Commission, Report No 108.
17. EPA (2011) Environmental Assessment Guidleine for Marine Dredging Programs EAG7. Perth, Western Australia: Environmental Protection Authority (EPA). pp. 36.
18. Hanley JR (2011) Environmental monitoring programs on recent capital dredging projects in the Pilbara (2003–10): a review. APPEA J: 273–294.
19. Wolanski E, Gibbs R (1992) Resuspension and clearing of dredge spoils after dredging, Cleveland Bay, Australia. Water environment research 1992: 910–914.
20. McArthur C, Ferry R, Proni J. (2002) Development of guidelines for dredged material disposal based on abiotic determinants of coral reef community structure. Proceedings of the third Speciality Conference on Dreding and Dredged Material Disposal Coasts, Oceans, Ports and Rivers Institute (COPRI) of ASCE. Orlando, FL, USA. 1–15.
21. Jones R, Fisher R, Stark C, Ridd P (2015) Temporal patterns in water quality from dredging in tropical environments. PlosOne 10: e0137112.
22. Koskela RW, Ringeltaube P, Small AR, Koskela TV, Fraser AR, Lee JD, et al. (2002) Using predictive monitoring to mitigate construction impacts in sensitive marine environments 10th Pacific Congress on Marine Science and Technology (PACON 2002) July 21–26, 2002, Chiba, Japan
23. Stoddart J, Anstee S (2004) Water quality, plume modelling and tracking before and during dredging in Mermaid Sound, Dampier, Western Australia. Corals of the Dampier Harbour: their survival and reproduction during the dredging programs of 2004: 9–30.
24. VBKO (2003) Protocol for the Field Measurementof Sediment Release from Dredgers. A practical guide to measuring sediment release from dredging plant for calibration and verification of numerical models. Reporrt produced for VBKO TASS project by HR Wallingford Ltd & Dredging Research Ltd Issue 1:83 pp.
25. Van Der Veer HW, Bergman MJN, Beukema JJ (1985) Dredging activities in the Dutch Wadden Sea: effects on macrobenthic infauna. Netherlands Journal of Sea Research 19: 183–190.
26. Nichols M, Diaz R, Schaffner LC (1990) Effects of hopper dredging and sediment dispersion, Chesapeake Bay. Environmental Geology and Water Sciences 15: 31–43.
27. Hitchcock D, Bell S (2004) Physical impacts of marine aggregate dredging on seabed resources in coastal deposits. Journal of Coastal Research 20: 101–114.
28. Duclos P-A, Lafite R, Le Bot S, Rivoalen E, Cuvilliez A (2013) Dynamics of Turbid Plumes Generated by Marine Aggregate Dredging: An Example of a Macrotidal Environment (the Bay of Seine, France). Journal of Coastal Research 29: 25–37.

29. Spearman J (2015) A review of the physical impacts of sediment dispersion from aggregate dredging. Marine Pollution Bulletin 94: 260–277. doi: 10.1016/j.marpolbul.2015.01.025 PMID: 25869201

30. Ruffin K (1998) The persistence of anthropogenic turbidity plumes in a shallow water estuary. Estuarine, Coastal and Shelf Science 47: 579–592.

31. Fredette T, French G (2004) Understanding the physical and environmental consequences of dredged material disposal: history in New England and current perspectives. Marine Pollution Bulletin 49: 93–102. PMID: 15234878

32. Cutroneo L, Castellano M, Pieracci A, Povero P, Tucci S, Capello M (2012) The use of a combined monitoring system for following a turbid plume generated by dredging activities in a port. Journal of Soils and Sediments 12: 797–809.

33. GBRMPA (2012) The use of hydrodynamic numerical modelling for dredging projects in the Great Barrier Reef Marine Park, Great Barrier Reef Marine Park Authority, Townsville. GBRMPA External Guideline. In: GBRMPA (ed), Townsville (Queensland, Australia).

34. Mulligan M (2009) 'Applying the learning' The Geraldton Port dredging project 2002–03. Paper to the Freight and Logistics Council of WA and Ports WA—1st of December 2009 Mulligan Environmental, Western Australia.

35. CEDA (2015) Environmental Monitoring Procedures. Information paper. Central Dredging Association (CEDA) Delft The Netherlands (http://www.dredging.org/media/):23 pp.

36. McCook L, Schaffelke B, Apte S, Brinkman R, Brodie J, Erftemeijer P, et al. (2015) Synthesis of current knowledge of the biophysical impacts of dredging and disposal on the Great Barrier Reef: report of an independent panel of experts.

37. Larcombe P, Costen A, Woolfe KJ (2001) The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology 48: 811–835.

38. Larcombe P, Ridd PV, Prytz A, Wilson B (1995) Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14: 163–171.

39. Orpin A, Ridd P, Thomas S, Anthony K, Marshall P, Oliver J (2004) Natural turbidity variability and weather forecasts in risk management of anthropogenic sediment discharge near sensitive environments. Mar Pollut Bull 49: 602–612. PMID: 15476839

40. Orpin AR, Ridd PV (2012) Exposure of inshore corals to suspended sediments due to wave-resuspension and river plumes in the central Great Barrier Reef: A reappraisal. Continental Shelf Research 47: 55–67.

41. Bivand R, Keitt T, Rowlingson B (2015) rgdal: Bindings for the Geospatial Data Abstraction Library. R package version 1.0–7. http://CRAN.R-project.org/package = rgdal.

42. Geoscience Australia (2004) Geodata Coast 100K 2004. Geoscience Australia, Canberra. <http://www.ga.gov.au/>.

43. Murrell P (2014) gridBase: Integration of base and grid graphics. R package version 0.4–7. http://CRAN.R-project.org/package = gridBase.

44. Adobe Illustrator (2012) (Version CS6) [Computer software]. San Jose, CA: Adobe Systems Incorporated.

45. Wood SN (2006) Generalized Additive Models: an introduction with R. Boca Raton, FL: CRC Press. 410 p.

46. R Core Team (2014) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

47. Tuszynski J (2013) caTools: Tools: moving window statistics, GIF, Base64, ROC AUC, etc. R package version 116 http://CRANR-projectorg/package = caTools.

48. Zeileis A, Grothendieck G (2005) zoo: S3 Infrastructure for Regular and Irregular Time Series. Journal of Statistical Software 14: 1–27.

49. Wood S, Scheipl F (2013) gamm4: Generalized additive mixed models using mgcv and lme4. R package version 0.2–2. http://CRANR-projectorg/package = gamm4.

50. ESRI (2013) ArcGIS Desktop, v10.2. Redlands CA, Environmental Systems Research Institute.

51. Carroll SS, Pearson DE (2000) Detecting and modeling spatial and temporal dependence in conservation biology. Conservation Biology 14: 1893–1897.

52. Cryer JD, Chan K-S (2008) Time series regression models. Time series analysis: with applications in R. pp. 249–276.

53. Kirk J (1994) Light and photosynthesis in aquatic ecosystems. Third Edition. Cambridge University Press, New York.

54. Kirk JT (1985) Effects of suspensoids (turbidity) on penetration of solar radiation in aquatic ecosystems. Perspectives in Southern Hemisphere Limnology. Springer.
55. Cavanaugh JE (1997) Unifying the derivations of the Akaike and corrected Akaike information criteria. Statistics & Probability Letters 31: 201–208.
56. Burnham KP, Anderson DR (2002) Model Selection and Multimodel Inference; A Practical Information-Theoretic Approach. New York: Springer. 488 p.
57. Bates DM, Watts DG (1988) Nonlinear Regression Analysis and Its Applications, Wiley
58. Bates DM, Chambers JM (1992) Nonlinear models. Chapter 10 of Statistical Models in S. In: Hastie JMCaTJ, editor: Wadsworth & Brooks/Cole.
59. ANZECC/ARMCANZ (2001) Australian and New Zealand guidelines for fresh and marine waters. Australian and New Zealand Environment and Conservation Council & Agriculture Resource Management Council of Australia and New Zealand, Canberra.
60. Evans RD, Murray KL, Field SN, Moore JAY, Shedrawi G, Huntley BG, et al. (2012) Digitise This! A Quick and Easy Remote Sensing Method to Monitor the Daily Extent of Dredge Plumes. PLoS ONE 7: e51668. doi: 10.1371/journal.pone.0051668 PMID: 23240055
61. Harris CA, Scott AP, Johnson AC, Panter GH, Sheahan D, Roberts M, et al. (2014) Principles of Sound Ecotoxicology. Environmental Science & Technology 48: 3100–3111.
62. Fox D (2001) Understanding the new ANZECC Water Quality Guidelines. http://www.environmetrics.net.au/docs/THE%20NEW%20ANZECC%20WATER%20QUALITY%20GUIDELINES_2_.pdf.
63. Macdonald RK, Ridd PV, Whinney JC, Larcombe P, Neil DT (2013) Towards environmental management of water turbidity within open coastal waters of the Great Barrier Reef. Mar Pollut Bull 74: 82–94. doi: 10.1016/j.marpolbul.2013.07.026 PMID: 23948091
64. Andrew NL, Mapstone BD (1987) Sampling and the description of spatial pattern in marine ecology. Oceanography and Marine Biology: an annual review 25: 39–90.
65. Cole RE, H T.R., Wood ML, Foster DM (2001) Statistical analysis of spatial pattern: a comparison of grid and hierarchical sampling approaches. Ecological Monitoring and Assessment 69: 85–99.
66. Osenberg CW, Schmitt RJ, Holbrook SJ, Abu-Saba KE, Flegal AR (1994) Detection of Environmental Impacts: Natural Variability, Effect Size, and Power Analysis. Ecological Applications 4: 16–30.
67. Gerrodette T (1987) A power analysis for detecting trends. Ecology 1987: 1364–1372.
68. Fairweather PG (1991) Statistical power and design requirements for environmental monitoring. Marine and freshwater research 42: 555–567.
69. Chapman MG (1999) Improving sampling designs for measuring restoration in aquatic habitats. Journal of Aquatic Ecosystem Stress and Recovery 6: 235–251.
70. Block WM, Franklin AB, James P. Ward J, Ganey JL, White GC (2001) Design and implementation of monitoring Studies to evaluate the success of ecological restoration on wildlife. Restoration Ecology 9: 293–303.
71. Millard SP, Lettenmaier DP (1986) Optimal design of biological sampling programs using the analysis of variance. Estuarine, coastal and shelf science 22: 637–656.
72. Green RH (1979) Sampling design and statistical methods for environmental biologists. New York, USA: Wiley.
73. Underwood AJ (1994) On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological applications 4: 3–15.
74. Hanley N, Spash CL (1993) Cost-benefit analysis and the environment. Vol. Hanley, Nick, and Clive L. Spash. Cost-benefit analysis and the environment. Vol. 499. Cheltenham: Edward Elgar, 1993. Cheltenham: Edward Elgar.
75. Anthony K, Larcombe P (2000) Coral reefs in turbid waters: sediment-induced stresses in corals and likely mechanisms of adaptation. Proceedings of the 9th International Coral Reef Symposium Bali, Indonesiaia 1: 239–244.

S1 File - Detailed distance decay analysis results

Supplementary Tables 1.A through to 1.C show the full subsets best model output for all variables examined statistically for distance decay relationships for each of the three dredging projects in the Pilbara. The optimal model is considered that within 2 AICc of that model with the lowest AICc value that has the fewest parameters (Burnham & Anderson 2002). Where there was more than one model within 2 AICc of the best model (that with the lowest AICc), all models within 2 AICc are shown. In this instance the ωi values show the relative AICc weight of each model, which is an indication of the relative strength of evidence for a given model in the complete model set. Supplementary Figures 1.A through to 1.D show plotted best model fits.

References

R Core Team (2014) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Burnham KP, Anderson DR (2002) Model Selection and Multimodel Inference; A Practical Information-Theoretic Approach. Springer, New York

ESRI (2013) ArcGIS Desktop, v10.2. . Redlands CA, Environmental Systems Research Institute

Wood S, Scheipl F (2013) gamm4: Generalized additive mixed models using mgcv and lme4. R package version 0.2-2. http://CRANR-projectorg/package=gamm4

Table S1.A. Generalised Additive Mixed Models (GAMM) results for the Barrow Island project. Shown are all top models for each response variable examined, defined as those models within 2 AICc of the best model. ωi values show the relative weight of evidence for each model.

Response metric	Top models	AICc	BIC	ωi	Number of parameters
Mean NTU	NS:Dredging+Distance:NS:Dredging	-152.7	-111.7	1.00	11
Running 7 day mean NTU	NS:Dredging+Distance:NS:Dredging	-164.5	-123.4	1.00	11
Running 14 day mean NTU	NS:Dredging+Distance:NS:Dredging	-213.8	-172.7	1.00	11
Running 7 day median NTU	NS:Dredging+Distance:NS:Dredging	199.6	240.7	1.00	11
Running 14 day median NTU	NS:Dredging+Distance:NS:Dredging	100.8	141.9	0.94	11
Running 7 day 80th percentile NTU	NS:Dredging+Distance:NS:Dredging	-50.9	-9.8	1.00	11
Running 14 day 80th percentile NTU	NS:Dredging+Distance:NS:Dredging	-111.2	-70.1	1.00	11
Median NTU	NS:Dredging+Distance:NS:Dredging	-213.4	-172.4	1.00	11
80th percentile NTU	NS:Dredging+Distance:NS:Dredging	-102.4	-61.4	1.00	11
95th percentile NTUs	NS:Dredging+Distance:NS:Dredging	15.5	56.5	1.00	11
Maximum NTU	EW:Dredging+Distance:EW:Dredging	31.1	72.1	0.53	11
	NS:Dredging+Distance:NS:Dredging	31.6	72.6	0.41	11
Mean DLI	Depth+Dredging+Distance:Dredging	-48.6	-21.1	0.59	8
	Depth+NS:Dredging+Distance:NS:Dredging	-47.6	-6.7	0.35	12
7 day running mean DLI	Depth+Dredging+Distance:Dredging	-128.0	-100.5	0.91	8
14 day running mean DLI	Depth+Dredging+Distance:Dredging	-365.5	-337.9	0.91	8
Proportion day <5 μmol photons m^{-2} s^{-1}	Depth+NS:Dredging+Distance:NS:Dredging	-623.0	-582.1	1.00	12
Proportion day <10 μmol photons m^{-2} s^{-1}	Depth+NS:Dredging+Distance:NS:Dredging	-614.0	-573.1	1.00	12
Proportion day <15 μmol photons m^{-2} s^{-1}	Depth+NS:Dredging+Distance:NS:Dredging	-604.6	-563.7	0.99	12
Proportion day <20 μmol photons m^{-2} s^{-1}	Depth+NS:Dredging+Distance:NS:Dredging	-443.6	-402.7	0.96	12

Table S1.B. Generalised Additive Mixed Models (GAMM) results for the Cape Lambert project. Shown are all top models for each response variable examined, defined as those models within 2 AICc of the best model. ωi values show the relative weight of evidence for each model.

Response metric	Top models	AICc	BICc	ωi	Number of parameters
Mean NTU	NS+EW:Dredging	-52.7	-28.0	0.32	8
	NS+EW	-51.6	-32.9	0.18	6
	NS	-51.5	-35.9	0.17	5
Running 7 day mean NTU	EW+NS:Dredging	-69.4	-44.6	0.36	8
	NS+EW	-68.6	-49.9	0.25	6
Running 14 day mean NTU	EW+NS:Dredging	110.0	134.8	0.52	8
	NS:Dredging	112.0	133.7	0.20	7
Running 7 day median NTU	EW+NS:Dredging	-42.1	-17.4	0.30	8
	NS+EW	-41.7	-23.0	0.25	6
	NS:Dredging	-40.2	-18.5	0.12	7
Running 14 day median NTU	EW+NS:Dredging	-60.3	-35.6	0.26	8
	NS:Dredging	-59.8	-38.0	0.19	7
	NS+EW	-59.3	-40.6	0.16	6
	NS	-58.9	-43.3	0.13	5
Running 7 day 80th percentile NTU	EW+NS:Dredging	-11.1	13.6	0.37	8
	NS+EW	-10.2	8.5	0.23	6
Running 14 day 80th percentile NTU	EW+NS:Dredging	198.4	223.2	0.62	8
Median NTU	NS+EW:Dredging	-56.4	-31.7	0.25	8
	NS	-56.0	-40.4	0.20	5
	NS+EW	-55.9	-37.2	0.19	6
	Distance+NS	-54.8	-36.1	0.11	6
80th percentile NTU	NS+EW:Dredging	227.3	252.1	0.30	8
	NS+EW	228.1	246.8	0.20	6
	NS	229.0	244.7	0.13	5
95th percentile NTUs	NS+EW:Dredging	295.9	320.7	0.34	8
	NS+EW	297.0	315.7	0.20	6
Maximum NTU	EW+NS:Dredging	331.1	355.9	0.37	8
	NS:Dredging	332.3	354.0	0.21	7

Table S1.C. Distance from dredging Generalised Additive Mixed Models (GAMM) results for the Burrup Peninsula project for all response metrics examined. Shown are all top models for each response variable examined, defined as those models within 2 AICc of the best model. ωi values show the relative weight of evidence for each model.

Response metric	Top models	AICc	BICc	ωi	Number of parameters
Mean NTU	EW:Dredging+Distance:EW:Dredging	-224.8	-192.5	0.74	9
Running 7 day mean NTU	Distance+NS	-230.7	-209.0	0.38	6
	Dredging+Distance:Dredging	-229.8	-204.6	0.24	7
	EW:Dredging+Distance:EW:Dredging	-229.7	-197.4	0.23	9
Running 14 day mean NTU	EW:Dredging+Distance:EW:Dredging	-285.7	-253.4	0.62	9
	Dredging+Distance:Dredging	-284.0	-258.8	0.26	7
Running 7 day median NTU	EW:Dredging+Distance:EW:Dredging	-239.2	-206.9	0.39	9
	Distance+NS	-238.5	-216.8	0.27	6
	Dredging+Distance:Dredging	-237.7	-212.4	0.18	7
Running 14 day median NTU	EW:Dredging+Distance:EW:Dredging	-311.2	-278.8	0.84	9
Running 7 day 80th percentile NTU	Distance+NS	-102.4	-80.7	0.66	6
Running 14 day 80th percentile NTU	Distance+NS	-191.0	-169.3	0.34	6
	Dredging+Distance:Dredging	-190.4	-165.1	0.26	7
	EW:Dredging+Distance:EW:Dredging	-190.0	-157.7	0.21	9
Median NTU	EW:Dredging+Distance:EW:Dredging	-282.5	-250.2	0.65	9
80th percentile NTU	EW:Dredging+Distance:EW:Dredging	-178.4	-146.0	0.78	9
95th percentile NTUs	EW:Dredging+Distance:EW:Dredging	-44.7	-12.4	0.58	9
	Dredging+Distance:Dredging	-43.8	-18.6	0.37	7
Maximum NTU	EW:Dredging+Distance:EW:Dredging	-34.7	-2.4	0.62	9
	Dredging+Distance:Dredging	-33.5	-8.3	0.34	7

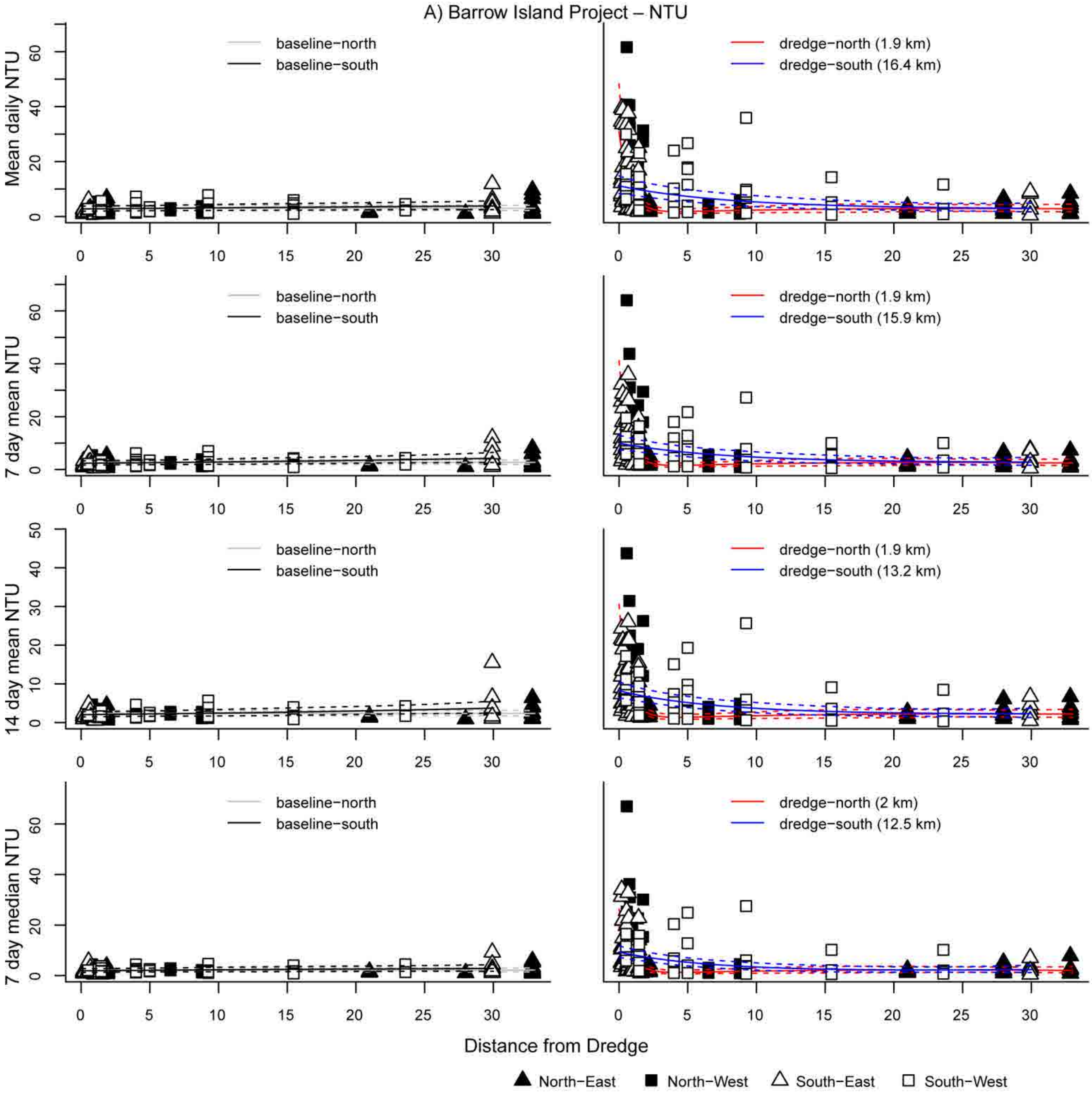


Figure S1.A (part 1). Distance decay relationships for turbidity (NTU) based water quality metrics at Barrow Island. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

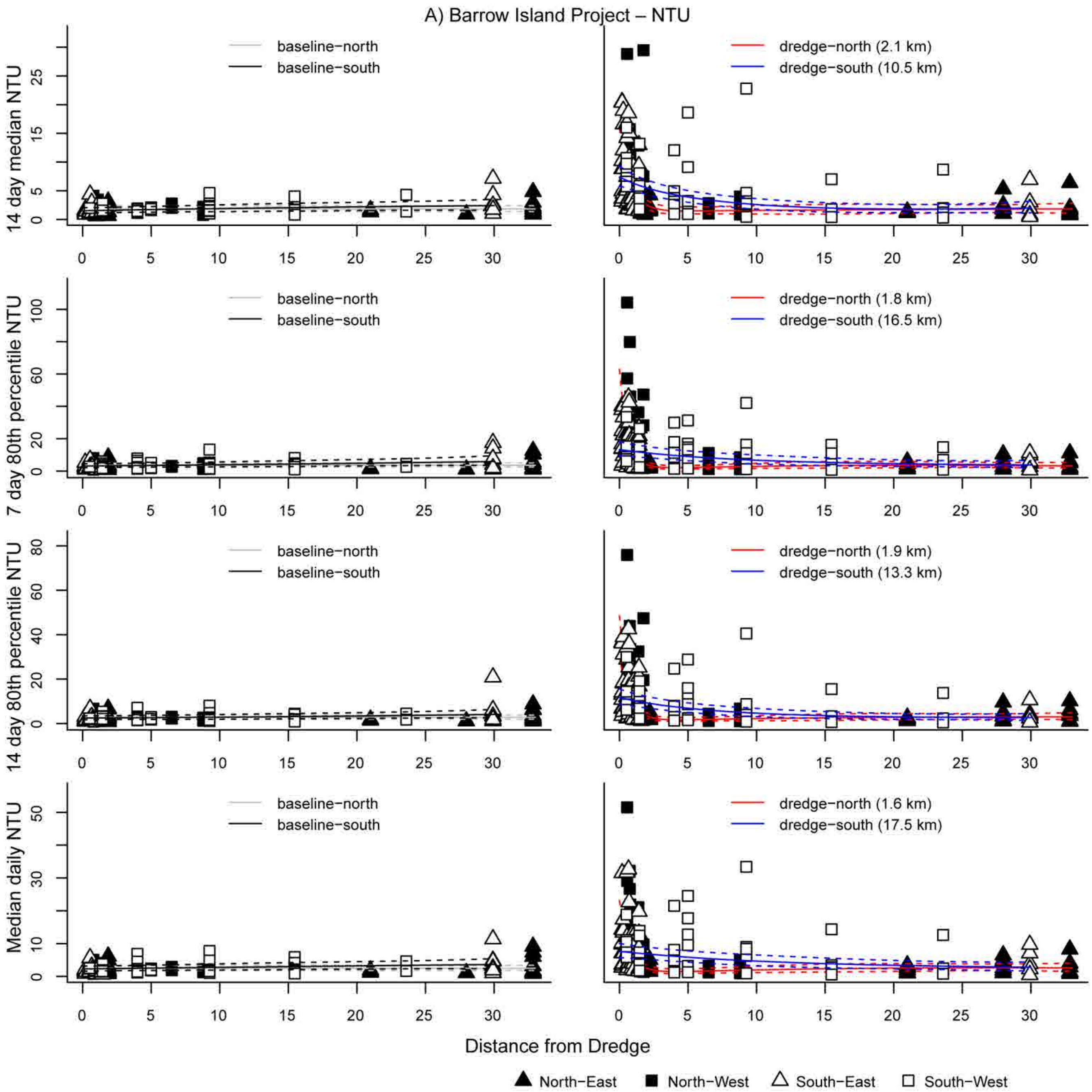


Figure S1.A (part 2). Distance decay relationships for turbidity (NTU) based water quality metrics at Barrow Island. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

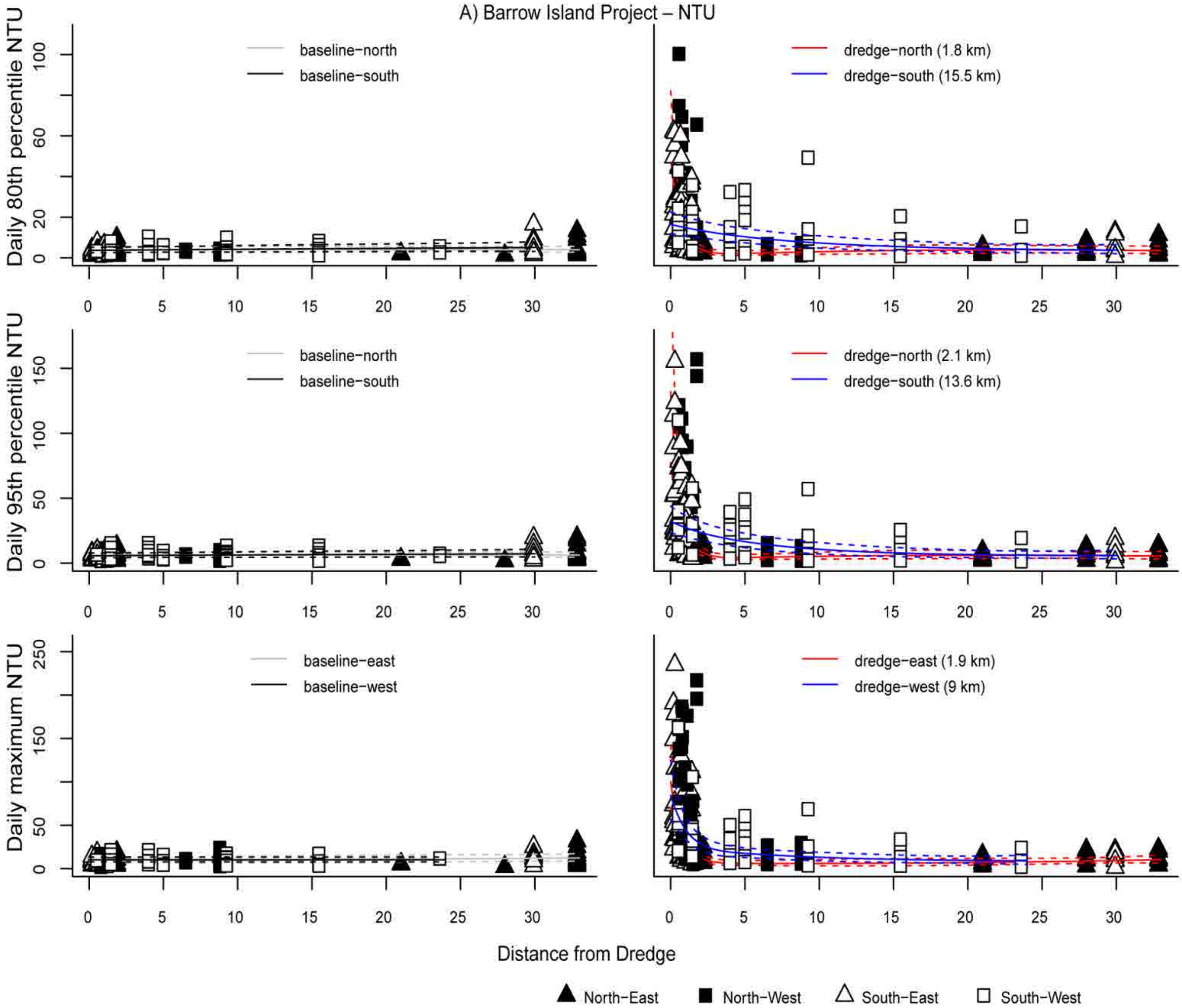


Figure S1.A (part 3). Distance decay relationships for turbidity (NTU) based water quality metrics at Barrow Island. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

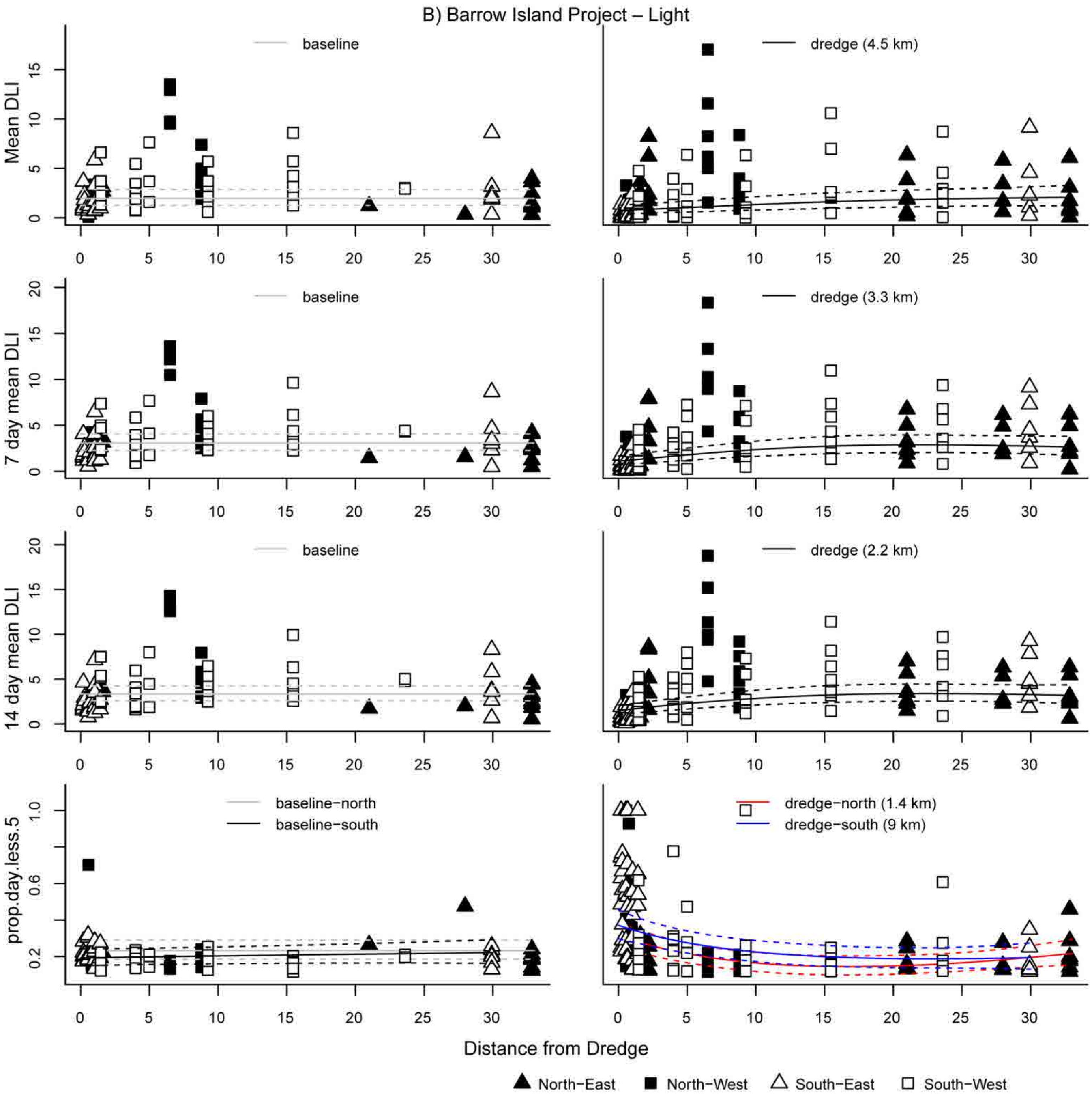


Figure S1.B (part 1). Distance decay relationships for light (PAR) based water quality metrics at Barrow Island. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 5th percentile values for each site and period (baseline or dredge).

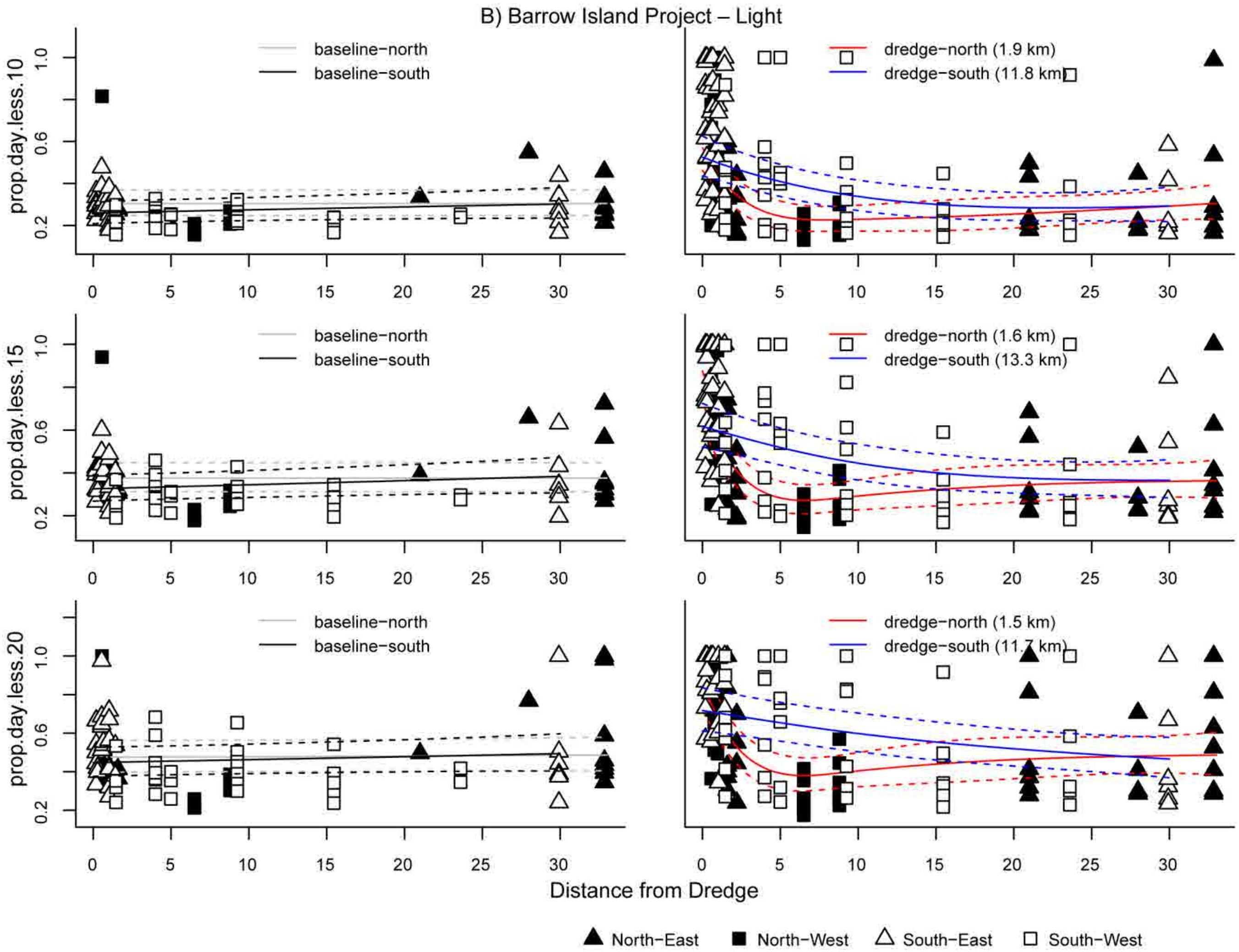


Figure S1.B (part 2). Distance decay relationships for light (PAR) based water quality metrics at Barrow Island. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 5th percentile values for each site and period (baseline or dredge).

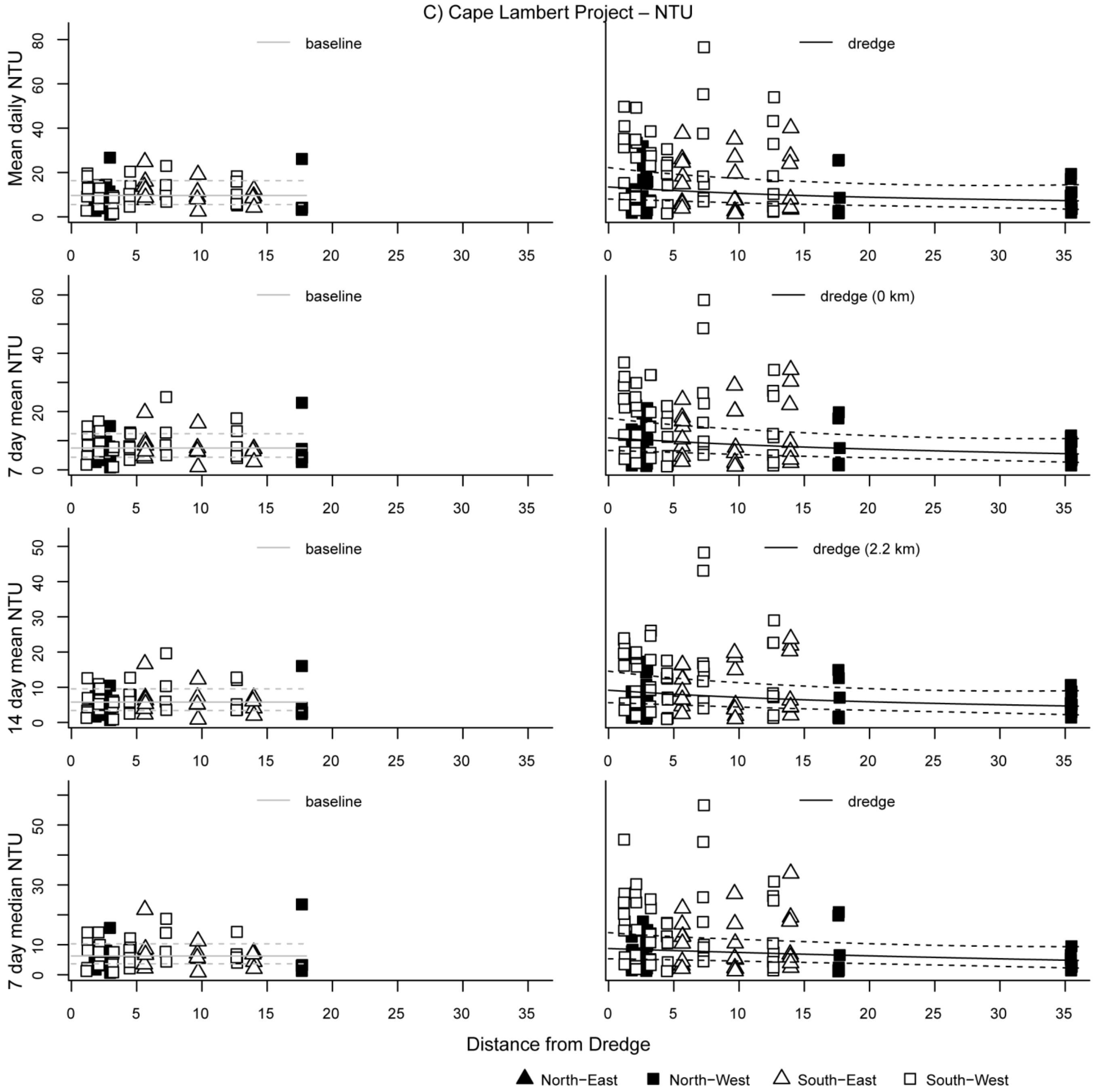


Figure S1.C (part 1). Distance decay relationships for turbidity (NTU) based water quality metrics at Cape Lambert. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80^{th} percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95^{th} percentile values for each site and period (baseline or dredge).

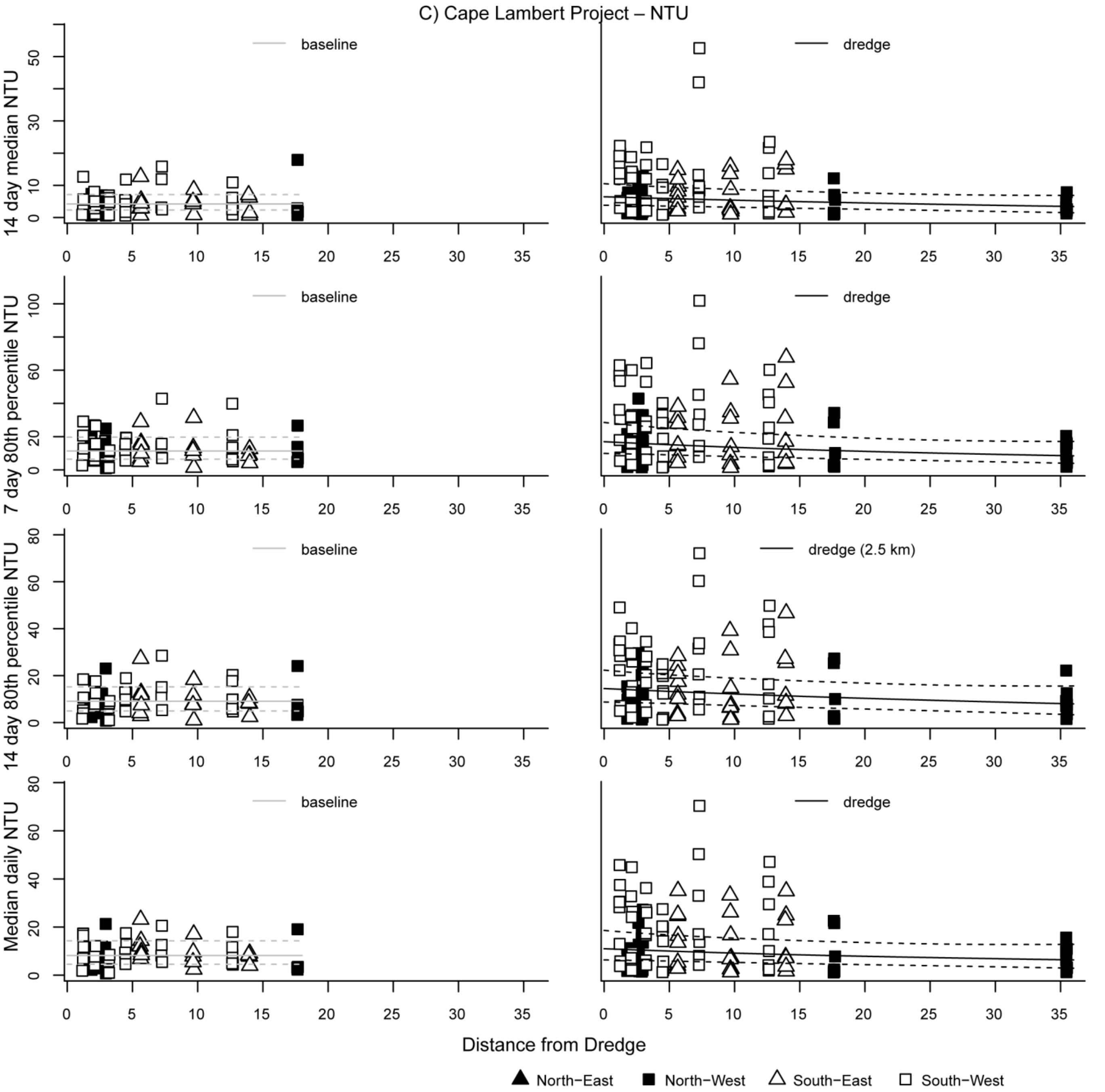


Figure S1.C (part 2). Distance decay relationships for turbidity (NTU) based water quality metrics at Cape Lambert. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

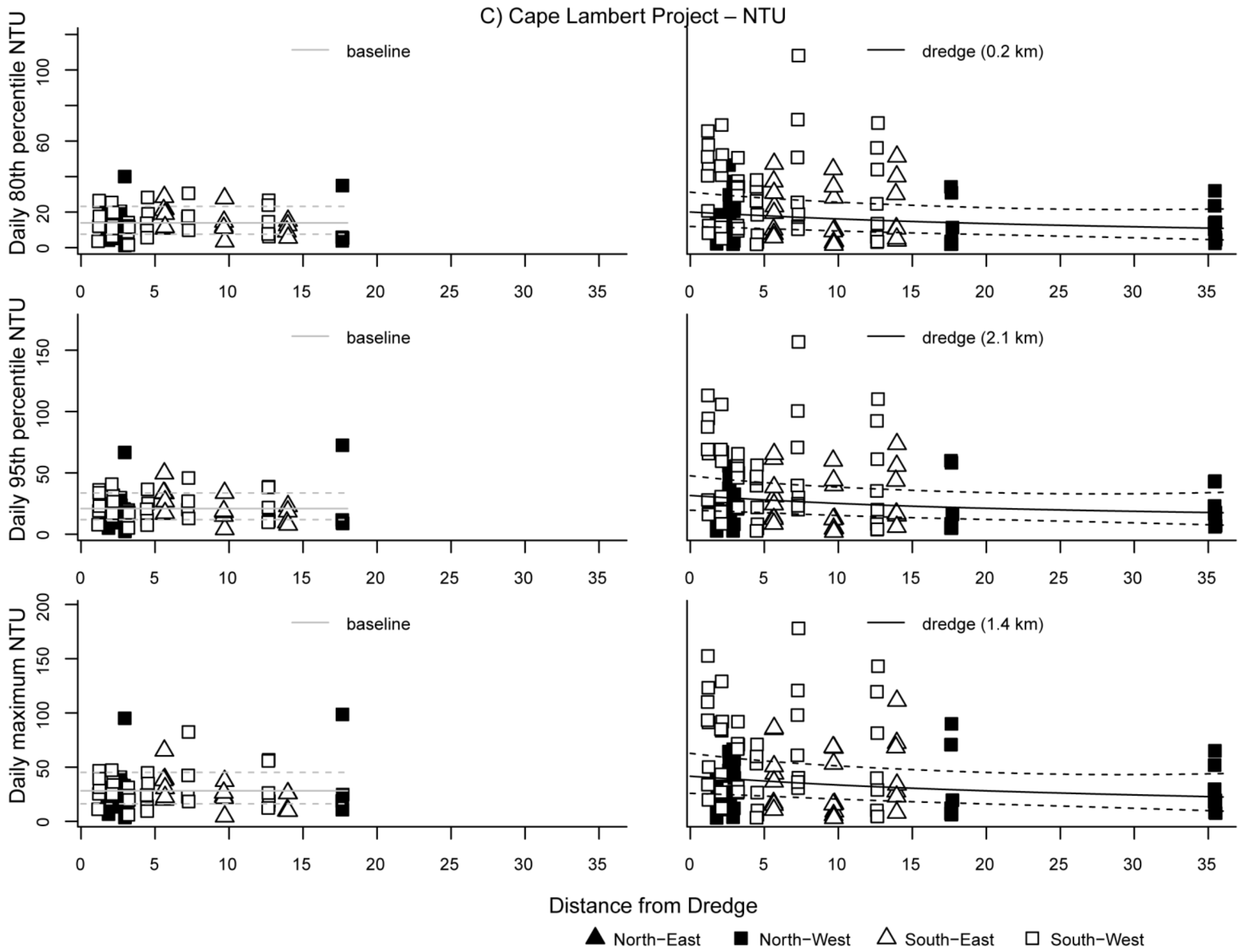


Figure S1.C (part 3). Distance decay relationships for turbidity (NTU) based water quality metrics at Cape Lambert. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

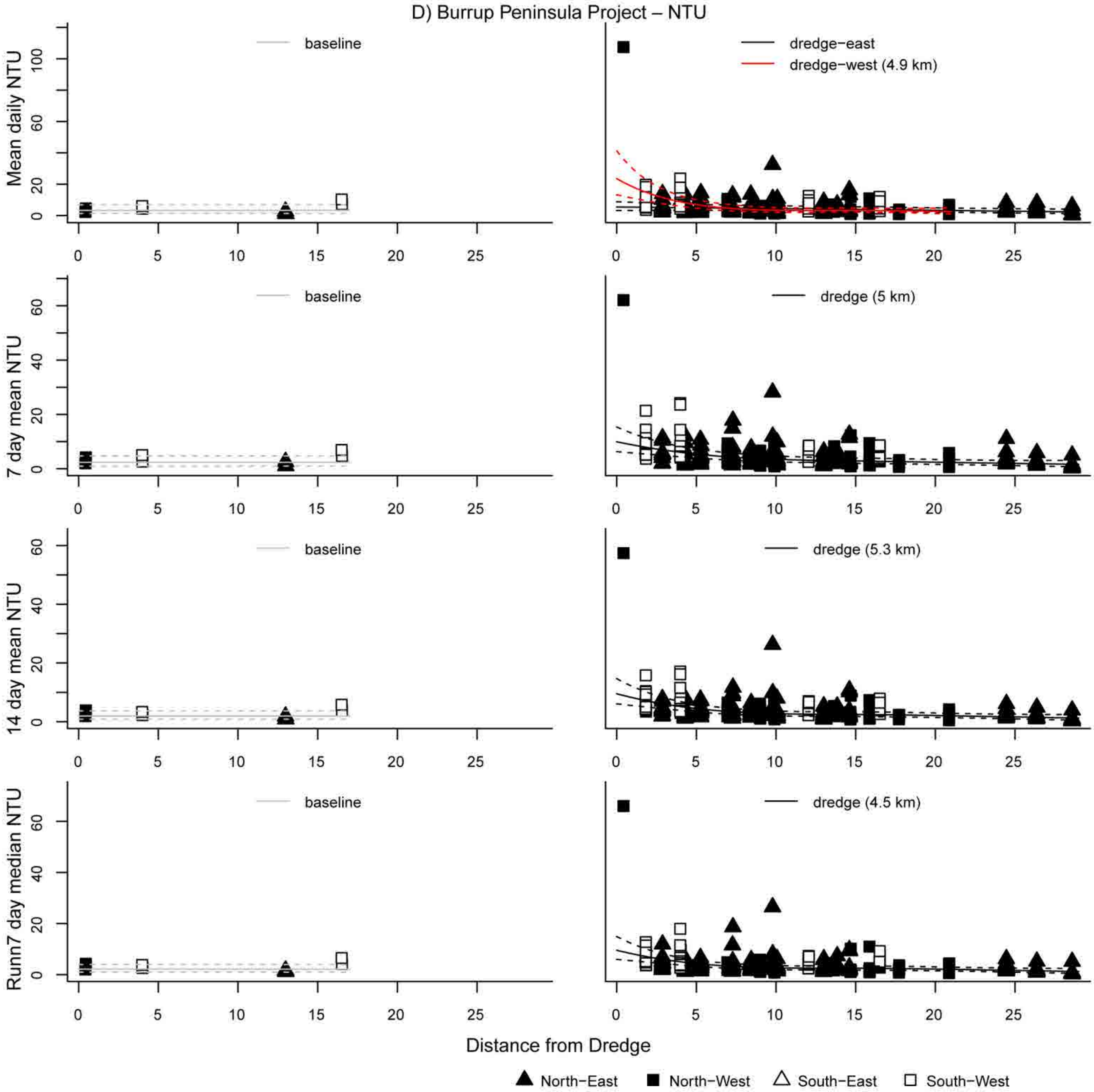


Figure S1.D (part 1). Distance decay relationships for turbidity (NTU) based water quality metrics at Burrup Peninsula. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

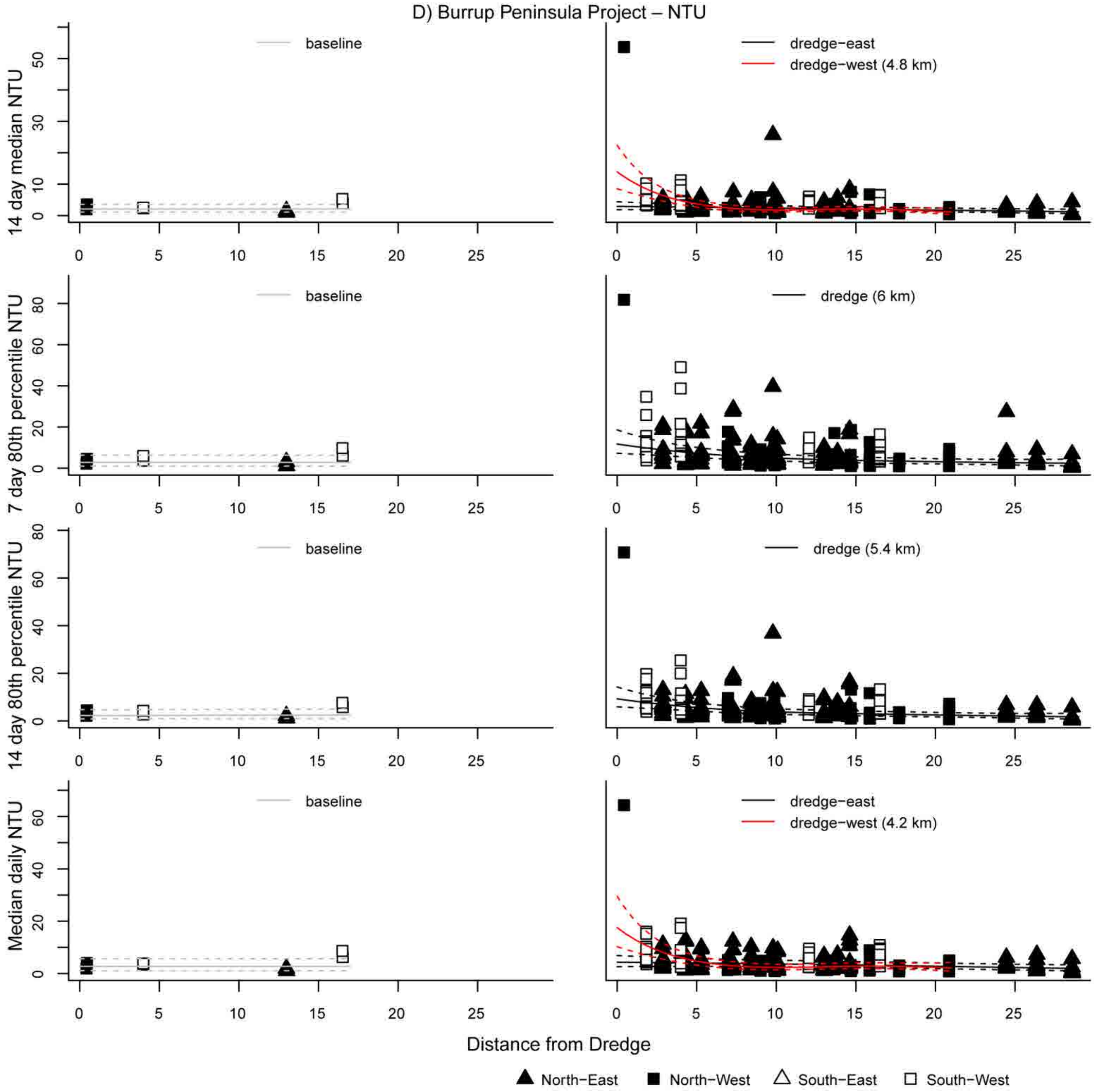


Figure S1.D (part 2). Distance decay relationships for turbidity (NTU) based water quality metrics at Burrup Peninsula. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

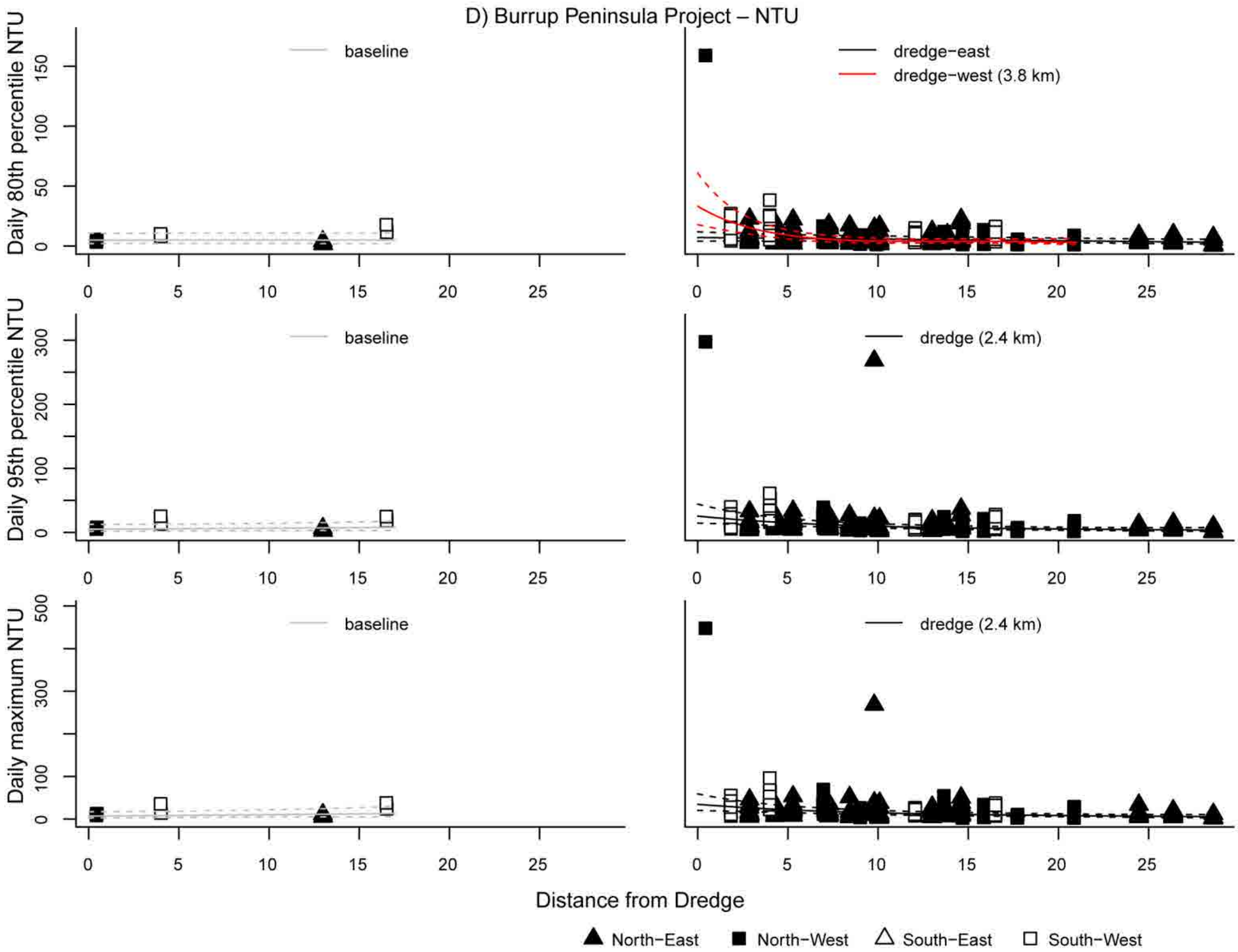


Figure S1.D (part 3). Distance decay relationships for turbidity (NTU) based water quality metrics at Burrup Peninsula. Solid lines represent fitted best fit Generalised Additive Mixed Models (GAMM), with dashed lines indicating 95% confidence bounds for the fitted curves. Baseline and dredge periods were fitted as a two way interaction with distance from dredge, or as a three way interaction as appropriate (North/South or East/West of the location of the primary dredging activity, see methods for further details). Values in parentheses indicate the distance at which the fitted curve falls below the 80th percentile of the baseline value (i.e. the dredging effect becomes negligible). Data points represent quarterly 95th percentile values for each site and period (baseline or dredge).

S1 Table - Detailed summary data

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	Δ1H	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W
Barrow	**Island**	Max	40.1	82.9	2.1	19	16.7	0.9	8.3	8.4	1	6.7	4.4	0.7	6.1	3.5	0.6
Name:	**AHC**	99th	12.2	10.9	0.9	10.9	8.5	0.8	8	7.3	0.9	6.4	4	0.6	6	3.5	0.6
Distn:	32.8	95th	5.1	4.8	0.9	4.7	4.4	0.9	5.4	3.3	0.6	5	2.7	0.5	5.6	3.1	0.6
Depth:	6.9	80th	1.8	1.5	0.8	1.7	1.6	0.9	1.9	1.8	0.9	2.1	1.8	0.8	2.1	1.6	0.8
Base.:	668	Med.	0.9	0.7	0.8	0.9	0.7	0.8	0.9	0.9	1	1	0.9	0.9	1	1.1	1.1
Dred.:	500	Mean	1.6	1.3	0.8	1.5	1.2	0.8	1.6	1.2	0.8	1.6	1.1	0.7	1.6	1.2	0.7
Barrow	**Island**	Max	68.6	68.2	1	15	17.8	1.2	4.3	6.7	1.6	2.8	5.6	2	2.7	4.7	1.7
Name:	**ANT**	99th	4.6	9.3	2	4.2	8.1	1.9	4	6.4	1.6	2.8	5.5	2	2.5	4.7	1.9
Distn:	8.8	95th	2.5	3.8	1.5	2.4	3.7	1.6	2.4	4.7	1.9	2.1	4.1	1.9	2	4.3	2.1
Depth:	3.9	80th	1.7	1.8	1	1.9	2	1.1	1.7	2	1.2	1.6	2.1	1.3	1.6	2.4	1.5
Base.:	756	Med.	1.1	0.9	0.8	1.2	0.9	0.8	1.2	1	0.8	1.3	1	0.8	1.3	1.1	0.8
Dred.:	376	Mean	1.3	1.4	1.1	1.4	1.4	1	1.4	1.5	1.1	1.3	1.5	1.2	1.3	1.6	1.2
Barrow	**Island**	Max	31	72.6	2.3	12	33.3	2.8	5.1	9.1	1.8	4.2	6.5	1.6	4.1	4.6	1.1
Name:	**BAT**	99th	6.9	18.1	2.6	4.9	15.4	3.2	4.3	8	1.9	3.7	4.9	1.3	2.7	3.3	1.2
Distn:	15.5	95th	3.7	5.1	1.4	3.8	5.1	1.3	3.4	5.7	1.7	2.8	3.7	1.3	2.6	2.8	1.1
Depth:	3.7	80th	1.8	1.4	0.8	1.9	1.6	0.8	1.8	1.9	1.1	1.8	2	1.1	1.8	1.8	1
Base.:	611	Med.	1	0.6	0.6	1	0.7	0.6	1.1	0.7	0.6	1.1	0.7	0.6	1.1	0.7	0.6
Dred.:	416	Mean	1.4	1.5	1.1	1.4	1.5	1.1	1.4	1.5	1.1	1.3	1.3	1	1.3	1.1	0.9
Barrow	**Island**	Max	68.6	67.8	1	15	21	1.4	4.3	6.4	1.5	2.8	4.1	1.5	2.7	3	1.1
Name:	**DIW**	99th	4.8	7.9	1.6	4.1	6.3	1.5	4	5.9	1.5	2.8	4	1.5	2.5	3	1.2
Distn:	6.5	95th	2.9	3	1	2.4	3.2	1.3	2.5	3.5	1.4	2.1	3.2	1.5	2.1	2.8	1.3
Depth:	1.9	80th	1.9	1.8	0.9	1.9	1.8	1	1.9	2	1.1	1.8	1.8	1	1.7	1.7	1
Base.:	222	Med.	1.1	0.9	0.8	1.2	0.9	0.8	1.3	1	0.8	1.3	1	0.8	1.2	1	0.8
Dred.:	390	Mean	1.4	1.3	0.9	1.4	1.3	0.9	1.4	1.3	1	1.4	1.3	1	1.3	1.2	0.9
Barrow	**Island**	Max	38.1	82.1	2.2	12.4	56.3	4.6	4.8	31.3	6.6	2.9	29.1	10	2.5	20.6	8.3
Name:	**DUG**	99th	8	38.1	4.7	5.9	38.3	6.5	3.7	28.2	7.5	2.3	26.5	11.3	2.3	20.5	8.7
Distn:	9.2	95th	3.8	14	3.7	3.2	13.9	4.3	2.6	13.6	5.2	2.1	9.6	4.6	2.1	7.2	3.4
Depth:	6	80th	1.7	2.7	1.6	1.6	3.1	1.9	1.6	4.3	2.6	1.7	4.2	2.5	1.7	3.9	2.3
Base.:	786	Med.	1	1	1	1.1	1.1	1	1.1	1.4	1.3	1.2	2.1	1.7	1.3	2.5	1.9
Dred.:	464	Mean	1.4	3	2.2	1.3	3	2.3	1.3	3.2	2.5	1.3	3.2	2.6	1.3	3.1	2.4
Barrow	**Island**	Max	40.1	35.4	0.9	19	19.2	1	8.3	4.7	0.6	6.7	3.1	0.5	6.1	2.8	0.5
Name:	**ELS**	99th	12.1	6.3	0.5	10.9	5.3	0.5	8	4.6	0.6	6.4	3	0.5	6	2.7	0.4
Distn:	21	95th	5	2.7	0.5	4.7	2.7	0.6	5.2	2.2	0.4	5	2.5	0.5	5.3	2.4	0.5
Depth:	7	80th	1.8	1.2	0.7	1.8	1.2	0.7	1.8	1.4	0.8	1.7	1.6	0.9	2.1	1.5	0.7
Base.:	133	Med.	1.1	0.8	0.8	1.1	0.9	0.8	1.2	1	0.8	1.3	1	0.8	1.3	1.2	0.9
Dred.:	361	Mean	1.6	1	0.6	1.6	1.1	0.7	1.6	1.1	0.6	1.7	1.1	0.7	1.7	1.2	0.7
Barrow	**Island**	Max	18.3	180.5	9.9	8.5	66.7	7.8	3.7	34.9	9.3	1.9	25.4	13.3	1.8	21.3	12.2
Name:	**LNG0**	99th	5.6	64	11.4	4.9	42.5	8.7	3.5	31.9	9.1	1.9	24.2	13	1.7	20.6	12.4
Distn:	0.2	95th	2.5	24.6	9.8	2.3	21.7	9.3	2.2	18.6	8.5	1.7	19.6	11.3	1.6	18.2	11.3
Depth:	8.6	80th	1.4	6.4	4.7	1.3	9	6.8	1.5	10.2	7	1.5	10.8	7.3	1.5	11.3	7.6
Base.:	457	Med.	1	2.4	2.5	1.1	3.1	2.9	1.1	3.8	3.3	1.2	4.1	3.5	1.2	4.5	3.7
Dred.:	479	Mean	1.2	6.1	5.3	1.2	6.2	5.2	1.2	6.4	5.2	1.2	6.5	5.5	1.2	6.6	5.6
Barrow	**Island**	Max	25.6	224.3	8.8	13.5	67.3	5	6.9	32.6	4.7	5.1	23.3	4.6	4	18.9	4.7
Name:	**LNG1**	99th	6.3	51.4	8.2	6.5	35.6	5.4	6	27.3	4.6	4.9	21.1	4.3	3.9	18.4	4.7
Distn:	0.5	95th	2.9	20.9	7.3	2.4	18	7.5	2.6	14.6	5.7	2.7	15	5.7	3.6	15.2	4.2
Depth:	8.9	80th	1.4	5.6	4.1	1.4	7.1	5.1	1.3	8.1	6	1.4	8.1	5.8	1.3	7.8	5.8
Base.:	629	Med.	1	2.2	2.2	1	2.7	2.6	1.1	3.8	3.5	1.1	4.3	3.9	1.1	4.3	3.8
Dred.:	481	Mean	1.2	5.2	4.2	1.3	5.2	4.2	1.3	5.3	4.3	1.3	5.4	4.2	1.3	5.4	4
Barrow	**Island**	Max	21.4	128.7	6	8.5	36.7	4.3	2.7	14.3	5.3	2.4	11.3	4.8	2.1	9.5	4.6
Name:	**LNG2**	99th	5.2	31.4	6	3.8	21	5.5	2.6	13.4	5.2	2.3	10.2	4.4	2.1	8.9	4.3
Distn:	1	95th	2.4	13.3	5.7	2.3	11.5	5	1.9	9.8	5.1	1.6	8.4	5.1	1.8	7.6	4.1
Depth:	6.6	80th	1.3	4.5	3.6	1.3	5.4	4	1.4	5.8	4.2	1.4	5.4	4	1.3	5.5	4.2
Base.:	632	Med.	0.9	1.9	2.2	1	2.2	2.3	1.1	2.7	2.5	1.1	2.7	2.5	1.1	3.2	2.9
Dred.:	510	Mean	1	3.8	3.6	1.1	3.7	3.5	1.1	3.7	3.4	1.1	3.6	3.3	1.1	3.6	3.3
Barrow	**Island**	Max	25.7	104.4	4.1	17.9	60.6	3.4	3.2	23.7	7.5	2.2	18.4	8.2	2.3	13.4	5.7
Name:	**LNG3**	99th	8.6	32.4	3.8	5.2	28.3	5.4	3.1	19.3	6.2	2.2	16.4	7.3	2.3	13.3	5.7
Distn:	4	95th	3.2	12.8	4	2.5	12.4	5	2.4	11.9	5	2	9.5	4.6	2	9.5	4.7
Depth:	6.2	80th	1.6	3.2	2	1.6	3.7	2.3	1.5	4.6	3	1.7	4.1	2.4	1.7	4.3	2.5
Base.:	655	Med.	1.1	1.5	1.3	1.2	1.5	1.3	1.2	1.8	1.5	1.2	2	1.7	1.2	2.4	1.9
Dred.:	493	Mean	1.4	3.3	2.3	1.3	3.3	2.5	1.3	3.3	2.6	1.2	3.1	2.5	1.2	3.1	2.5
Barrow	**Island**	Max	18.3	212.6	11.6	8.5	75.2	8.8	3.7	34.3	9.2	1.9	22.4	11.7	1.8	16.5	9.4
Name:	**LNGA**	99th	5.6	71.6	12.8	5	50.6	10.1	3.5	29.8	8.5	1.9	22	11.7	1.7	16.5	9.9

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	Δ1H	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W
Distn:	0.3	95th	2.5	24.7	9.8	2.3	21.9	9.6	2.2	19.7	8.9	1.7	18.8	10.9	1.6	15.4	9.5
Depth:	11.1	80th	1.5	6.2	4.2	1.5	8.7	6	1.6	10	6.4	1.5	10.9	7.3	1.5	10.7	7.2
Base.:	117	Med.	1.1	2.6	2.3	1.2	3.3	2.7	1.3	3.8	2.9	1.4	3.9	2.9	1.4	3.9	2.8
Dred.:	488	Mean	1.3	6.4	5.1	1.3	6.5	5	1.4	6.5	4.6	1.4	6.2	4.6	1.4	6	4.4
Barrow	**Island**	Max	18.3	335.6	18.4	8.5	89.1	10.5	3.7	42	11.2	2.9	27.8	9.5	2.9	22.1	7.7
Name:	**LNGB**	99th	5.6	52.2	9.3	5	40	7.9	3.5	35.4	10.1	2.9	26	8.9	2.8	21.6	7.6
Distn:	0.7	95th	3.1	20.9	6.7	3	18.7	6.3	2.9	14.6	5.1	2.8	11.5	4.2	2.7	10.4	3.8
Depth:	10.2	80th	2.1	5.8	2.7	2.3	7.4	3.2	2.5	9.1	3.7	2.5	7.7	3.1	2.5	6.9	2.8
Base.:	94	Med.	1.1	2.2	2.1	1.1	2.8	2.5	1.3	3.7	2.9	1.3	4.3	3.3	1.4	5.3	3.8
Dred.:	501	Mean	1.4	5.4	3.9	1.4	5.5	3.8	1.5	5.6	3.7	1.5	5.6	3.7	1.5	5.5	3.5
Barrow	**Island**	Max	18.3	173.2	9.5	8.5	63.3	7.4	3.7	25.1	6.7	1.9	18.6	9.7	1.8	13.9	7.9
Name:	**LNGC**	99th	5.3	47.4	8.9	4.8	33.5	7	3.5	20.8	6	1.9	15.4	8.3	1.7	13	7.9
Distn:	1.4	95th	2.3	18.1	7.7	2.2	18.3	8.3	2.2	14.1	6.4	1.7	12.2	7.1	1.6	11	6.9
Depth:	10.7	80th	1.4	5	3.6	1.4	6.3	4.6	1.4	7.3	5.1	1.4	7.1	5.1	1.4	6.8	4.8
Base.:	249	Med.	1.1	2	1.8	1.1	2.3	2.1	1.2	3.1	2.6	1.2	4	3.3	1.2	4.1	3.3
Dred.:	486	Mean	1.2	4.7	4	1.2	4.8	4	1.2	4.8	3.9	1.2	4.8	4	1.2	4.9	4.1
Barrow	**Island**	Max	28.7	34.6	1.2	13	21.6	1.7	3.8	6.3	1.7	2.9	4.2	1.4	2.7	3.4	1.3
Name:	**LOW**	99th	8.4	10.5	1.2	4.8	7.9	1.6	3.2	6.1	1.9	2.8	4.1	1.4	2.6	3.4	1.3
Distn:	1.9	95th	3.6	4.5	1.3	2.9	3.8	1.3	2.5	3.6	1.4	2.4	3.6	1.5	2.4	3.2	1.4
Depth:	2.9	80th	1.7	1.8	1.1	1.7	2	1.2	1.6	2	1.2	1.7	1.9	1.1	1.7	1.8	1.1
Base.:	692	Med.	1	0.8	0.8	1	0.9	0.9	1.2	1.1	0.9	1.3	1.1	0.9	1.3	1.2	0.9
Dred.:	459	Mean	1.4	1.4	1	1.3	1.4	1.1	1.3	1.4	1.1	1.3	1.4	1.1	1.4	1.4	1
Barrow	**Island**	Max	28.7	27.2	0.9	13	16.4	1.3	3.2	4.7	1.5	2.9	3.7	1.3	2.7	2.9	1.1
Name:	**LOW1**	99th	7.8	6.5	0.8	4.1	5.4	1.3	2.9	4.3	1.5	2.8	3.6	1.3	2.6	2.9	1.1
Distn:	1.6	95th	3.3	3	0.9	2.7	3	1.1	2.3	2.5	1.1	2.3	2.6	1.1	2.3	2.8	1.2
Depth:	6.9	80th	1.6	1.7	1.1	1.6	1.7	1.1	1.5	1.7	1.1	1.5	1.8	1.2	1.6	1.9	1.2
Base.:	226	Med.	1	1.1	1	1.1	1.1	1	1.2	1.3	1	1.3	1.3	1	1.2	1.3	1
Dred.:	449	Mean	1.4	1.3	1	1.3	1.3	1	1.3	1.4	1.1	1.3	1.4	1.1	1.3	1.5	1.1
Barrow	**Island**	Max	28.7	34.6	1.2	13	18.4	1.4	3.7	5.8	1.5	2.9	4.9	1.7	2.7	3.8	1.4
Name:	**LOW3**	99th	8.6	8.8	1	4.8	6.8	1.4	3.2	5.1	1.6	2.8	4.6	1.7	2.6	3.6	1.3
Distn:	2.2	95th	3.6	4.1	1.1	2.9	3.8	1.3	2.4	3.5	1.5	2.4	2.8	1.2	2.4	2.6	1.1
Depth:	4.5	80th	1.7	1.8	1.1	1.7	1.9	1.1	1.6	2	1.2	1.7	2	1.2	1.7	1.9	1.1
Base.:	2	Med.	1	1.1	1.1	1.1	1.2	1.1	1.3	1.3	1	1.3	1.2	0.9	1.3	1.2	0.9
Dred.:	460	Mean	1.4	1.5	1.1	1.3	1.5	1.1	1.3	1.5	1.1	1.3	1.4	1	1.4	1.4	1
Barrow	**Island**	Max	19.9	234.3	11.8	10.9	90.9	8.3	3.2	32.5	10	2.5	20	8	2.4	17.2	7.3
Name:	**MOF1**	99th	6.7	56.6	8.4	4.2	36.8	8.8	2.9	19.3	6.6	2.4	16.5	6.9	2.3	15.3	6.6
Distn:	0.8	95th	2.9	18.6	6.4	2.8	15.9	5.7	2.5	14.3	5.7	2.4	14.6	6.2	2.1	13.9	6.6
Depth:	6.2	80th	1.7	5.2	3	1.6	6.7	4.3	1.7	7.8	4.6	1.7	8.9	5.3	1.7	11	6.5
Base.:	678	Med.	1.1	1.9	1.8	1.1	2.5	2.3	1.2	2.7	2.3	1.3	3.1	2.5	1.3	4.2	3.2
Dred.:	505	Mean	1.3	4.9	3.8	1.2	4.9	3.9	1.3	4.7	3.7	1.3	5.2	4	1.3	5.9	4.6
Barrow	**Island**	Max	29.5	106.1	3.6	12.1	51.8	4.3	4.5	12.8	2.9	3.6	4.1	1.1	3.3	3.2	1
Name:	**MOF3**	99th	7.4	29.5	4	6	23.6	3.9	4.1	12.4	3	3.2	4	1.3	3	3.2	1.1
Distn:	1.5	95th	3.4	12.2	3.6	3.5	12.3	3.5	3.2	7.6	2.4	3	3.9	1.3	2.9	3.2	1.1
Depth:	4.8	80th	1.6	3.5	2.1	2	4.2	2.1	2.6	4.9	1.8	2.7	2.4	0.9	2.8	2.3	0.8
Base.:	657	Med.	1	1.5	1.5	1.1	1.8	1.6	1.3	2.1	1.6	1.3	1.9	1.5	1.3	1.9	1.5
Dred.:	487	Mean	1.3	3.2	2.4	1.5	3.4	2.3	1.6	3	1.9	1.6	2	1.2	1.7	2	1.2
Barrow	**Island**	Max	19.9	433.9	21.8	10.9	178.8	16.3	3.3	75.8	22.7	2.5	47.4	18.9	2.4	33.7	14.2
Name:	**MOFA**	99th	6.7	90.1	13.4	4.2	72.4	17.1	3	65	21.5	2.4	44.4	18.4	2.3	33.7	14.5
Distn:	0.6	95th	3	28.3	9.6	2.8	26.8	9.5	2.5	21.7	8.8	2.3	26.5	11.3	2.1	27.5	13
Depth:	4.9	80th	1.9	6	3.1	1.9	6.9	3.7	1.9	9.1	4.8	1.9	8.4	4.4	1.9	7.3	4
Base.:	144	Med.	1.3	2.3	1.9	1.3	2.9	2.3	1.4	3.2	2.3	1.4	3.3	2.3	1.4	3.4	2.5
Dred.:	471	Mean	1.5	7	4.9	1.4	7	5	1.4	6.8	4.8	1.4	6.4	4.5	1.4	6.1	4.3
Barrow	**Island**	Max	19.9	165.4	8.3	10.9	76.3	7	3.2	28.7	8.8	2.5	17.3	6.8	2.4	10.1	4.3
Name:	**MOFB**	99th	7	45	6.5	4.2	29.5	7.1	3	16.4	5.5	2.5	12.6	5.1	2.3	10	4.3
Distn:	1	95th	3.1	13.2	4.3	3	14.4	4.8	2.5	11	4.3	2.4	7.8	3.3	2.1	6.5	3.1
Depth:	7.5	80th	1.9	4.2	2.2	1.8	4.9	2.8	1.8	5.8	3.3	1.8	5.7	3.2	1.7	5.4	3.1
Base.:	130	Med.	1.3	1.9	1.5	1.3	2.3	1.8	1.4	2.8	2.1	1.4	3	2.2	1.4	3	2.1
Dred.:	521	Mean	1.5	4.1	2.8	1.4	4.1	2.9	1.4	4.1	2.9	1.4	3.8	2.8	1.4	3.6	2.6
Barrow	**Island**	Max	19.9	370.3	18.6	10.9	152.9	14	3.2	56	17.3	2.8	32.9	11.7	2.8	26.4	9.5
Name:	**MOFC**	99th	6.7	78.8	11.8	4.2	50.3	11.9	2.9	46.6	15.9	2.8	31.6	11.4	2.8	25.1	9
Distn:	0.8	95th	3.1	25.2	8.1	2.9	25.4	8.8	2.8	20.7	7.4	2.8	19	6.9	2.8	23.4	8.5
Depth:	6.9	80th	2.1	6.4	3	2.1	7.8	3.6	2.3	11.1	4.8	2.2	11.4	5.1	2.1	12.4	5.9
Base.:	121	Med.	1.2	2.2	1.8	1.2	3	2.4	1.3	3.7	2.8	1.4	5.3	3.9	1.4	7.2	5.2

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	Δ1H	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W
Dred.:	460	Mean	1.5	6.5	4.4	1.5	6.6	4.5	1.5	6.9	4.7	1.5	7.4	4.9	1.5	8	5.2
Barrow	**Island**	Max	40.1	51.6	1.3	19	30.1	1.6	8.3	7.6	0.9	6.7	6.4	1	6.1	4.7	0.8
Name:	**REFN**	99th	12	12.4	1	10.8	12	1.1	8	6.8	0.9	6.4	6.3	1	6	4.7	0.8
Distn:	28	95th	5	4.8	0.9	4.7	4.4	0.9	5.3	5.7	1.1	5	3.7	0.7	5.6	3.4	0.6
Depth:	7.2	80th	1.7	1.9	1.1	1.7	2.1	1.2	1.9	2.2	1.2	2	2.4	1.2	2.2	2.4	1.1
Base.:	91	Med.	0.9	0.9	1	0.9	0.9	1.1	0.9	1	1.1	1	1.2	1.2	1	1.3	1.3
Dred.:	370	Mean	1.5	1.5	1	1.5	1.5	1	1.5	1.6	1	1.6	1.6	1	1.6	1.6	1
Barrow	**Island**	Max	75.2	37.5	0.5	30.4	20.9	0.7	12.3	11.5	0.9	9.2	7.9	0.9	8.3	6	0.7
Name:	**REFS**	99th	19.4	14.5	0.7	16.8	13.4	0.8	12	10.8	0.9	9.1	6.7	0.7	7.9	5.3	0.7
Distn:	23.6	95th	7.5	5.4	0.7	6.8	4.8	0.7	7.3	3.9	0.5	8	3.2	0.4	5.9	3.6	0.6
Depth:	5	80th	3.9	1.8	0.5	3.9	1.8	0.5	4	1.9	0.5	4	1.8	0.5	4.1	1.7	0.4
Base.:	146	Med.	1.8	0.8	0.5	1.8	0.9	0.5	2	1	0.5	2	1.1	0.5	2.2	1.4	0.7
Dred.:	374	Mean	2.8	1.5	0.5	2.6	1.5	0.6	2.6	1.4	0.5	2.8	1.4	0.5	2.9	1.4	0.5
Barrow	**Island**	Max	75.2	44.6	0.6	30.4	31.4	1	12.3	8.4	0.7	9.2	6.6	0.7	8.3	5.1	0.6
Name:	**SBS**	99th	19.7	12.2	0.6	17.8	11.2	0.6	12	7.7	0.6	9.1	5.2	0.6	7.9	4	0.5
Distn:	29.9	95th	7.7	5	0.6	7.1	4.7	0.7	7.6	3.8	0.5	7.9	3.2	0.4	5.9	2.9	0.5
Depth:	4.7	80th	3.4	2.1	0.6	3.4	2.1	0.6	3.5	2.4	0.7	3.6	2.3	0.6	3.5	2.1	0.6
Base.:	599	Med.	1.5	1	0.7	1.6	1.1	0.7	1.7	1.2	0.7	1.8	1.3	0.8	1.9	1.4	0.7
Dred.:	454	Mean	2.5	1.6	0.6	2.4	1.6	0.7	2.4	1.6	0.6	2.5	1.5	0.6	2.5	1.4	0.6
Barrow	**Island**	Max	28.7	242.8	8.5	5.1	81.3	16	2	24.8	12.3	1.4	3.6	2.6	1.2	2	1.6
Name:	**T1**	99th	4.1	33.6	8.3	4.1	22	5.3	2	15.4	7.7	1.4	3.4	2.5	1.2	2	1.6
Distn:	1.8	95th	2	5.1	2.6	1.8	4.7	2.6	1.9	3.5	1.8	1.4	3.2	2.4	1.2	2	1.6
Depth:	6.6	80th	1.2	2.8	2.3	1.1	2.8	2.5	1.4	2.7	1.9	1.4	2.1	1.6	1.2	2	1.6
Base.:	81	Med.	0.9	1.7	1.9	0.9	1.7	1.9	0.9	1.8	1.9	1.3	1.9	1.5	1.2	2	1.6
Dred.:	558	Mean	1.1	3.2	2.9	1.1	2.6	2.4	1.1	2.2	2	1.2	1.8	1.6	1.2	2	1.6
Barrow	**Island**	Max	70.6	161.8	2.3	7.7	20.4	2.7	1	3.7	3.7	-	2.9	-	-	1.8	-
Name:	**T2**	99th	4.6	11.5	2.5	7.4	10.1	1.4	1	3.6	3.7	-	2.7	-	-	1.8	-
Distn:	1.5	95th	2.1	4.5	2.1	3.5	4.2	1.2	1	3.2	3.2	-	2.6	-	-	1.8	-
Depth:	6.6	80th	1.2	2.8	2.3	1.1	2.8	2.6	1	2.6	2.6	-	2.2	-	-	1.7	-
Base.:	81	Med.	0.9	1.9	2.1	1	2.1	2.1	1	2.1	2.1	-	1.7	-	-	1.6	-
Dred.:	455	Mean	1.2	2.5	2.1	1.3	2.4	1.8	1	2.2	2.2	-	1.8	-	-	1.6	-
Barrow	**Island**	Max	16.1	372	23.1	4.8	63.1	13.1	3.7	16	4.3	1	9.1	9.3	-	6.8	-
Name:	**T3**	99th	5.9	17.5	2.9	3.8	18.6	4.9	3.7	15.6	4.3	1	9.1	9.3	-	6.8	-
Distn:	1.1	95th	3.7	5	1.3	3.6	5.5	1.6	3.5	6.9	1.9	1	7.9	8	-	6.8	-
Depth:	6.6	80th	3.2	2.8	0.9	3.2	3	0.9	3.4	3.3	1	1	4.5	4.6	-	6	-
Base.:	81	Med.	1.1	2	1.8	1.1	2.1	1.8	1	2.4	2.3	1	2.4	2.5	-	3.9	-
Dred.:	511	Mean	1.8	3	1.6	1.8	2.8	1.6	1.6	3.1	1.9	1	3.4	3.5	-	3.8	-
Barrow	**Island**	Max	5.7	227.1	40.1	1.9	33.3	17.5	1.2	15	12.4	1	8.6	8.3	-	8	-
Name:	**T4**	99th	2.5	24.1	9.7	1.7	17.8	10.2	1.2	14.7	12.5	1	7.3	7.1	-	7.9	-
Distn:	0.9	95th	1.7	10.9	6.3	1.5	9.4	6.4	1.1	8.5	7.7	1	7	7	-	7.3	-
Depth:	6.6	80th	1.1	5.9	5.2	1.1	6.4	6	1	6.4	6.6	0.9	6.2	7	-	7	-
Base.:	81	Med.	0.8	3.6	4.5	0.8	3.8	4.5	0.8	4.2	5	0.7	3.2	4.5	-	3.3	-
Dred.:	548	Mean	0.9	4.7	5.1	0.9	4.6	5.1	0.8	4.5	5.3	0.8	4.1	5.1	-	4.5	-
Barrow	**Island**	Max	16.5	237.6	14.4	3.1	62.8	20.3	1.2	23	18.9	1.2	17.9	15.4	-	13.6	-
Name:	**T5**	99th	3.6	48.7	13.6	3	39.7	13.2	1.2	17.3	14.3	1.2	15.9	13.7	-	11.1	-
Distn:	0.7	95th	2	19.4	9.5	2.8	18.2	6.5	1.2	14	11.5	1.2	11.3	9.7	-	9	-
Depth:	6.6	80th	1.4	6.7	4.7	1.3	8	6.1	1.2	8.7	7.3	1.2	9.2	7.9	-	8.3	-
Base.:	81	Med.	1.1	3.9	3.4	1.2	4.4	3.7	1.1	5.8	5.2	1.2	6.7	5.7	-	6.9	-
Dred.:	558	Mean	1.3	6.5	5.1	1.3	6.5	5	1.1	6.6	5.8	1.2	7.1	6.1	-	7.1	-
Barrow	**Island**	Max	23.7	261.1	11	3	47	15.6	-	19.2	-	-	14.2	-	-	-	-
Name:	**T6**	99th	5.6	43.5	7.8	3	30.6	10.2	-	18.5	-	-	14.1	-	-	-	-
Distn:	0.5	95th	3.6	18.7	5.2	2.9	17.2	5.8	-	14.9	-	-	14	-	-	-	-
Depth:	6.6	80th	2.3	8.3	3.5	2.2	8.9	4	-	10	-	-	7.5	-	-	-	-
Base.:	79	Med.	1.5	5	3.4	1.6	5.7	3.6	-	6.4	-	-	6.3	-	-	-	-
Dred.:	523	Mean	1.8	7.1	4	1.8	7.3	4.2	-	7.5	-	-	7.5	-	-	-	-
Barrow	**Island**	Max	15.4	202.9	13.2	5.5	65.7	12	1.1	25.1	23.5	-	8.6	-	-	6.5	-
Name:	**T7**	99th	7.1	37.6	5.3	5.3	28.6	5.4	1.1	14.1	13.2	-	8.5	-	-	6.5	-
Distn:	1.4	95th	2.2	13	5.9	4.3	13.8	3.2	1.1	10.8	10.2	-	8.2	-	-	6.5	-
Depth:	6.6	80th	1.4	5.1	3.8	1.5	5.7	3.9	1.1	7.2	6.8	-	5.8	-	-	6.3	-
Base.:	74	Med.	1.1	3.2	2.9	1.2	3.3	2.8	1.1	3.9	3.6	-	4.3	-	-	5.2	-
Dred.:	566	Mean	1.3	4.9	3.7	1.5	4.9	3.3	1.1	4.8	4.5	-	4.7	-	-	5.4	-
Barrow	**Island**	Max	38.1	119.4	3.1	12.4	72.3	5.9	4.8	27	5.7	2.3	22.3	9.5	2.4	16.2	6.9
Name:	**TR**	99th	8	35.4	4.4	5.8	31.2	5.3	3.6	22.6	6.2	2.3	20.6	9	2.2	16	7.2

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	**Details**	**Stat.**	**B1H**	**D1H**	**Δ1H**	**B1D**	**D1D**	**Δ1D**	**B1W**	**D1W**	**Δ1W**	**B2W**	**D2W**	**Δ2W**	**B3W**	**D3W**	**Δ3W**
Distn:	5	95th	3.7	17.3	4.7	3.1	17.4	5.6	2.6	12.8	4.9	2	10.7	5.3	2.1	10.5	5.1
Depth:	4.5	80th	1.6	3.5	2.2	1.6	3.9	2.4	1.6	5.8	3.6	1.7	4.9	2.9	1.7	4	2.4
Base.:	267	Med.	1	1.4	1.4	1	1.5	1.5	1.1	1.9	1.7	1.1	1.8	1.7	1.1	1.8	1.6
Dred.:	450	Mean	1.3	3.7	2.8	1.3	3.7	2.8	1.3	3.7	2.9	1.2	3.4	2.7	1.3	2.9	2.3

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	Δ1H	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W
Site	**Details**	**Stat.**	**B1H**	**D1H**	**Δ1H**	**B1D**	**D1D**	**Δ1D**	**B1W**	**D1W**	**Δ1W**	**B2W**	**D2W**	**Δ2W**	**B3W**	**D3W**	**Δ3W**
Burrup.	**Penin.**	Max	13.4	53.1	4	7.8	26.1	3.4	2.7	11.2	4.1	1.7	8.4	4.9	1.3	7	5.3
Name:	**ANG2**	99th	5.5	11.3	2.1	5.3	9.8	1.8	2.7	8.6	3.2	1.7	7.8	4.7	1.3	6.6	5
Distn:	10.1	95th	2.4	4	1.6	1.9	4	2.1	2.2	4.3	2	1.5	4.5	2.9	1.3	4.3	3.3
Depth:	2.6	80th	1.5	1.5	1	1.5	1.5	1	1.5	1.8	1.2	1.3	1.6	1.2	1.2	1.5	1.2
Base.:	15	Med.	0.9	0.9	1	1	0.9	0.9	0.9	1	1.1	0.9	1	1.1	1.1	1	0.9
Dred.:	887	Mean	1.1	1.4	1.3	1.1	1.4	1.3	1	1.5	1.4	1	1.4	1.5	1	1.4	1.4
Burrup.	**Penin.**	Max	-	268.2	-	-	37.7	-	-	14	-	-	10.4	-	-	8.8	-
Name:	**ANG3**	99th	-	16.5	-	-	12.5	-	-	12.7	-	-	10.2	-	-	8.6	-
Distn:	9.8	95th	-	6.5	-	-	6.6	-	-	7.3	-	-	9	-	-	7.8	-
Depth:	0.8	80th	-	2.7	-	-	2.9	-	-	2.8	-	-	3	-	-	3.1	-
Base.:	0	Med.	-	1.9	-	-	2.1	-	-	2.2	-	-	2.2	-	-	2.3	-
Dred.:	892	Mean	-	2.9	-	-	2.7	-	-	2.8	-	-	2.9	-	-	3	-
Burrup.	**Penin.**	Max	13.4	96.6	7.2	7.8	19.5	2.5	2.7	8.5	3.1	1.7	5.7	3.3	1.3	4.1	3.1
Name:	**ANGI**	99th	5.4	9.5	1.8	5.3	10.4	1.9	2.7	6.3	2.3	1.7	5.4	3.2	1.3	4	3
Distn:	13	95th	2.4	3.6	1.5	1.9	3.7	2	2.2	4.4	2	1.5	3.8	2.5	1.3	3.8	2.9
Depth:	5.6	80th	1.4	1.3	0.9	1.4	1.3	0.9	1.4	1.4	1	1.3	1.4	1.1	1.2	1.8	1.4
Base.:	123	Med.	0.9	0.7	0.8	0.9	0.8	0.8	0.9	0.9	0.9	0.9	0.9	1	1.1	0.9	0.8
Dred.:	922	Mean	1.1	1.2	1.1	1.1	1.2	1.2	1	1.2	1.2	1	1.2	1.3	1	1.3	1.3
Burrup.	**Penin.**	Max	15.2	463.1	30.5	5.8	118.4	20.5	4.2	60.5	14.2	3.9	56.8	14.6	-	46.3	-
Name:	**CHC4**	99th	6.6	196.2	29.6	5.1	113.5	22.1	4.2	60.4	14.2	3.9	56.5	14.5	-	46.3	-
Distn:	0.4	95th	4.7	113.1	24.1	4.2	95.8	22.6	4.1	58.1	14	3.9	55.6	14.3	-	46.2	-
Depth:	1.9	80th	3	53	17.4	3.3	54.6	16.6	3.7	51.9	14.1	3.9	50.4	13.1	-	46.1	-
Base.:	96	Med.	1.4	21.4	15.4	1.4	27.6	19.4	2	43.9	22	3.8	45	11.8	-	45.9	-
Dred.:	49	Mean	1.9	35.4	18.4	2	34.9	17.7	2.5	34.6	13.7	3.8	42.3	11.1	-	45.8	-
Burrup.	**Penin.**	Max	13.4	183.1	13.7	7.8	26.2	3.4	2.7	10	3.7	1.9	6.6	3.4	1.3	5.5	4.2
Name:	**COBN**	99th	5.4	9.9	1.8	5.3	9.2	1.7	2.7	7	2.6	1.9	5.5	2.9	1.3	4.9	3.7
Distn:	8.4	95th	2.5	4.4	1.7	2.2	4.3	2	2.2	4.3	2	1.6	4.2	2.6	1.3	4.2	3.2
Depth:	2.5	80th	1.6	2.2	1.4	1.6	2.2	1.3	1.5	2.5	1.6	1.3	2.4	1.8	1.2	2.2	1.7
Base.:	15	Med.	0.9	1.3	1.4	1	1.3	1.4	0.9	1.3	1.5	0.9	1.3	1.4	1.1	1.2	1.1
Dred.:	971	Mean	1.2	1.8	1.6	1.1	1.8	1.6	1.1	1.8	1.7	1	1.8	1.8	1	1.7	1.7
Burrup.	**Penin.**	Max	-	143.4	-	-	50.2	-	-	16.2	-	-	9.1	-	-	1.7	-
Name:	**CONI**	99th	-	18.8	-	-	19.9	-	-	11.5	-	-	7.9	-	-	1.7	-
Distn:	7.3	95th	-	5.5	-	-	5.6	-	-	4.9	-	-	3.9	-	-	1.7	-
Depth:	2.8	80th	-	2.5	-	-	2.6	-	-	2	-	-	1.6	-	-	1.4	-
Base.:	0	Med.	-	1.5	-	-	1.3	-	-	1.1	-	-	1.1	-	-	1.1	-
Dred.:	884	Mean	-	2.3	-	-	2.3	-	-	1.7	-	-	1.5	-	-	1.1	-
Burrup.	**Penin.**	Max	-	92.3	-	-	38.1	-	-	14.7	-	-	9.2	-	-	6.5	-
Name:	**CRTS**	99th	-	9.9	-	-	10.3	-	-	11.6	-	-	8.8	-	-	6.5	-
Distn:	14.7	95th	-	2.3	-	-	2.1	-	-	3.4	-	-	5.6	-	-	5.9	-
Depth:	5.5	80th	-	1.2	-	-	1.2	-	-	1.2	-	-	1.2	-	-	1.5	-
Base.:	0	Med.	-	0.7	-	-	0.8	-	-	0.8	-	-	0.8	-	-	0.8	-
Dred.:	982	Mean	-	1.1	-	-	1.1	-	-	1.2	-	-	1.3	-	-	1.4	-
Burrup.	**Penin.**	Max	15.2	187.9	12.4	5.8	79	13.7	4.2	55.5	13.1	3.9	43.2	11.1	-	35.6	-
Name:	**DPAN**	99th	6.7	101.3	15.2	5.1	77.4	15.1	4.2	55.4	13.1	3.9	43	11	-	35.5	-
Distn:	0.6	95th	4.7	71.4	15.3	4.2	66.3	15.7	4.1	53	12.8	3.9	42.6	10.9	-	34.8	-
Depth:	0	80th	3	48.3	15.9	3.3	50.9	15.6	3.7	47.7	12.9	3.9	39.6	10.3	-	31.6	-
Base.:	5	Med.	1.4	29.3	21.3	1.4	30.7	21.5	2	34.4	17.2	3.8	37.5	9.9	-	30.2	-
Dred.:	47	Mean	1.9	31.3	16.5	2	31.2	16	2.5	32.9	13	3.8	36.3	9.6	-	30.6	-
Burrup.	**Penin.**	Max	-	111.3	-	-	32	-	-	10.6	-	-	6.6	-	-	5	-
Name:	**ELI1**	99th	-	16.2	-	-	11	-	-	6.8	-	-	5.5	-	-	4.9	-
Distn:	7	95th	-	4	-	-	4.3	-	-	3.3	-	-	2.5	-	-	2.2	-
Depth:	3.5	80th	-	1.8	-	-	2.1	-	-	2.2	-	-	2.1	-	-	1.9	-
Base.:	0	Med.	-	1.2	-	-	1.3	-	-	1.6	-	-	1.6	-	-	1.6	-
Dred.:	908	Mean	-	1.8	-	-	1.8	-	-	1.8	-	-	1.7	-	-	1.7	-
Burrup.	**Penin.**	Max	13.4	28.8	2.2	7.8	9.2	1.2	2.7	7.7	2.8	1.9	5.3	2.8	1.3	4.8	3.6
Name:	**FFP1**	99th	5.6	7.6	1.3	5.3	5.9	1.1	2.7	5.2	1.9	1.9	5.2	2.8	1.3	4.7	3.5
Distn:	13.8	95th	2.6	4.1	1.6	2.2	3.9	1.8	2.2	3.5	1.6	1.6	3.6	2.2	1.3	3.7	2.9
Depth:	2.5	80th	1.6	2.4	1.5	1.6	2.3	1.5	1.5	2.3	1.5	1.4	2.1	1.5	1.2	2.1	1.7
Base.:	16	Med.	0.9	1.5	1.6	1	1.6	1.6	0.9	1.7	1.8	0.9	1.7	1.9	1.1	1.7	1.5
Dred.:	984	Mean	1.2	1.9	1.6	1.1	1.9	1.6	1.1	1.9	1.7	1	1.9	1.9	1	1.9	1.9

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	Δ1H	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W
Burrup.	**Penin.**	Max	13.4	253.5	19	7.8	40.6	5.2	2.7	16	5.9	1.7	11.3	6.6	1.3	8.7	6.6
Name:	**GIDI**	99th	5.4	16.3	3	5.4	16.1	3	2.7	11.7	4.3	1.7	10	6	1.3	8.5	6.4
Distn:	14.6	95th	2.4	5.6	2.4	1.9	5.4	2.8	2.4	7.1	3	1.5	6.7	4.4	1.3	5.7	4.3
Depth:	5	80th	1.4	2	1.4	1.4	2	1.4	1.4	2	1.4	1.3	1.9	1.4	1.2	2	1.6
Base.:	10	Med.	0.8	0.9	1.1	0.9	1.1	1.2	0.9	1.2	1.4	0.9	1.2	1.4	1.1	1.3	1.1
Dred.:	956	Mean	1.1	1.8	1.7	1	1.8	1.7	1	1.9	1.9	1	1.8	1.9	1	1.9	1.9
Burrup.	**Penin.**	Max	-	263.4	-	-	57.5	-	-	2.9	-	-	1.9	-	-	1.6	-
Name:	**HAM3**	99th	-	8.2	-	-	6.2	-	-	2.6	-	-	1.8	-	-	1.5	-
Distn:	24.5	95th	-	3.7	-	-	3.1	-	-	1.8	-	-	1.4	-	-	1.2	-
Depth:	7.4	80th	-	1.8	-	-	1.6	-	-	1.2	-	-	1.1	-	-	1	-
Base.:	0	Med.	-	1.1	-	-	1	-	-	0.9	-	-	0.9	-	-	0.9	-
Dred.:	843	Mean	-	1.6	-	-	1.3	-	-	1	-	-	0.9	-	-	0.9	-
Burrup.	**Penin.**	Max	13.4	36.9	2.8	7.8	13.8	1.8	2.7	6.6	2.4	1.7	5	2.9	1.3	4.2	3.2
Name:	**HAM4**	99th	5.4	7.9	1.4	5.3	6.1	1.1	2.7	5.3	2	1.7	4.6	2.8	1.3	4.1	3.1
Distn:	26.4	95th	2.3	3.6	1.5	1.9	3.2	1.7	2.2	2.6	1.2	1.5	2.7	1.8	1.3	2.4	1.8
Depth:	6.2	80th	1.3	1.5	1.1	1.3	1.5	1.1	1.3	1.5	1.1	1.3	1.3	1	1.2	1.3	1
Base.:	16	Med.	0.8	0.7	0.9	0.8	0.9	1	0.8	1	1.2	0.9	1	1.1	1.1	1	0.9
Dred.:	892	Mean	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.1	1.1
Burrup.	**Penin.**	Max	13.4	160.1	12	7.8	14.9	1.9	2.7	7.4	2.7	1.7	6.3	3.7	1.3	3.2	2.4
Name:	**HGPT**	99th	5.4	7.3	1.3	5.4	6.5	1.2	2.7	6	2.2	1.7	4.9	2.9	1.3	3.1	2.4
Distn:	9	95th	2.4	2.9	1.3	1.9	2.7	1.4	2.3	2.3	1	1.5	1.9	1.3	1.3	1.9	1.5
Depth:	2.8	80th	1.4	1.7	1.2	1.4	1.7	1.2	1.4	1.6	1.1	1.3	1.5	1.1	1.2	1.4	1.1
Base.:	12	Med.	0.9	1.1	1.2	1	1.1	1.2	0.9	1.1	1.3	0.9	1	1.2	1.1	1	0.9
Dred.:	914	Mean	1.1	1.4	1.3	1.1	1.4	1.3	1	1.3	1.3	1	1.2	1.2	1	1.1	1.1
Burrup.	**Penin.**	Max	15.2	425.1	28	5.8	247.2	42.9	4.2	104.8	24.7	3.9	55.5	14.3	-	34.1	-
Name:	**HOLD**	99th	6.6	227.4	34.6	5.1	189.2	37	4.2	103.9	24.5	3.9	55.5	14.2	-	34	-
Distn:	0.3	95th	4.6	97.9	21.3	4.2	96.4	22.9	4.1	84	20.3	3.9	53.8	13.8	-	33.3	-
Depth:	-	80th	3	36.4	12.2	3.3	39.8	12.2	3.7	36.5	9.9	3.9	32.7	8.5	-	31.1	-
Base.:	5	Med.	1.3	15.7	11.6	1.4	18.2	13.4	2	26.5	13.3	3.8	25.3	6.7	-	21.2	-
Dred.:	83	Mean	1.8	28	15.2	1.9	27.9	14.8	2.5	27.7	11	3.8	23.4	6.2	-	20.9	-
Burrup.	**Penin.**	Max	67	128.7	1.9	16.6	63.2	3.8	2.7	24.8	9.1	1.4	17.3	12.2	-	13.3	-
Name:	**KGBY**	99th	19.3	34.1	1.8	15.6	21.8	1.4	2.7	23.9	8.9	1.4	16.6	11.7	-	12.9	-
Distn:	4	95th	6.6	11.6	1.8	4.8	9.1	1.9	2.7	9.6	3.6	1.4	12.4	8.7	-	11.5	-
Depth:	1.4	80th	2.1	3.5	1.6	2.5	4.2	1.7	2.4	4.3	1.8	1.4	4.4	3.1	-	4.7	-
Base.:	114	Med.	1	1.7	1.6	1.4	2.2	1.6	1.5	2.6	1.8	1.4	2.9	2.1	-	2.9	-
Dred.:	920	Mean	2.1	3.4	1.6	2.1	3.4	1.6	1.7	3.6	2.1	1.4	3.9	2.8	-	4	-
Burrup.	**Penin.**	Max	-	56.8	-	-	15.9	-	-	6.2	-	-	4.3	-	-	3.4	-
Name:	**LANI**	99th	-	7.9	-	-	6.8	-	-	5.4	-	-	4.1	-	-	3.3	-
Distn:	20.9	95th	-	2.8	-	-	2.9	-	-	2.6	-	-	2.8	-	-	2.6	-
Depth:	1.8	80th	-	1	-	-	1	-	-	1.2	-	-	1.3	-	-	1.2	-
Base.:	0	Med.	-	0.5	-	-	0.6	-	-	0.6	-	-	0.7	-	-	0.7	-
Dred.:	983	Mean	-	0.9	-	-	0.9	-	-	0.9	-	-	1	-	-	1	-
Burrup.	**Penin.**	Max	13.4	17.3	1.3	7.8	9.2	1.2	2.7	6	2.2	1.7	4	2.4	1.3	3	2.3
Name:	**LEGD**	99th	5.5	4.6	0.8	5.4	4.6	0.9	2.7	3.9	1.4	1.7	3	1.8	1.3	2.3	1.7
Distn:	28.6	95th	2.4	1.3	0.5	1.9	1.2	0.6	2.4	1.3	0.5	1.5	1.1	0.7	1.3	1.3	1
Depth:	9.2	80th	1.3	0.6	0.5	1.4	0.6	0.5	1.4	0.7	0.5	1.3	0.7	0.5	1.2	0.7	0.5
Base.:	11	Med.	0.8	0.4	0.5	0.8	0.4	0.4	0.9	0.4	0.4	0.9	0.4	0.5	1.1	0.4	0.4
Dred.:	871	Mean	1	0.5	0.5	1	0.5	0.5	1	0.5	0.6	1	0.5	0.5	1	0.5	0.5
Burrup.	**Penin.**	Max	-	66.9	-	-	25.7	-	-	8.6	-	-	5.5	-	-	4.4	-
Name:	**MAL2**	99th	-	13.6	-	-	9.2	-	-	8.5	-	-	5.4	-	-	4.3	-
Distn:	13.7	95th	-	5	-	-	5	-	-	4.2	-	-	5.3	-	-	4.2	-
Depth:	-	80th	-	2.3	-	-	2.4	-	-	2.3	-	-	2.3	-	-	2.5	-
Base.:	0	Med.	-	1.5	-	-	1.6	-	-	1.6	-	-	1.7	-	-	1.7	-
Dred.:	902	Mean	-	2.1	-	-	2.1	-	-	2	-	-	2.1	-	-	2.2	-
Burrup.	**Penin.**	Max	-	61.8	-	-	28.7	-	-	9.8	-	-	6.3	-	-	4.7	-
Name:	**MALI**	99th	-	5.1	-	-	3.7	-	-	3.2	-	-	3.5	-	-	1.5	-
Distn:	9.9	95th	-	2.3	-	-	2.1	-	-	1.8	-	-	1.5	-	-	1.4	-
Depth:	3.5	80th	-	1.5	-	-	1.4	-	-	1.4	-	-	1.3	-	-	1.2	-
Base.:	0	Med.	-	1	-	-	1.1	-	-	1.1	-	-	1.1	-	-	1.1	-
Dred.:	923	Mean	-	1.3	-	-	1.3	-	-	1.2	-	-	1.2	-	-	1.1	-
Burrup.	**Penin.**	Max	-	75.3	-	-	26.7	-	-	6.3	-	-	4.6	-	-	4.1	-
Name:	**MIDI**	99th	-	14	-	-	11.2	-	-	5.9	-	-	4.5	-	-	4	-
Distn:	12.1	95th	-	6.9	-	-	6.2	-	-	5.3	-	-	3.3	-	-	3.2	-

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	Δ1H	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W
Depth:	3.2	80th	-	4.2	-	-	4.1	-	-	3.1	-	-	3	-	-	3	-
Base.:	0	Med.	-	2.7	-	-	2.6	-	-	2.2	-	-	2.1	-	-	2	-
Dred.:	933	Mean	-	3.4	-	-	3.3	-	-	2.6	-	-	2.4	-	-	2.3	-
Burrup.	**Penin.**	Max	-	54.6	-	-	16.7	-	-	10.3	-	-	6.3	-	-	4.5	-
Name:	**MIDR**	99th	-	9.5	-	-	11.9	-	-	10.1	-	-	6.1	-	-	4.4	-
Distn:	15.9	95th	-	2.6	-	-	2.9	-	-	2.4	-	-	3.1	-	-	3.3	-
Depth:	4.2	80th	-	1.6	-	-	1.3	-	-	1.2	-	-	1.4	-	-	1.5	-
Base.:	0	Med.	-	1.1	-	-	0.9	-	-	0.8	-	-	0.8	-	-	0.8	-
Dred.:	860	Mean	-	1.4	-	-	1.3	-	-	1.2	-	-	1.1	-	-	1	-
Burrup.	**Penin.**	Max	-	120.2	-	-	9.1	-	-	3	-	-	2.5	-	-	2	-
Name:	**NELS**	99th	-	4	-	-	4	-	-	2.6	-	-	2.1	-	-	1.9	-
Distn:	17.7	95th	-	2.1	-	-	2.3	-	-	2.2	-	-	1.8	-	-	1.9	-
Depth:	3.2	80th	-	1.3	-	-	1.2	-	-	1.4	-	-	1.6	-	-	1.6	-
Base.:	0	Med.	-	0.9	-	-	0.9	-	-	0.7	-	-	0.7	-	-	0.7	-
Dred.:	867	Mean	-	1.1	-	-	1	-	-	1	-	-	1	-	-	1	-
Burrup.	**Penin.**	Max	20.7	81.2	3.9	5.8	42.6	7.4	4.2	13	3.1	3.9	8.2	2.1	-	6.7	-
Name:	**NWIT**	99th	7	14.3	2.1	5.1	13.7	2.7	4.2	10.7	2.5	3.9	8	2.1	-	6.1	-
Distn:	4.3	95th	4.7	4.8	1	4.2	4.5	1.1	4.1	5.8	1.4	3.9	6	1.6	-	5.7	-
Depth:	2.3	80th	3	1.9	0.6	3.2	1.9	0.6	3.6	2.1	0.6	3.9	2.3	0.6	-	3	-
Base.:	15	Med.	1.5	1.1	0.8	1.7	1.2	0.8	2.2	1.3	0.6	3.8	1.3	0.4	-	1.4	-
Dred.:	881	Mean	2	1.8	0.9	2	1.8	0.9	2.5	1.9	0.8	3.6	2	0.6	-	2.1	-
Burrup.	**Penin.**	Max	15.2	77.9	5.1	5.8	41.9	7.3	4.2	12.2	2.9	3.9	7.8	2	-	6.3	-
Name:	**SCON**	99th	7	16.1	2.3	5.1	13.3	2.6	4.2	9.1	2.2	3.9	7.5	1.9	-	6.2	-
Distn:	5.3	95th	4.7	6.2	1.3	4.2	5.7	1.4	4.1	5.3	1.3	3.9	5.4	1.4	-	5.6	-
Depth:	2	80th	3	2.2	0.7	3.2	2.6	0.8	3.6	2.8	0.8	3.9	2.9	0.8	-	2.7	-
Base.:	15	Med.	1.5	1.3	0.9	1.7	1.4	0.8	2.2	1.5	0.7	3.8	1.4	0.4	-	1.4	-
Dred.:	979	Mean	2	2.2	1.1	2	2.2	1.1	2.5	2.1	0.9	3.6	2.1	0.6	-	2.1	-
Burrup.	**Penin.**	Max	-	172.8	-	-	67.7	-	-	22	-	-	16.5	-	-	13.6	-
Name:	**SUP2**	99th	-	26	-	-	31.5	-	-	21.7	-	-	16.1	-	-	13.5	-
Distn:	1.8	95th	-	10.1	-	-	9.9	-	-	10.1	-	-	15.1	-	-	12.9	-
Depth:	2.2	80th	-	5.4	-	-	4.9	-	-	4.5	-	-	4.4	-	-	4.5	-
Base.:	0	Med.	-	3.6	-	-	3.2	-	-	2.7	-	-	2.7	-	-	2.6	-
Dred.:	866	Mean	-	4.7	-	-	4.4	-	-	4	-	-	4.1	-	-	4.1	-
Burrup.	**Penin.**	Max	-	71.1	-	-	31.5	-	-	11.4	-	-	8.3	-	-	6.4	-
Name:	**SWIT**	99th	-	14.2	-	-	11.5	-	-	10.5	-	-	8.2	-	-	6.4	-
Distn:	2.9	95th	-	5.8	-	-	5.6	-	-	6.5	-	-	7.3	-	-	6.1	-
Depth:	3	80th	-	2.9	-	-	2.8	-	-	2.3	-	-	2.2	-	-	2.3	-
Base.:	0	Med.	-	1.7	-	-	1.6	-	-	1.4	-	-	1.5	-	-	1.4	-
Dred.:	928	Mean	-	2.4	-	-	2.2	-	-	2	-	-	2.1	-	-	2	-
Burrup.	**Penin.**	Max	37.5	132.2	3.5	19.4	23.8	1.2	7.6	8.7	1.1	6	6	1	4.9	5.2	1.1
Name:	**WINI**	99th	19.8	17.4	0.9	13.6	13.7	1	7.4	8.1	1.1	6	5.9	1	4.9	5.1	1
Distn:	16.5	95th	11.7	8.1	0.7	8.6	6.7	0.8	6.7	3.9	0.6	5.6	5.7	1	4.9	4.9	1
Depth:	1.4	80th	4	3.9	1	4.8	3.5	0.7	4.7	3	0.6	4.8	2.8	0.6	4.5	2.6	0.6
Base.:	106	Med.	1.5	2.4	1.6	1.9	2.3	1.2	3	2.2	0.8	3.1	2.2	0.7	2.8	2.3	0.8
Dred.:	907	Mean	3.1	3.3	1.1	3.1	3	1	3.3	2.6	0.8	3.2	2.6	0.8	2.9	2.6	0.9

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	Δ1H	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W
Site	**Details**	**Stat.**	**B1H**	**D1H**	**Δ1H**	**B1D**	**D1D**	**Δ1D**	**B1W**	**D1W**	**Δ1W**	**B2W**	**D2W**	**Δ2W**	**B3W**	**D3W**	**Δ3W**
Cape	**Lamb.**	Max	553.4	166.7	0.3	332.7	85.9	0.3	14.4	26.4	1.8	13.2	14.5	1.1	10.6	13.1	1.2
Name:	**BLR**	99th	94.2	41.3	0.4	40.3	37.3	0.9	12.5	22.8	1.8	11.6	13.9	1.2	9.6	12.1	1.3
Distn:	4.5	95th	16.7	18.4	1.1	13.2	19	1.4	9.1	14.5	1.6	7.9	12.2	1.6	7	9.9	1.4
Depth:	3	80th	5.4	4	0.7	5.3	4.4	0.8	5.2	6	1.2	4.6	6.5	1.4	3.7	6.1	1.7
Base.:	457	Med.	1.4	1.2	0.8	1.6	1.2	0.8	1.6	1.5	0.9	1.3	2.1	1.6	0.9	2.8	3.2
Dred.:	699	Mean	6.1	3.9	0.6	4.8	4	0.8	2.9	3.8	1.3	2.6	3.7	1.4	2.2	3.7	1.7
Cape	**Lamb.**	Max	81	97	1.2	26.6	38.1	1.4	10.6	16.1	1.5	6.3	9.7	1.5	4.7	7.8	1.6
Name:	**BTR**	99th	20.7	20.6	1	17.7	19	1.1	9.5	12.2	1.3	6.3	9	1.4	4.5	7.3	1.6
Distn:	1.8	95th	9.6	9.3	1	7.5	8.9	1.2	7.2	8.8	1.2	5.3	7.4	1.4	4.1	6.4	1.5
Depth:	12	80th	3.5	3.5	1	3.3	3.5	1.1	3.6	4.3	1.2	3.9	3.8	1	3	3.8	1.2
Base.:	467	Med.	1.4	1.5	1.1	1.5	1.7	1.1	1.6	1.9	1.2	1.4	2.2	1.5	0.6	2.6	4.1
Dred.:	646	Mean	2.7	2.8	1	2.5	2.8	1.1	2.4	2.8	1.2	2.1	2.7	1.3	1.5	2.7	1.8
Cape	**Lamb.**	Max	153.7	162.9	1.1	32.6	65.8	2	11.3	27.1	2.4	5	16.4	3.3	4	11.4	2.8
Name:	**BZI**	99th	20.1	43.1	2.2	17.7	36.9	2.1	7.9	19.5	2.5	4.9	15.8	3.2	3.9	11.2	2.9
Distn:	2.6	95th	8.8	13.7	1.6	7.4	13.1	1.8	5.4	10.9	2	3.5	9.2	2.7	3.7	7.9	2.2
Depth:	3	80th	2.8	2.9	1	3	3.3	1.1	2.8	3.8	1.3	2.5	5	2	2.5	4.8	1.9
Base.:	536	Med.	0.9	1	1.2	1.2	1.3	1.1	1.5	1.7	1.1	1.8	2	1.1	1.8	2.5	1.4
Dred.:	689	Mean	2.3	3.2	1.4	2.2	3.3	1.5	2	3.2	1.6	1.8	3.2	1.8	1.8	3.2	1.8
Cape	**Lamb.**	Max	166.6	120.7	0.7	54.4	58.3	1.1	28	24.2	0.9	19.8	15.7	0.8	13.8	11.5	0.8
Name:	**BZR**	99th	26.8	38.5	1.4	30.1	34.3	1.1	16.1	20.5	1.3	12.3	15.2	1.2	4.4	11.4	2.6
Distn:	2.9	95th	10.1	15.1	1.5	9	15	1.7	7.9	13.9	1.7	5.8	11.8	2.1	3.8	10.5	2.8
Depth:	4	80th	3	4	1.3	2.9	4.3	1.5	2.9	6.1	2.1	2.9	6.8	2.4	2.6	6.6	2.6
Base.:	388	Med.	1	1.4	1.5	1.1	1.6	1.4	1.3	1.8	1.4	1.3	2.1	1.6	1.2	2.6	2.2
Dred.:	689	Mean	2.7	3.7	1.4	2.7	3.7	1.4	2.2	3.9	1.7	2	3.9	2	1.7	3.9	2.4
Cape	**Lamb.**	Max	79.5	207.6	2.6	23.6	103	4.4	9.7	39.9	4.1	6.6	27.4	4.1	5.6	20.2	3.6
Name:	**CLW**	99th	17.2	58.5	3.4	13.9	53	3.8	8.8	33.7	3.9	6.4	25.6	4	5.4	19.7	3.6
Distn:	3.2	95th	9.4	24	2.6	8.3	24.2	2.9	7.1	20.3	2.8	5.7	18.9	3.3	4.9	17.1	3.5
Depth:	4	80th	3.5	5.5	1.6	3.5	6	1.7	3.2	7.4	2.3	3.7	8.9	2.4	3.8	9.5	2.5
Base.:	381	Med.	1.1	1.6	1.4	1.3	1.8	1.4	1.5	2.5	1.7	1.7	2.9	1.7	1.7	3.4	2
Dred.:	682	Mean	2.5	5.3	2.1	2.4	5.3	2.2	2.3	5.4	2.4	2.2	5.5	2.5	2.2	5.5	2.5
Cape	**Lamb.**	Max	165.7	217.3	1.3	52.6	82.1	1.6	20.1	32.3	1.6	14.1	26.7	1.9	10.4	20	1.9
Name:	**DIE**	99th	27.6	58.2	2.1	25.4	55	2.2	18.7	29.1	1.6	12.9	24.7	1.9	10.3	18.5	1.8
Distn:	12.7	95th	11.2	20.2	1.8	11.6	21.5	1.8	10.7	20.9	1.9	8.5	16.7	2	8.7	15	1.7
Depth:	3	80th	3.3	2.9	0.9	3.4	3.3	1	4.3	5.1	1.2	4.3	6.5	1.5	3.9	6.8	1.7
Base.:	448	Med.	1.3	1	0.8	1.5	1.1	0.7	1.8	1.3	0.7	2.1	1.7	0.8	2.3	2.3	1
Dred.:	695	Mean	3	4.2	1.4	3	4.2	1.4	3.1	4	1.3	3	4.2	1.4	2.8	4.3	1.5
Cape	**Lamb.**	Max	114.4	183.3	1.6	46.4	66.1	1.4	28	24.5	0.9	20.5	16.8	0.8	3.4	12.7	3.7
Name:	**DLI**	99th	26.2	30.9	1.2	23.5	30.6	1.3	21.7	21.2	1	15	14.9	1	3.4	12.4	3.7
Distn:	17.7	95th	8.3	7.8	0.9	7.6	8.5	1.1	4.5	11.9	2.6	3	11.4	3.8	2.6	8.9	3.4
Depth:	9	80th	2	1.7	0.8	2.1	1.8	0.9	2.2	1.8	0.8	2.3	3.2	1.4	2.1	4.5	2.2
Base.:	425	Med.	0.7	0.8	1.1	0.8	0.9	1	1.2	0.9	0.8	1.3	1	0.8	1.4	1.1	0.8
Dred.:	675	Mean	2.1	2.2	1	2.1	2.2	1.1	2	2.3	1.2	1.7	2.5	1.4	1.5	2.6	1.7
Cape	**Lamb.**	Max	6.5	207.9	31.9	1.8	58.3	32	1.4	18.3	13.4	-	10.8	-	-	8.4	-
Name:	**DOI**	99th	2.5	26.9	10.7	1.8	21	11.9	1.4	12.4	9.1	-	10.6	-	-	7.9	-
Distn:	35.4	95th	2.2	8.9	4	1.7	8.7	5	1.4	9	6.6	-	7.1	-	-	7.3	-
Depth:	7	80th	1.5	2.8	1.9	1.5	3.1	2	1.3	3.5	2.7	-	3.6	-	-	3.9	-
Base.:	13	Med.	1.2	1.7	1.4	1.2	1.8	1.5	1.1	2.1	1.9	-	2.3	-	-	2.5	-
Dred.:	686	Mean	1.2	2.9	2.3	1.2	2.9	2.4	1.2	2.9	2.5	-	2.9	-	-	2.9	-
Cape	**Lamb.**	Max	77.4	174.5	2.3	32.5	101.5	3.1	17.9	40	2.2	9.9	25.2	2.5	-	18.8	-
Name:	**DPI**	99th	44.5	41.1	0.9	32.2	37.2	1.2	17.9	26	1.5	9.9	20.3	2	-	14.1	-
Distn:	51.3	95th	34.6	13.7	0.4	29.1	14	0.5	17.7	13.6	0.8	9.9	10.2	1	-	9	-
Depth:	5	80th	18.4	3.5	0.2	18.6	3.7	0.2	16.7	4.1	0.2	9.9	3.6	0.4	-	3.5	-
Base.:	15	Med.	5.5	1.1	0.2	8.2	1.1	0.1	12.5	1.4	0.1	9.9	1.5	0.2	-	1.4	-
Dred.:	644	Mean	9.8	3.5	0.4	10.1	3.4	0.3	11.8	3.1	0.3	9.9	2.8	0.3	-	2.6	-
Cape	**Lamb.**	Max	86.3	182.4	2.1	38.2	93.7	2.5	18.6	44.9	2.4	11	23.9	2.2	8.1	18.8	2.3
Name:	**HAT**	99th	23.3	50.7	2.2	23	48.1	2.1	18.3	35.1	1.9	11	22.7	2.1	8.1	18	2.2
Distn:	13.9	95th	10.6	19	1.8	9.7	18.7	1.9	11.9	20.3	1.7	10.6	18.5	1.7	3.4	14.9	4.4
Depth:	4	80th	4.5	5.4	1.2	4.3	6.1	1.4	3.9	6.9	1.8	3.1	7.2	2.3	0.6	6.6	10.2
Base.:	389	Med.	1.4	1.3	0.9	1.4	1.4	1	1.2	1.8	1.5	0.6	3	5	0.6	3.4	6.1
Dred.:	661	Mean	3.1	4.6	1.5	2.9	4.6	1.6	2.7	4.9	1.8	2	4.8	2.4	1	4.8	4.9

Table S1.A. Max, 99th, 95th, 80th percentiles, median and mean NTU values over 1 h, 1 d, 14 d, and 21 d running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("∆"). For each site the distance from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown. NTU values approximate total suspendid solid concentrations with a linear conversion factor of between 1.1 and 2.1.

Site	Details	Stat.	B1H	D1H	∆1H	B1D	D1D	∆1D	B1W	D1W	∆1W	B2W	D2W	∆2W	B3W	D3W	∆3W
Cape	**Lamb.**	Max	206.8	247.2	1.2	61.8	127.3	2.1	27.6	77.7	2.8	21	50.3	2.4	15.1	37.2	2.5
Name:	**MAN**	99th	38.1	85.4	2.2	39.7	81.6	2.1	27	56.8	2.1	20.8	49.4	2.4	14.9	35.5	2.4
Distn:	7.3	95th	17.5	34.5	2	16	34.2	2.1	15	35.6	2.4	14.9	31.7	2.1	13	31.6	2.4
Depth:	3	80th	7	7.8	1.1	6.8	7.8	1.1	5.8	10.4	1.8	5.4	13.6	2.5	5.3	13.4	2.5
Base.:	354	Med.	2.3	2.3	1	2.5	2.8	1.1	2.8	3.5	1.2	3.1	4.7	1.5	2.7	6	2.2
Dred.:	654	Mean	5.1	7.7	1.5	4.9	7.7	1.6	4.6	8.2	1.8	4.4	8.7	2	4	8.9	2.2
Cape	**Lamb.**	Max	51.7	238.9	4.6	31.7	88.4	2.8	10	36.1	3.6	7.4	21.3	2.9	6.7	21.3	3.2
Name:	**MDR**	99th	32.4	64.9	2	18.1	55.3	3.1	9.9	30.1	3	7	20.4	2.9	6.6	18.9	2.9
Distn:	2.1	95th	13.2	27.1	2.1	11.4	28.6	2.5	8.3	23	2.8	6.4	18.9	3	6.4	15.6	2.4
Depth:	3	80th	4.2	7.4	1.8	4.4	8.8	2	5.2	12.1	2.3	4.8	13.2	2.7	4.2	13.3	3.1
Base.:	382	Med.	1.4	2.1	1.5	1.8	2.3	1.3	2.3	3.6	1.5	2.3	5.2	2.3	2.1	6.8	3.2
Dred.:	685	Mean	3.4	6.4	1.9	3.1	6.5	2.1	3.1	7	2.3	2.9	7.2	2.5	2.7	7.4	2.7
Cape	**Lamb.**	Max	63.3	142.7	2.3	37.7	77	2	19	37.9	2	13.7	20.9	1.5	10.1	16.4	1.6
Name:	**PLR**	99th	27.1	44.6	1.6	24	40.8	1.7	18.5	27.9	1.5	13.5	20	1.5	10	16.1	1.6
Distn:	9.7	95th	10.6	15.4	1.5	9.7	14.5	1.5	9.5	18.6	2	10.5	16	1.5	9.7	13.7	1.4
Depth:	3	80th	3.8	4	1.1	3.6	4.4	1.2	4.7	5.9	1.2	5.7	5.9	1	6	8.9	1.5
Base.:	399	Med.	1.4	1.3	0.9	1.4	1.4	1	1.7	1.7	1	2.4	2.2	0.9	2.3	3.1	1.4
Dred.:	692	Mean	3	3.8	1.3	2.8	3.9	1.4	3.1	4.1	1.3	3.3	4.3	1.3	3.5	4.7	1.4
Cape	**Lamb.**	Max	172.6	220	1.3	54.6	76.2	1.4	17.1	40.3	2.4	14.4	23.5	1.6	11	16.5	1.5
Name:	**PWR**	99th	29.2	74.5	2.6	24.8	59.6	2.4	16.7	37.1	2.2	14.2	23.4	1.6	11	16.5	1.5
Distn:	1.2	95th	15.7	36.1	2.3	14.3	32.4	2.3	11.4	26.8	2.3	12.1	21.3	1.8	10.5	16.3	1.6
Depth:	6	80th	4.8	12.4	2.6	4.5	14.6	3.2	4.6	17.7	3.9	6.8	17.2	2.5	7.2	12.3	1.7
Base.:	399	Med.	1.3	3.3	2.5	1.6	4.1	2.5	2.2	7.1	3.3	2.7	10.3	3.8	4.2	6.7	1.6
Dred.:	629	Mean	3.7	8.9	2.4	3.6	9	2.5	3.4	10.1	3	4.3	10.6	2.5	4.8	8.3	1.7
Cape	**Lamb.**	Max	101.5	137.7	1.4	45.4	63.4	1.4	25.8	26.6	1	16.1	18.4	1.1	8.2	16.3	2
Name:	**SMSB**	99th	32.7	46.7	1.4	28.4	40.5	1.4	18.8	24.2	1.3	12.9	17.1	1.3	8	15.8	2
Distn:	5.6	95th	14.2	21.1	1.5	12.6	20.1	1.6	8.1	17.9	2.2	6.4	14.2	2.2	6	12.5	2.1
Depth:	4	80th	4.9	6.7	1.4	4.8	7.4	1.6	4.5	8.2	1.8	4.5	8.3	1.8	3.8	8.2	2.2
Base.:	481	Med.	1.4	2.2	1.5	1.7	2.5	1.5	2.1	3.3	1.6	2.1	4.3	2.1	2.1	4.9	2.3
Dred.:	698	Mean	3.7	5.3	1.4	3.5	5.3	1.5	3.1	5.4	1.7	2.8	5.5	2	2.5	5.5	2.2

Table S1.B. Min, 1st, 5th, 20th percentiles, median and mean DLI values (mol photons/m2) over 1 d, 14 d, 21 d and 30 d (1mth) running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the Distace from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown.

Site	Details	Stat.	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W	B4W	D4W	Δ4W
Barrow	**Island**	Min	0.1	0	0	0.4	0.2	0.4	0.5	0.7	1.4	0.5	1.4	2.6	0.8	2.1	2.9
Name:	**AHC**	1st	0.3	0.1	0.3	0.5	0.5	0.9	0.5	1.4	2.5	0.6	2.1	3.5	0.8	2.3	2.8
Distn:	32.8	5th	0.6	0.7	1.1	1	1.9	2	1.1	2.3	2	1.2	2.5	2.1	1.3	2.6	2
Depth:	6.9	20th	2.1	2.8	1.3	2.3	3	1.3	2.3	3.1	1.4	2.3	3.2	1.4	2.3	3.2	1.4
Base.:	612	Med.	3.8	5	1.3	3.6	4.8	1.3	3.5	4.7	1.3	3.5	4.7	1.3	3.5	4.8	1.4
Dred.:	548	Mean	3.5	4.8	1.4	3.5	4.8	1.4	3.4	4.9	1.4	3.4	4.9	1.4	3.4	5	1.4
Barrow	**Island**	Min	0.5	0.1	0.2	2.2	1.1	0.5	2.8	1.5	0.6	2.8	1.8	0.7	3	2.2	0.7
Name:	**ANT**	1st	1.7	0.6	0.4	2.5	1.6	0.6	2.8	1.7	0.6	2.8	1.9	0.7	3	2.4	0.8
Distn:	8.8	5th	2.4	1.9	0.8	2.9	2.5	0.9	3	2.4	0.8	3	2.7	0.9	3.1	2.7	0.9
Depth:	3.9	20th	4	4.1	1	3.9	4.1	1.1	3.7	4.2	1.1	3.7	4	1.1	3.7	4.1	1.1
Base.:	692	Med.	6.1	6.8	1.1	5.8	6.9	1.2	5.7	7	1.2	5.6	6.9	1.2	5.4	6.9	1.3
Dred.:	388	Mean	6	6.7	1.1	5.8	6.6	1.2	5.6	6.6	1.2	5.4	6.6	1.2	5.2	6.5	1.3
Barrow	**Island**	Min	0	0.1	4	1.2	0.9	0.7	1.9	1.2	0.6	2.3	1.8	0.8	2.5	3	1.2
Name:	**BAT**	1st	0.8	0.5	0.6	1.6	1.4	0.9	2.1	1.6	0.8	2.4	2.1	0.9	2.6	3.4	1.3
Distn:	15.5	5th	2	2	1	2.8	2.7	1	2.8	3.3	1.2	2.6	3.8	1.5	2.7	3.9	1.4
Depth:	3.7	20th	4.1	4.7	1.1	4.1	4.8	1.2	4.2	4.9	1.2	4.2	4.7	1.1	4.4	4.6	1.1
Base.:	621	Med.	6.5	8.2	1.3	6.6	8	1.2	6.4	8	1.2	6.5	8	1.2	6.7	8.1	1.2
Dred.:	488	Mean	6.8	8	1.2	6.8	7.9	1.2	6.8	7.9	1.2	6.9	8	1.2	7	8.1	1.2
Barrow	**Island**	Min	6.2	0.9	0.1	10.2	3.6	0.3	12.1	4.3	0.4	13.2	4.7	0.4	13.3	5.3	0.4
Name:	**DIW**	1st	8.9	1.5	0.2	10.6	4.4	0.4	12.8	4.8	0.4	13.2	5.1	0.4	14.4	5.6	0.4
Distn:	6.5	5th	11.2	5.2	0.5	12.2	5.9	0.5	13.5	6.2	0.5	13.6	6.5	0.5	14.6	6.2	0.4
Depth:	1.9	20th	13.1	9.1	0.7	13.7	10.2	0.8	14.3	11	0.8	15.1	11	0.7	15.2	11.6	0.8
Base.:	238	Med.	16.1	15	0.9	16.5	14.6	0.9	17	14.9	0.9	17.2	15	0.9	17.3	14.7	0.8
Dred.:	507	Mean	16.7	14.6	0.9	17.1	14.6	0.9	17.5	14.6	0.8	17.7	14.6	0.8	18.1	14.5	0.8
Barrow	**Island**	Min	0	0	0	1.3	0.2	0.1	2.3	1	0.5	2.1	1.3	0.6	2.6	1.9	0.7
Name:	**DUG**	1st	0.4	0	0	1.7	0.5	0.3	2.4	1.3	0.5	2.3	1.8	0.8	2.6	1.9	0.7
Distn:	9.2	5th	1.3	0.3	0.2	2.5	1.7	0.7	2.6	2.3	0.9	2.8	2.5	0.9	3	3.2	1.1
Depth:	6	20th	3.4	2.5	0.8	3.6	3	0.8	3.7	3.4	0.9	3.8	3.7	1	3.9	4.2	1.1
Base.:	561	Med.	5.3	5	0.9	6	5.1	0.9	6.2	5.1	0.8	6.1	5.1	0.8	6	5.2	0.9
Dred.:	439	Mean	5.4	4.9	0.9	5.6	5	0.9	5.6	5.1	0.9	5.6	5.2	0.9	5.6	5.4	1
Barrow	**Island**	Min	1	0.1	0.1	1.4	1.5	1.1	1.7	2.1	1.3	1.8	2.5	1.4	2	2.6	1.3
Name:	**ELS**	1st	1	0.2	0.2	1.4	1.7	1.2	1.7	2.2	1.3	1.8	2.6	1.4	2	2.7	1.4
Distn:	21	5th	1.4	0.8	0.6	1.5	2.2	1.5	1.7	2.5	1.4	1.9	2.7	1.5	2.1	3	1.4
Depth:	7	20th	2.8	3.1	1.1	2.1	3.2	1.5	2	3.3	1.6	2	3.1	1.6	2.4	3.2	1.3
Base.:	133	Med.	4.8	5	1.1	3.9	4.9	1.3	3.7	5	1.4	3.6	5.3	1.5	3.3	5.2	1.6
Dred.:	411	Mean	4.5	5	1.1	3.8	5	1.3	3.3	5	1.5	3.3	5	1.5	3.3	5	1.5
Barrow	**Island**	Min	0.1	0	0	1	0.1	0.1	1.5	0.2	0.2	1.4	0.3	0.2	1.8	0.4	0.2
Name:	**LNG0**	1st	0.3	0	0	1.2	0.2	0.1	1.5	0.3	0.2	1.6	0.3	0.2	1.8	0.4	0.2
Distn:	0.2	5th	1	0	0	1.6	0.3	0.2	1.8	0.4	0.2	1.9	0.4	0.2	1.9	0.4	0.2
Depth:	8.6	20th	1.9	0.3	0.2	2	0.6	0.3	2.1	0.6	0.3	2.2	0.6	0.3	2.2	0.7	0.3
Base.:	476	Med.	2.9	1.1	0.4	2.7	1.2	0.4	2.5	1.3	0.5	2.5	1.3	0.5	2.4	1.3	0.5
Dred.:	482	Mean	3.1	1.5	0.5	3.1	1.5	0.5	3.2	1.6	0.5	3.2	1.5	0.5	3.2	1.5	0.5
Barrow	**Island**	Min	0	0	0	0.5	0.1	0.1	0.8	0.2	0.3	0.8	0.3	0.4	1.2	0.4	0.3
Name:	**LNG1**	1st	0.1	0	0	0.7	0.1	0.2	0.9	0.3	0.4	0.9	0.5	0.5	1.2	0.5	0.4
Distn:	0.5	5th	0.7	0.1	0.1	1	0.3	0.3	1	0.4	0.4	1.2	0.6	0.5	1.3	0.7	0.5
Depth:	8.9	20th	1.4	0.4	0.3	1.5	0.7	0.5	1.7	0.8	0.5	1.7	0.9	0.5	1.8	0.9	0.5
Base.:	450	Med.	2.8	1.2	0.4	2.8	1.5	0.5	2.9	1.5	0.5	2.9	1.5	0.5	2.9	1.9	0.6
Dred.:	478	Mean	3.1	1.7	0.5	3.1	1.7	0.5	3.1	1.7	0.5	3.2	1.7	0.5	3.3	1.8	0.5
Barrow	**Island**	Min	0	0	0	0.9	0.2	0.3	1.2	0.3	0.3	1.3	0.3	0.3	1.8	0.4	0.2
Name:	**LNG2**	1st	0.2	0	0.2	1.1	0.3	0.3	1.2	0.4	0.3	1.4	0.4	0.3	1.8	0.5	0.3
Distn:	1	5th	0.9	0.2	0.2	1.3	0.4	0.3	1.7	0.5	0.3	1.8	0.5	0.3	1.9	0.5	0.3
Depth:	6.6	20th	2	0.8	0.4	2.1	1.1	0.5	2.1	1.2	0.6	2.5	1.2	0.5	2.7	1.2	0.4
Base.:	636	Med.	3.9	2.2	0.6	4.1	2.3	0.6	4.2	2.4	0.6	4.2	2.5	0.6	4.3	2.6	0.6
Dred.:	442	Mean	4	2.6	0.6	4	2.6	0.6	4.2	2.6	0.6	4.2	2.6	0.6	4.3	2.6	0.6
Barrow	**Island**	Min	0	0	0	0.7	0.5	0.6	1.3	0.7	0.5	1.6	1.6	1	1.9	1.9	1
Name:	**LNG3**	1st	0.2	0	0.1	1.1	0.6	0.5	1.7	1.2	0.7	1.9	1.7	0.9	2	1.9	0.9
Distn:	4	5th	0.9	0.4	0.4	1.8	1.1	0.6	2	1.8	0.9	2.1	2	0.9	2.1	2.1	1
Depth:	6.2	20th	2.3	1.6	0.7	2.7	2.1	0.8	2.9	2.3	0.8	3	2.4	0.8	3.4	2.4	0.7
Base.:	628	Med.	4	3.6	0.9	4.5	3.6	0.8	4.5	4.1	0.9	4.9	4.7	1	5.3	4.8	0.9
Dred.:	466	Mean	4.2	3.8	0.9	4.6	3.9	0.9	4.7	4.2	0.9	4.8	4.3	0.9	5	4.5	0.9
Barrow	**Island**	Min	0.3	0	0	1.9	0.1	0.1	2.5	0.2	0.1	2.7	0.3	0.1	2.7	0.3	0.1
Name:	**LNGA**	1st	0.4	0	0	1.9	0.2	0.1	2.5	0.2	0.1	2.7	0.3	0.1	2.7	0.3	0.1
Distn:	0.3	5th	1.6	0.1	0	2.1	0.2	0.1	2.6	0.3	0.1	2.7	0.3	0.1	2.8	0.4	0.1
Depth:	11.1	20th	2.4	0.3	0.1	2.6	0.5	0.2	2.8	0.5	0.2	2.8	0.5	0.2	2.8	0.5	0.2
Base.:	113	Med.	2.8	0.8	0.3	2.9	0.9	0.3	2.9	1	0.3	2.9	1.1	0.4	2.9	1.2	0.4

Table S1.B. Min, 1st, 5th, 20th percentiles, median and mean DLI values (mol photons/m2) over 1 d, 14 d, 21 d and 30 d (1mth) running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the Distace from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown.

Site	Details	Stat.	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W	B4W	D4W	Δ4W
Dred.:	468	Mean	2.8	1	0.4	2.9	1	0.4	2.9	1.1	0.4	2.9	1.1	0.4	2.9	1.2	0.4
Barrow	**Island**	Min	0.5	0	0	1.4	0.1	0.1	2.2	0.2	0.1	2.4	0.3	0.1	2.6	0.4	0.1
Name:	**LNGB**	1st	0.6	0	0	1.4	0.1	0.1	2.2	0.3	0.1	2.4	0.4	0.2	2.6	0.5	0.2
Distn:	0.7	5th	1	0.1	0.1	2	0.3	0.2	2.4	0.5	0.2	2.5	0.6	0.2	2.7	0.6	0.2
Depth:	10.2	20th	2.4	0.4	0.2	2.7	0.7	0.2	2.8	0.8	0.3	2.8	0.8	0.3	2.9	0.8	0.3
Base.:	115	Med.	3	1.2	0.4	3	1.3	0.4	3	1.3	0.4	3.1	1.5	0.5	3.2	2	0.6
Dred.:	481	Mean	3.1	1.6	0.5	3.4	1.6	0.5	3.4	1.7	0.5	3.4	1.7	0.5	3.4	1.8	0.5
Barrow	**Island**	Min	0.1	0	0	0.7	0.1	0.1	1.6	0.3	0.2	1.5	0.4	0.3	2	0.4	0.2
Name:	**LNGC**	1st	0.5	0	0	1	0.1	0.1	1.6	0.3	0.2	1.6	0.5	0.3	2	0.5	0.2
Distn:	1.4	5th	1	0	0	1.5	0.2	0.2	1.7	0.5	0.3	2	0.5	0.3	2.2	0.6	0.3
Depth:	10.7	20th	2.5	0.3	0.1	2.5	0.5	0.2	2.6	0.7	0.3	2.6	0.6	0.2	2.8	0.7	0.2
Base.:	241	Med.	3.3	1	0.3	3.4	1.1	0.3	3.5	1	0.3	3.6	1.1	0.3	3.7	1	0.3
Dred.:	424	Mean	3.1	1.2	0.4	3.2	1.3	0.4	3.2	1.3	0.4	3.3	1.3	0.4	3.4	1.3	0.4
Barrow	**Island**	Min	2.1	-	-	5.4	-	-	-	-	-	-	-	-	-	-	-
Name:	**LOW**	1st	2.2	-	-	5.4	-	-	-	-	-	-	-	-	-	-	-
Distn:	1.9	5th	4.2	-	-	5.4	-	-	-	-	-	-	-	-	-	-	-
Depth:	2.9	20th	6.8	-	-	5.4	-	-	-	-	-	-	-	-	-	-	-
Base.:	75	Med.	11.6	-	-	9	-	-	-	-	-	-	-	-	-	-	-
Dred.:	0	Mean	10.3	-	-	9	-	-	-	-	-	-	-	-	-	-	-
Barrow	**Island**	Min	0.7	0	0	2.4	0.4	0.2	3.5	0.5	0.2	3.6	0.9	0.2	3.8	1.1	0.3
Name:	**LOW1**	1st	1	0.1	0.1	3	0.6	0.2	3.5	0.8	0.2	3.7	0.9	0.2	3.8	1.2	0.3
Distn:	1.6	5th	2.6	0.9	0.3	3.2	1.5	0.5	3.6	1.6	0.4	3.8	1.6	0.4	3.9	1.5	0.4
Depth:	6.9	20th	3.6	2.3	0.7	3.7	2.5	0.7	3.9	2.5	0.6	4.1	2.4	0.6	4.1	2.3	0.6
Base.:	173	Med.	4.3	3.9	0.9	4.3	3.8	0.9	4.3	3.9	0.9	4.3	3.9	0.9	4.3	3.7	0.9
Dred.:	524	Mean	4.2	4	1	4.2	3.9	0.9	4.3	3.8	0.9	4.3	3.7	0.9	4.3	3.6	0.8
Barrow	**Island**	Min	6.3	0	0	9.3	1.1	0.1	-	1.2	-	-	1.9	-	-	2.3	-
Name:	**LOW3**	1st	6.5	0.4	0.1	9.3	1.3	0.1	-	1.5	-	-	1.9	-	-	2.5	-
Distn:	2.2	5th	7.1	1.5	0.2	9.4	2.4	0.3	-	2.5	-	-	2.8	-	-	3.2	-
Depth:	4.5	20th	8.6	4.2	0.5	9.8	4.6	0.5	-	4.9	-	-	4.7	-	-	4.6	-
Base.:	10	Med.	10.4	7.7	0.7	10.3	7.4	0.7	-	7.2	-	-	7.1	-	-	7	-
Dred.:	447	Mean	9.7	7.5	0.8	10.1	7.5	0.7	-	7.4	-	-	7.3	-	-	7.1	-
Barrow	**Island**	Min	0.5	0	0	0.9	0.1	0.2	1	0.4	0.4	1	0.5	0.5	1.4	0.6	0.4
Name:	**MOF1**	1st	0.7	0	0.1	1	0.3	0.3	1	0.5	0.4	1	0.5	0.5	1.6	0.6	0.4
Distn:	0.8	5th	1.1	0.2	0.2	1.3	0.6	0.4	1.8	0.6	0.4	1.9	0.6	0.3	2.1	0.7	0.3
Depth:	6.2	20th	2.1	1	0.5	2.3	1.2	0.5	2.4	1.5	0.6	2.5	1.6	0.6	2.9	1.7	0.6
Base.:	562	Med.	3.6	2.2	0.6	3.6	2.2	0.6	3.6	2.3	0.6	3.6	2.4	0.6	3.5	2.5	0.7
Dred.:	512	Mean	3.6	2.2	0.6	3.6	2.2	0.6	3.6	2.2	0.6	3.7	2.3	0.6	3.7	2.3	0.6
Barrow	**Island**	Min	0.4	0	0	1.9	0.3	0.1	2.2	0.4	0.2	2.3	0.7	0.3	2.4	0.9	0.4
Name:	**MOF3**	1st	0.7	0.1	0.1	2.1	0.5	0.3	2.3	0.6	0.3	2.5	0.8	0.3	2.5	1	0.4
Distn:	1.5	5th	1.4	0.5	0.4	2.4	0.9	0.4	2.5	1	0.4	2.6	1.2	0.5	2.7	1.1	0.4
Depth:	4.8	20th	3	1.8	0.6	3.2	2.1	0.6	3.2	2.5	0.8	3.1	2.7	0.9	3.2	2.8	0.9
Base.:	549	Med.	4.9	3.8	0.8	5.1	3.7	0.7	5.2	3.9	0.8	5	4.1	0.8	5.1	4.5	0.9
Dred.:	487	Mean	4.9	3.9	0.8	5	3.9	0.8	5	4.1	0.8	5	4.2	0.8	4.9	4.4	0.9
Barrow	**Island**	Min	0	0	0	0.6	0	0	0.9	0.1	0.1	1.2	0.5	0.4	1.5	0.8	0.5
Name:	**MOFA**	1st	0	0	0.1	0.7	0.2	0.3	0.9	0.3	0.3	1.3	0.5	0.4	1.5	0.8	0.6
Distn:	0.6	5th	0.2	0.1	0.7	1.2	0.6	0.5	1.2	1	0.8	1.5	1.2	0.8	1.7	1.3	0.7
Depth:	4.9	20th	1.7	1.1	0.7	2	1.8	0.9	2.1	2	1	2	2.3	1.1	2	2.5	1.3
Base.:	137	Med.	2.8	2.9	1.1	2.6	2.9	1.1	2.4	3.2	1.3	2.5	3.3	1.3	2.6	3.3	1.3
Dred.:	456	Mean	3.5	3.1	0.9	3.4	3.2	0.9	3.1	3.3	1.1	3	3.4	1.1	3	3.4	1.2
Barrow	**Island**	Min	0.9	0	0	1.2	0.2	0.2	1.3	0.3	0.2	1.7	0.4	0.2	2.2	0.5	0.2
Name:	**MOFB**	1st	1.1	0.1	0.1	1.2	0.3	0.3	1.4	0.4	0.3	1.9	0.4	0.2	2.3	0.5	0.2
Distn:	1	5th	1.4	0.2	0.2	1.5	0.4	0.3	2.2	0.5	0.2	2.6	0.6	0.2	2.8	0.6	0.2
Depth:	7.5	20th	3.2	0.9	0.3	3.4	1.1	0.3	3.6	1.1	0.3	3.7	1	0.3	3.8	0.9	0.2
Base.:	211	Med.	4	2.3	0.6	4.1	2.4	0.6	4	2.4	0.6	4	2.4	0.6	4.1	2.4	0.6
Dred.:	488	Mean	3.8	2.2	0.6	3.9	2.2	0.6	3.9	2.2	0.6	3.9	2.2	0.6	4	2.2	0.5
Barrow	**Island**	Min	0.8	0	0	1.2	0	0	1.4	0.2	0.1	1.6	0.2	0.1	2	0.4	0.2
Name:	**MOFC**	1st	1	0	0	1.2	0.2	0.1	1.4	0.2	0.1	1.6	0.2	0.2	2	0.5	0.3
Distn:	0.8	5th	1.3	0.1	0.1	1.4	0.3	0.2	1.5	0.4	0.3	1.7	0.5	0.3	2.1	0.7	0.3
Depth:	6.9	20th	2.6	0.8	0.3	3	1.1	0.4	3.2	1.2	0.4	3.2	1.7	0.5	3.2	1.7	0.5
Base.:	154	Med.	3.9	2.3	0.6	3.9	2.4	0.6	4.1	2.6	0.6	4	2.7	0.7	4.2	2.6	0.6
Dred.:	471	Mean	3.8	2.2	0.6	3.9	2.3	0.6	3.9	2.4	0.6	3.9	2.4	0.6	4	2.4	0.6
Barrow	**Island**	Min	0.1	0	0	1.5	0.3	0.2	1.9	0.5	0.3	2.2	1.2	0.5	2.3	1.8	0.8
Name:	**REFN**	1st	0.1	0.1	1.1	1.6	0.4	0.3	1.9	0.8	0.4	2.2	1.2	0.6	2.3	3	1.3
Distn:	28	5th	1.1	0.8	0.7	1.7	2.1	1.2	2	2.3	1.1	2.2	2.7	1.2	2.3	3.3	1.4
Depth:	7.2	20th	2.2	3.4	1.6	2.3	3.5	1.6	2.2	3.8	1.7	2.3	3.9	1.7	2.4	4.2	1.8

Table S1.B. Min, 1st, 5th, 20th percentiles, median and mean DLI values (mol photons/m2) over 1 d, 14 d, 21 d and 30 d (1mth) running average period at all sites during the baseline period ("B", before dredging) or for during the duration of the dredging program ("D"). The ratio of dredging/baseline is also shown ("Δ"). For each site the Distace from dredging activities (Distn), the site depth (Depth) and the number of sampling days during baseline (Base) and dredging (Dred) are shown.

Site	Details	Stat.	B1D	D1D	Δ1D	B1W	D1W	Δ1W	B2W	D2W	Δ2W	B3W	D3W	Δ3W	B4W	D4W	Δ4W
Base.:	93	Med.	3.3	5.9	1.8	3.2	6.1	1.9	2.6	6.1	2.4	2.4	5.9	2.5	2.5	6	2.4
Dred.:	426	Mean	3.4	5.3	1.6	3.2	5.4	1.7	2.9	5.5	1.9	2.8	5.6	2	2.6	5.8	2.2
Barrow	**Island**	Min	1.2	0	0	3.4	0.4	0.1	4.4	0.7	0.2	4.8	1.4	0.3	5.4	1.9	0.3
Name:	**REFS**	1st	1.6	0.1	0	3.7	0.8	0.2	4.6	0.9	0.2	4.9	1.5	0.3	5.4	2	0.4
Distn:	23.6	5th	3.8	1.3	0.4	4.4	2.6	0.6	4.8	2.3	0.5	5.3	2.4	0.5	5.8	2.5	0.4
Depth:	5	20th	5.6	4.4	0.8	5.8	4.7	0.8	5.9	4.7	0.8	6.1	4.8	0.8	6.3	4.8	0.8
Base.:	144	Med.	7	7.2	1	6.8	7.2	1.1	6.7	7.2	1.1	6.7	7.5	1.1	6.7	7.6	1.1
Dred.:	429	Mean	7.1	7	1	6.9	7	1	6.6	7.1	1.1	6.6	7.1	1.1	6.6	7.2	1.1
Barrow	**Island**	Min	0.1	0	0.4	0.4	0.7	1.7	0.5	1.6	3.5	0.7	2.5	3.6	0.8	3	3.7
Name:	**SBS**	1st	0.2	0.1	0.5	0.5	0.9	1.9	0.7	2.1	3.2	0.8	3.2	4.2	0.9	3.3	3.5
Distn:	29.9	5th	0.7	1.4	1.9	1.1	2.6	2.5	1.3	3.2	2.4	1.3	3.6	2.9	1.4	3.9	2.8
Depth:	4.7	20th	2.9	4.6	1.6	3.1	5.1	1.7	3.4	5.3	1.5	3.7	5.2	1.4	3.9	5.5	1.4
Base.:	605	Med.	5.9	7.2	1.2	5.7	6.9	1.2	5.8	7.2	1.2	5.9	7.5	1.3	5.6	7.8	1.4
Dred.:	502	Mean	6	7	1.2	5.9	7.1	1.2	5.8	7.2	1.2	5.6	7.3	1.3	5.6	7.4	1.3
Barrow	**Island**	Min	0.9	0	0	1.7	0.1	0	1.8	0.2	0.1	1.9	0.6	0.3	2.8	1	0.4
Name:	**TR**	1st	1.5	0.1	0	1.7	0.3	0.2	1.9	0.4	0.2	1.9	0.8	0.4	3.1	1.2	0.4
Distn:	5	5th	2	0.3	0.1	2.1	1.2	0.6	2.1	1.4	0.6	3.3	1.6	0.5	4.3	1.6	0.4
Depth:	4.5	20th	5.6	2.4	0.4	5.1	3.4	0.7	5.4	3	0.6	5.7	2.6	0.5	6.3	2.4	0.4
Base.:	241	Med.	7.8	5.6	0.7	7.9	5.4	0.7	8	5.6	0.7	8.1	5.5	0.7	8.6	5.3	0.6
Dred.:	464	Mean	7.7	5.7	0.7	7.8	5.6	0.7	8	5.5	0.7	8.2	5.4	0.7	8.5	5.2	0.6

Appendices – Supplementary Information

Appendix 1. Analysis of temporal periodicity

Background

Understanding periodicities or cycles in water quality data is essential for planning and managing future dredging projects and is very important if time is incorporated into the water quality trigger values (see below). Many of the factors governing turbidity and light availability are under distinct cycles including daily and seasonal solar elevation cycles, seasonal cloud cover cycles (Wright 1997). Regular and more systematic cycles include tidal cycles (Holloway 1983a, Margvelashvili et al. 2008), as well as daily cycles (sea-breezes) and seasonal wind cycles (Holloway & Nye 1985a, Lowe et al. 2012). However, cryptic and less predictable patterns may also occur such as meteorological phenomena including patterns of cloud formation (Wright 1997), and large-scale pressure systems such as the intra-seasonal (30 to 60 day wave) Madden-Julian oscillations (MJO) (Madden & Julian 1994).

Materials and Methods

Temporal periodicities across the three study regions were performed on turbidity and wind data, and wave data at Barrow Island, to investigate the dominant periodic turbidity cycles, their driving mechanisms (tides, waves) and whether any changes occur during dredging. Water quality data were collected during dredging across the three study regions, and prior to dredging at Barrow Island and Cape Lambert. Seafloor pressure measurements were also collected at Barrow Island to ascertain the wave motion on the seafloor. Barrow Island and Cape Lambert data were sampled every ten minutes and Burrup Peninsula every 30 minutes. Monitoring locations covered a variety of proximities to the dredge zone, from impact sites close to the dredge to reference sites up to 33 km north and south of the dredge. Wind data at Barrow Island, Karratha (close to Burrup Peninsula) and Roebourne (close to Cape Lambert) airports were measured every three hours from and provided by the Bureau of Meteorology (2014).

Analysis of temporal periodicities in turbidity from the three dredging programs, wind data (collected every 3 hrs at Barrow Island and Karratha (close to Burrup Peninsula) and Roebourne (close to Cape Lambert) airports Bureau of Meteorology (2014) and wave data at Barrow Island, was conducted using wavelet methods developed by Torrence and Compo (1995), with bias rectification developed by Liu et al. (2007). Wavelet spectral plots show the temporal location of periodic events present in a time series, and the relative amplitude (energy) of that event compared to the energy at other locations in the time series, and compared to events with different frequencies.

The wavelet transform uses a mother wavelet, in this case the 'Morlet' wavelet with scale 's' (closely related to period), to determine the presence and amplitude of that scale at time t in the time series. The wavelet transform is convoluted with the time series by translating along the time series at varying scales. The Torrence and Compo method performs a discrete Fourier transform of the time series, xn, and mother wavelet ψ0, then calculates the wavelet coefficients by performing an inverse transform of the convolution: (equation (4) in Torrence & Compo 1995).

$$W_n(s) = \sum_{k=0}^{N-1} x_k \, \psi^*(s\omega_k) e^{i\omega_k n\delta t} \qquad (1)$$

Where Wn(s) is the wavelet transform at scale s and translation along the time series n, xk is the Fourier transformed time series with time step δt, ψ* is the complex conjugate of the Fourier transformed Morlet wavelet ψ0, and ωk is the angular frequency. The wavelet transforms at all scales across the time series are then squared and log2 transformed to display the wavelet spectral power. To analyse the dominant periodicities in a time series, similar to an analysis in the frequency domain, the wavelet power at each scale is averaged over the whole time series. This is called a global wavelet spectrum and is displayed on the right hand side of each wavelet spectrum (Torrence & Compo 1995). Comparisons were made of the global wavelet spectrum calculated at each site for the baseline and dredge periods separately, as well as comparisons of the global wavelet spectrum at all sites for the baseline period and dredge period at Barrow Island and Cape Lambert. At Burrup Peninsula comparisons were made only during the dredge period.

A bias exists in the global wavelet spectrum where energy in the longer period bands is enhanced and energy in the shorter period bands are attenuated. This bias has been corrected using methods developed by Liu et al. (2007), by dividing the wavelet power at each scale by that scale.

Edge effects that result from repetition of the time series, required during the Fourier transform, can distort the power in the wavelet spectra at the maximum periods. As time series are finite and the Fourier transform uses infinite sine and cosine functions for frequency detection, the Fourier transform loops the time series to create an infinite series. High frequency changes at the beginning and end of each loop results in distortions of the power in these regions. These are excluded from the wavelet transform by use of a cone of influence, the black area between the wavelet power spectrum and the bottom graph of the original time series.

Due to differences in the length of the baseline time series at Barrow Island, with baseline data measurements at around half the sites beginning six months prior to dredging, which was a particularly low energetic period, only sites with sufficient baseline time series were included in the global wavelet spectrum comparison. All sites were included in the dredge period comparison as the time series lengths were very similar, and inclusion of as many dredge impact sites as possible was preferable. The Burrup Peninsula had insufficient data during the baseline period therefore only the dredge study was included in both wavelet and global spectrum analyses.

Peak periodicities within the data were examined by time averaging the energy in each frequency band across the time series, called the global wavelet spectrum (Torrence & Compo 1995), which provides analysis similar to a Fourier transform. Peak periodicities in the baseline period and dredge period for each variable were calculated separately to compare if the principal cycles were affected by dredging.

Due to differences in baseline time series length at Barrow Island, with baseline data measurements at around half the sites beginning six months prior to dredging, which was a particularly a low energetic period, only sites with sufficient baseline time series were included in the global wavelet spectrum comparison. All sites were included in the dredge period comparison as the time series lengths were very similar.

Results

The spectral analysis clearly identified periodic patterns in the turbidity data for the 3 Pilbara dredging datasets at the semi-diurnal (particularly during the dredge phase), diurnal, spring/neap and longer period weather band periods of 1 week to months.

The strongest peak in the wave global spectra for turbidity at all Barrow Island sites occurred at either the semi-diurnal and/or daily sea breeze across the baseline and dredge periods (Figure A1.2). The semi-diurnal (~12 h) peak was stronger during the dredge phase but only at the LNG and MOF sites at Barrow Island which were the sites closest to the dredging (Figures A1.1 & A1.2). During the baseline period, and at reference sites during dredging, this semi-diurnal peak was of similar strength or weaker than the diurnal peak and the longer period weather bands. However, at Cape Lambert, the semi-diurnal peak was stronger at sites both within and further from the dredge zone and the peak was stronger during the dredge phase than during the baseline study (Figures A1.3a & A1.4). There was also a strong peak at sites within and away from the dredge zone at Burrup Peninsula (comparison cannot be made to the baseline study because of the lack of baseline data, Figures A1.3b & A1.5).

At Cape Lambert there was stronger energy across both small and larger period bands at site PWR than at site DLI (Figure A.1.4) and at Burrup Peninsula, between December 2007 and November 2008 (the period with the most complete continuous data), the energy from December 2007 to April 2008 was stronger than for the rest of that period and was higher at dredge site SUP2 than reference site WINI (Figure A1.5).

Seasonal cycles were weak and inconsistent across monitoring sites in each region. The strong seasonal cycle in the zonal wind across the three study regions (Figures A1.1, and A1.3) was present but weaker in the wave global spectrum at Barrow Island (Figure A1.1), and was either weak or not present in the turbidity global spectra at Barrow Island and Burrup Peninsula (Figures A1.1 and A1.3). A seasonal peak in the Cape Lambert turbidity data is present although not dominant during the dredge period (Figure A1.3). As the global wavelet spectra were calculated on the baseline and dredge periods separately, the length of the time series across all three regions is not sufficient to detect any seasonal periodicities in the global spectra, however any seasonal trends would be seen in the complete time series spectra.

The dominant periodicities in the wind were consistent at the three airports, with strong daily sea breeze and seasonal peaks in the zonal wind and only the strong daily peak in the meridional component (Figures A1.1 & A1.3). Irregularly shaped intermittent energetic features were also present, with periods ranging from 4 to 100 days in the zonal and meridional spectral plots. Higher energy regions appearing in the 30 to 100 day period range were possibly due to the Madden Julian Oscillation (MJO), which is well known for its intra-seasonal and intra-annual characteristics, causing it to appear at uneven intervals (Zhang 2005). The larger period events were less energetic than the daily sea breeze and seasonal cycles, and were slightly more energetic in the east/west direction than north/south.

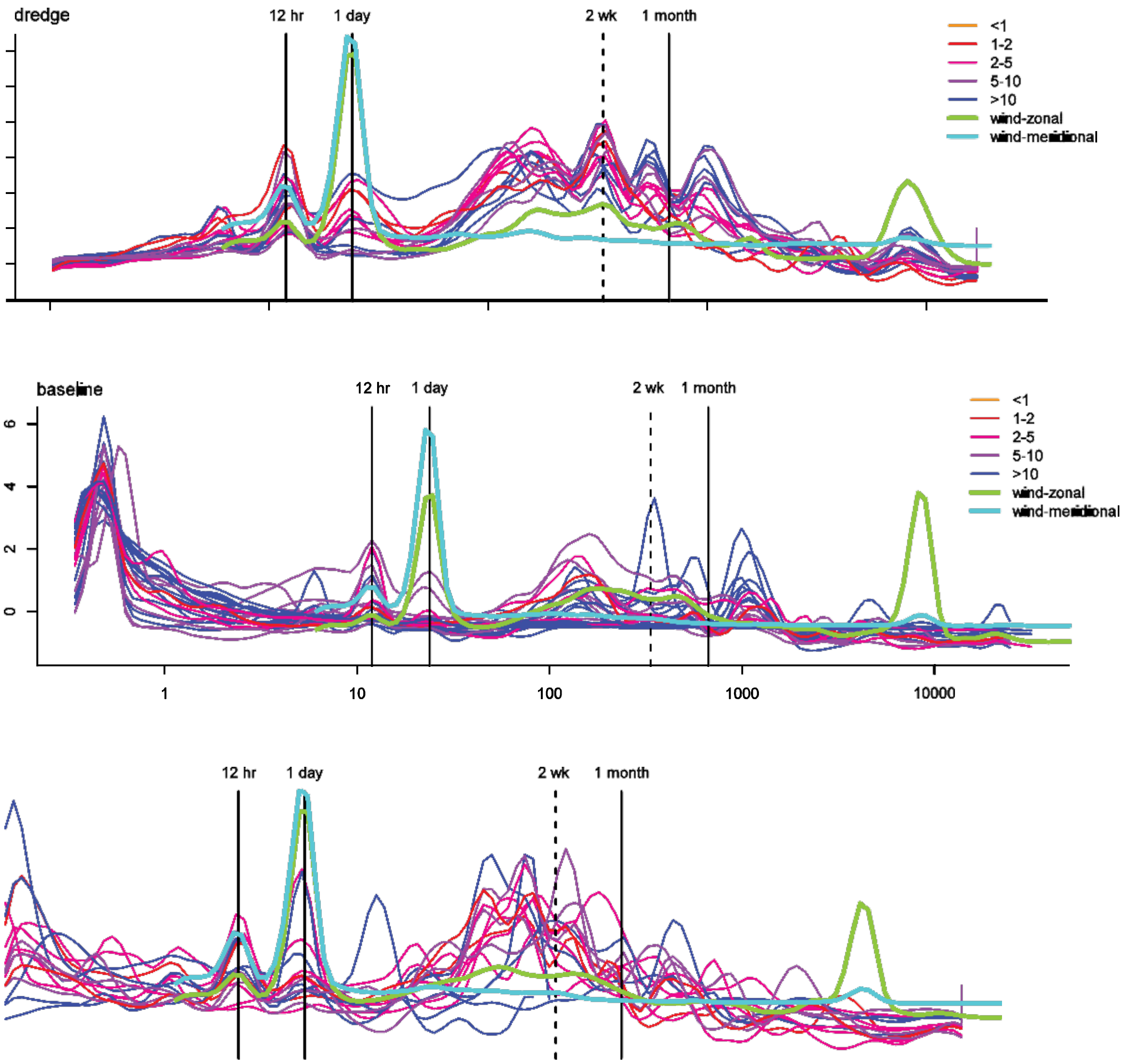


Figure A1. Global wavelet spectrum of turbidity for the Cape Lambert project (A) during the baseline (upper figure) and dredging (lower figure) periods; and Burrup Peninsula (B). Fine coloured lines show normalised temporal spectral power values across the range of periods examined, with colours grading from dark blue (sites >10km from dredging) to red (sites <1km from dredging). Overlaid are the normalised temporal spectral power curves for the zonal (light green) and meridional (light blue) wind data.

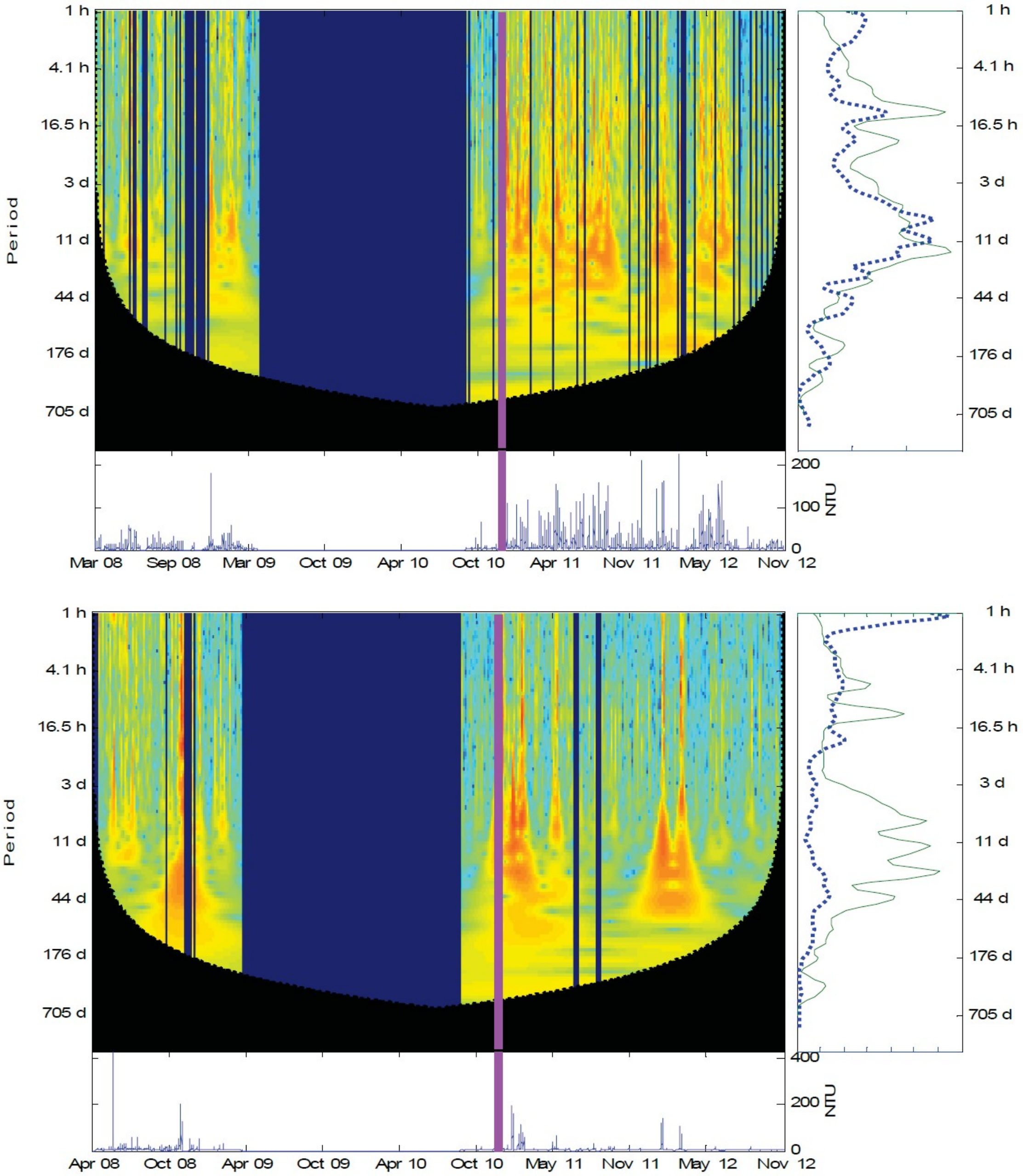
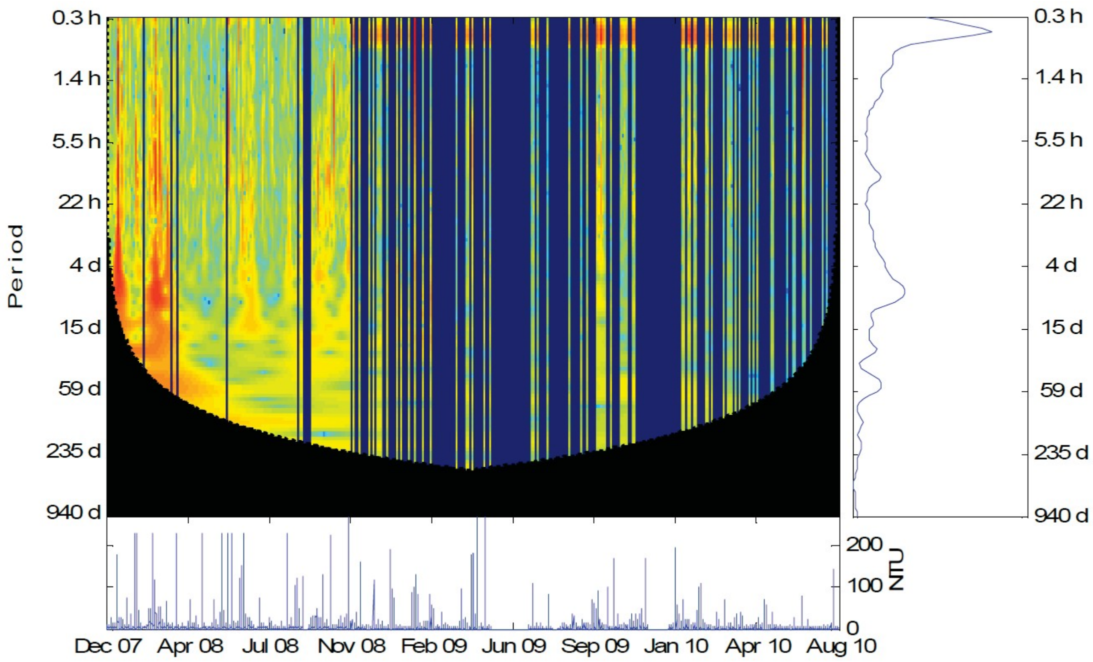


Figure A1.4. Spectral analysis for the Cape Lambert project, showing a representative dredge impacted site (PWR, upper figure) and a representative reference site (DLI, lower figure). The three panels on each figure are Wavelet spectrum (top left), global wavelet spectrum (right) and original time series (bottom). Areas of high energy are red, and low energy are yellow and green. Blue bands indicate gaps in the data, and the black curved area between the top and bottom plots is outside the cone of influence. The solid purple line running from the wavelet spectrum through to the original time series shows the start of dredging. The global wavelet spectral plot shows the peaks in the baseline data (blue dotted line) and dredge data (green solid line).



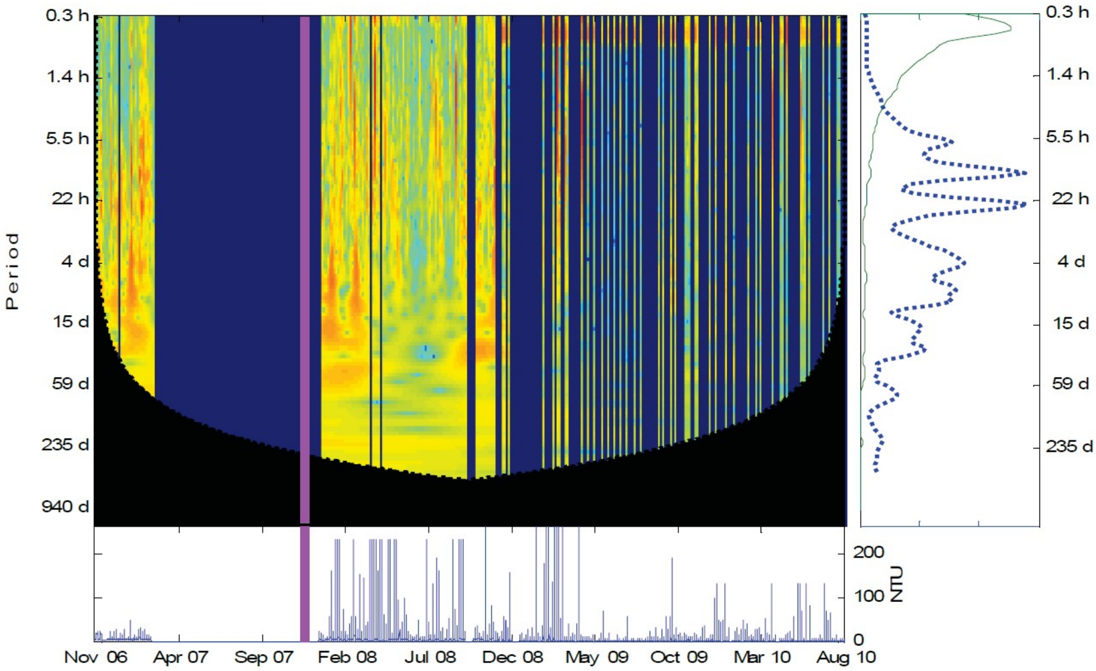


Figure A1.5. Spectral analysis for the Burrup Peninsula project, showing a representative dredge impacted site (SUP2, upper figure) and a representative reference site (WINII, lower figure). The three panels on each figure are Wavelet spectrum (top left), global wavelet spectrum (right) and original time series (bottom). Areas of high energy are red, and low energy are yellow and green. Blue bands indicate gaps in the data, and the black curved area between the top and bottom plots is outside the cone of influence. The solid purple line running from the wavelet spectrum through to the original time series shows the start of dredging. The global wavelet spectral plot shows the peaks in the baseline data (blue dotted line) and dredge data (green solid line).

Discussion and Conclusions

Analysis of temporal periodicities in turbidity and where possible wind and wave data were conducted using wavelet methods which show the temporal location of periodic events present in a time series. The dominant periodicities across all dredging projects, during both the baseline and dredge studies, occurred at the strong semi-diurnal tidal frequency (Holloway 1983b, Holloway & Nye 1985b, Kvale 2006), diurnal frequency was probably due to the strong daily sea breeze characteristic of the WA coast (Verspecth & Pattariatchi 2010), the spring/neap tidal frequency (Kvale 2006) and the longer period weather bands from 1 week to months (Schiller & Brassington 2011). Higher energy regions appearing in the 30 to 100 day period range were possibly due to the 30-60 Madden Julian Oscillation (MJO)(Madden & Julian 1994, Zhang 2005).

The peak at the semi-diurnal period was higher during the dredge period at sites close to the dredge. This peak was the same height or smaller than peaks at other frequencies during the baseline study and at sites greater than 2 km from the dredge zone during dredging. This could be due to changes in sediment type caused by dredging, whereby finer sediment is deposited by the dredge activity and is more easily resuspended by wave and tidal activity.

There was a lack of seasonal cycles in the turbidity spectra across the three study regions. Seasonal periodicities in the global wavelet spectra were weak and the locations of the peaks were inconsistent between monitoring sites. Although there were seasonal cycles in the wind data they are weak or non-existent in the turbidity data. This is consistent with other research of seasonal turbidity cycles in the region. Margvelashvili et al. (2006) found no seasonal effect on turbidity due to the lack of seasonal differences in the monthly bottom shear stress patterns responsible for sediment resuspension. Inconsistencies in the lower energy seasonal peaks were because of the length of the time series. As the global wavelet spectrum analysis was performed separately on the baseline and dredge data, and the maximum dredge period time series length is only 18 months, there are not enough cycles for the wavelet transform to precisely detect any periodicities.

References

Bureau of Meteorology (2014) Wind data at Barrow Island Airport, Karratha Airport and Roebourne Airport 2006 to 2012.

Holloway P (1983a) Tides on the Australian north-west shelf. Marine and Freshwater Research 34:213-230

Holloway P (1983b) Tides on the Australian north-west shelf. Marine and Freshwater Research 34(213-230

Holloway P, Nye H (1985a) Leeuwin current and wind distributions on the southern part of the Australian North West Shelf between January 1982 and July 1983. Marine and Freshwater Research 36:123-123

Holloway P, Nye H (1985b) Leeuwin current and wind distributions on the southern part of the Australian North West Shelf between January 1982 and July 1983. Marine and Freshwater Research 36:123

Kvale EP (2006) The origin of neap–spring tidal cycles. Marine Geology 235:5-18

Liu Y, San Liang X, Weisberg RH (2007) Rectification of the Bias in the Wavelet Power Spectrum.

Journal of Atmospheric and Oceanic Technology 24:2093-2102

Lowe RJ, Ivey GN, Brinkman RM, Jones NL (2012) Seasonal circulation and temperature variability near the North West Cape of

Australia. Journal of Geophysical Research 117:C04010-C04010

Madden RA, Julian PR (1994) Observations of the 40-50- day tropical oscillation - A review. Monthly Weather Review 122:814-837

Margvelashvili N, Saint-Cast F, Condie SA (2008) Numerical modelling of the suspended sediment transport in Torres Strait. Continental Shelf Research 28:2241-2256 Schiller A, Brassington GB (2011) Operational Oceanography in the 21st Century.

Torrence C, Compo GP (1995) A Practical Guide to Wavelet Analysis.

Verspecth F, Pattariatchi C (2010) On the significance of wind event frequency for particulate resuspension and light attenuation in coastal waters. Continental Shelf Research

Wright W (1997) Tropical-extratropical cloudbands and Australian rainfall: I. Climatology. International journal of climatology 17:807-829

Zhang C (2005) Madden - Julian oscillation. Reviews of Geophysics 43:1-36