Estimating sediment deposition fields around dredging activities

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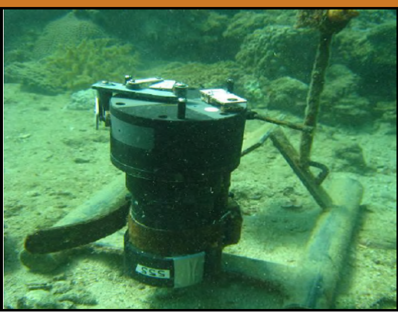
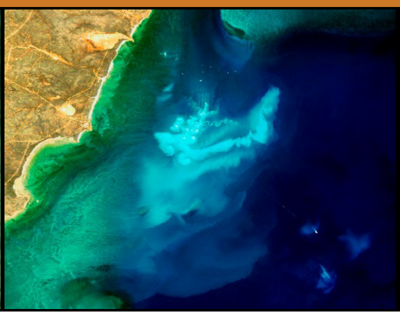
WAMSI Dredging Science Node

Theme 4 Report

Project 4.3

November 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.

Funding Sources

The $20 million 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

woodside Chevron western australian marine science institution bhpbilliton

Critical data

RioTinto

Legal Notice

Year of publication: 2017

Metadata: http://catalogue.aodn.org.au/geonetwork/srv/eng/metadata.show?uuid=c9d5edc9-92f1-4180-923d-90614e35d263

Citation: Stark C, Whinney J, Ridd P, Jones R (2017). Estimating sediment deposition fields around dredging activities. Final Report of Theme 4 - Project 4.3 prepared the Western Australian Marine Science Institution. Perth, Western Australia 26 pp.

Author Contributions: Contributed to analysis and figure preparation: CS, JW, PR, RJ. Wrote the manuscript: CS, RJ, PR. All authors read and approved the final report.

Corresponding author and Institution: Clair Stark (JCU).

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: None

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

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: JCU Geophysical laboratory Neph 1000 series nephelometer, light and pressure sensor deployed at Barrow Island (Source: JCU)

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 29 August 2010.

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

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Executive Summary

Environmental guidelines associated with dredging in Western Australia encourages dredging proponents to make scientifically sound predictions of the likely areal extent of any environmental effects associated with any turbidity-generating activities (EPA 2016). Smothering of benthic organisms by high levels of sediment deposition is known to be one of the key cause-effect pathways associated with dredging activities (Jones et al. 2016). The problem is that there are currently no reliable techniques to measure sedimentation over appropriate scales (i.e. mg cm^{-2} d^{-1}). In this study we assess an alternative approach – a statistical turbidity model – to estimate sediment deposition and the size of a sediment deposition zone around a dredging project. The underlying principle is based on the difference in the likely deposition rates or accumulation magnitude that would occur between turbidity caused by natural sediment resuspension events and turbidity caused by dredging activities. Natural resuspension in the shallow reef environment is typically caused by tidal currents, swell and especially wind-driven waves. High suspended sediment concentrations (SSCs) can be generated but typically occur under energetic conditions where the water column hydrodynamics are sufficient to keep at least some of the sediments from settling. Sediment deposition will occur but during quiescent periods, and following entrainment and dilution, and over a period where energy in the water column is gradually decreasing. In contrast, dredging can create high SSCs in a low energy water column where the ambient hydrodynamics are often insufficient to keep the sediment load in suspension. The sediments can rapidly fall out of suspension according to particle specific settling velocities. Sediment deposition generated under such conditions could exceed those during natural resuspension events, and which nearby organisms are physiologically adapted to. Furthermore, the increased sedimentation in a low energy environment during dredging is more likely to remain *in-situ* with no wave activity to resuspend and remove the accumulation.

Turbidity can be predicted by a model (see below) based on the collection of only a few variables including pressure fluctuations at the seafloor induced by surface gravity waves. The model, developed by the James Cook University Marine Geophysics Lab, is an additive power model which predicts daily turbidity from water pressure measurements which have been transformed into estimates of the natural turbidity resuspension mechanisms - waves and tides. Other elements can also be incorporated into the model, for example wind speed. Model inputs were calibrated against (daily averaged) turbidity measurements. The primary purpose of the model is to estimate natural turbidity levels, and these modelled values can be used during dredging to decouple the natural and dredge related turbidity i.e. the measured turbidity is a combination of natural + dredged turbidity, therefore subtracting the modelled (natural) turbidity from the measured (natural + dredged) turbidity provides an estimate of the turbidity caused solely by dredging. Furthermore, seafloor sediment deposition can also be estimated from the model - if the measured turbidity exceeds the estimate from the model — and in the absence of alternative explanations such as sediments within river plumes — then an assumption is made that the difference is caused by a dredging plume and could result in high levels of sediment accumulation. The greater the difference between the measured and the predicted (modelled) turbidity value, hereafter referred to as the overburden, then the greater the probability of high sedimentation rates (rate of accumulation).

$$\hat{T}(t) = a_0 X_{rms}^{b_0}(t) + a_1 X_{rms}^{b_1}(t-1) + a_2 X_{wh}^{b_2}(t) + a_3 X_{tc}^{b_3}(t) + a_4 X_{tr}^{b_4}(t) + a_4 X_{w}^{b_4}(t) + a_5$$

Where: $\hat{T}\,(t)$ is the estimated turbidity at time *t*, *Xrms* is the root mean square (RMS) of pressure fluctuation at the seafloor induced by surface gravity waves, *Xrms* (t-1) is the seafloor RMS pressure fluctuations from the previous day, *Xwh* is the water height, *Xtc* refers to tidal current, *Xtr* is tidal range and *Xw* is wind.

The performance of the model to predict dredge related turbidity was evaluated at two different locations with different hydrodynamic settings: an offshore clear water environment on the eastern side of Barrow Island[1] (Western Australia), and a turbid coastal environment at Hay Point (North Queensland). During the dredging

[1]Gorgon Gas Development Barrow Island Nature Reserve: WA Environmental Protection Authority (EPA) Bulletin 1221 Ministerial Statement No. 800

phase of the Barrow Island project information from optical back scatter (OBS) deposition sensors (Ridd et al. 2001) was also available. Although these devices could not provide accurate measurements of sediment deposition at small temporal scales (see below) they could provide a relative index of sediment deposition across sites at different distances from the dredging, allowing an assessment of the modelling approach and also a semi-quantitative estimate of the sediment deposition field.

The model parameters, $a_{0\text{-}4}$ and $b_{0\text{-}4}$, were optimised by fitting the model input variables to the corresponding turbidity measurements using the first half of the baseline data (fit period) for each of multiple sites at Hay Point and Barrow Island. The success of the fit at the sites was tested using the second half of the baseline data (test period) by calculating the R^2 values between measured and modelled turbidity.

Overall the ability of the model to predict natural turbidity was strong when applied to the more turbid environment of Hay Point, where during the test period 83% of the sites had R^2 >0.5; however, the model performance was much weaker at the Barrow Island sites, where only 38% of the sites had R^2 >0.5. Waves were found to influence the turbidity model more than the other input variables at both sites. At some of the Hay Point sites waves on the previous day were also a significant component, whereas at Barrow Island the previous day waves had negligible influence. Wind influence (measured at Barrow Island sites only) was minor compared to the influence of waves.

Overall the measured turbidity levels during the dredging period at Barrow Island were much higher than predicted by the turbidity model. The median daily overburden (up to ~5 NTU) and maximum daily overburden (up to ~70 NTU), was higher at sites close to dredging and decreased with increasing distance from dredging (hence under less influence from the plumes).

During the Barrow Island project optical back scatter (OBS) deposition sensors (Ridd et al. 2001) were also deployed at the turbidity monitoring sites at different distances from the dredging activities. The sensors detect sediment accumulation over periods of several hours on a smooth glassy surface and can also provide an estimate of sediment deposition. However, inspection of the data showed sediment frequently moved off the sensor plate and resettled again within the 2 h accumulation period, preventing calculation of an absolute sedimentation rate. Nevertheless, they could provide a relative sediment deposition index (SDI) by averaging any evidence of sediment deposition over the day. Median deposition levels at sites within 0.5 km to the south of the main excavation site were up to 7 × higher than at distantly located reference sites which had deposition and overburden levels similar to baseline (background) conditions. As with the overburden modelling, the deposition sensors indicated a decrease in sediment deposition with increasing distance from the dredging. The model performance for identifying overburdens at Hay Point could not be tested as there was no dredging phase.

Considerations for predicting and managing the impacts of dredging

The turbidity modelling approach is a simple and cost effective method that has the potential to identify turbidity associated with dredging activities (as opposed to natural resuspension events), which could result in enhanced levels of sediment deposition. This knowledge would provide dredging operators with the ability to better manage the intensity and duration of sediment deposition events on sensitive receptors. The turbidity model performed well in the test phase at Hay Point, however the modelling approach could not always accurately predict turbidity in the testing period at the Barrow Island sites. The difference in model performance was most likely due to the different ambient water quality conditions and local hydrodynamics. Hay Point is a coastal region and more exposed to wind and wave events, and there were numerous short-term turbidity peaks >20 NTU to fit the model. In contrast, at the offshore Barrow Island sites there were only occasional turbidity events during the model fit period, preventing a good fit of the model input variables. The Barrow Island sites are on the lee of an offshore island, and are protected from wave activity and is generally a clearer water environment. **Since the usefulness of the model depends on sufficient turbidity events in the baseline phase to allow fitting, the conclusions are it cannot be used generically and would need to be evaluated at each site and location.**

The modelling approach was tested against *in situ* deposition sensors based on an early, prototype version described by Ridd et al. (2001). As noted above, these instruments provided information on depositing sediments but, due to the smooth surface and the design and geometry of the sensor, could only provide a relative index of sediment deposition as opposed to absolute values. The sensor head has since been re-designed based on this analysis as part of the WAMSI Dredging Science Node (Whinney et al. 2017).

Despite these limitations of both techniques, the combined approaches suggested that at Barrow Island a sediment deposition field occurred <10 km south of the main dredging area (from the overburden modelling) or <3 km (from the deposition sensors measurements). The latter, smaller, distance is consistent with images of hundreds of individual coral heads photographed at the turbidity and sediment deposition monitoring sites as part of a coral health monitoring program, which showed high levels of sediment covering in this area. It is also consistent with analyses of mucus sheet production in massive *Porites* spp. corals, which is considered a bioindicator of sediment deposition, and which showed frequent mucous sheet production in an area <5 km south of the dredging (Bessell-Browne et al. 2017).

Recently, Fisher et al. (2015) undertook spatial analyses of water quality during the Barrow Island project, showing a predominantly southward movement of plumes during the dredging project consistent with satellite (MODIS) observations of surface plumes (Evans et al. 2012). Fisher et al. (2015) used the P_{50}–P_{80}[2] approach of ANZECC/ARMCANZ (2001) to estimate distances of detectable effects on turbidity. **For the mean and median daily turbidity, the P_{50}–P_{80} approach indicated clear effect on water quality at distances 15–20 km south of the dredging, much further than the extent of the deposition field. Turbid plumes of water from dredging can clearly travel great distances, but measurable changes in sediment deposition occur over a much smaller area, closer to the source.**

The turbidity modelling/overburden estimation technique has shown some potential, but further research is needed, using the approach in different marine environmental settings (turbid and clear water environments) and testing of sediment deposition estimation fields against newly designed sediment deposition sensors (Whinney et al. 2017) before it could be used reliably.

Pre-development Surveys

If the turbidity modelling/overburden approach is attempted then calibration and validation of the model is needed, involving fitting the model input variables (wave and tidal data) to the measured turbidity levels, then testing the model fit accuracy against a separate section of baseline turbidity data to determine model performance. Spectral analysis of baseline turbidity data in the Pilbara region (see Fisher et al. 2017) has shown that natural periodicities are present and most dominant cycles were semi-diurnal and diurnal signals (caused by tides and daily sea breezes) and spring-neap signals. **Pre-development surveys should be sufficiently long enough to incorporate semi-diurnal to spring-neap tidal cycles in turbidity data for accurate tidally driven resuspension modelling. At least 6 months of pre-development data should be collected to allow a fit and test of the model although this may be less in more coastal, nearshore environments where turbidity events are more frequent.**

Monitoring

If the turbidity model is performing well, then it can be used to calculate the daily overburden and when summed over time would provide an integrated value of exposure to sediment from dredging as opposed to natural re-suspension events.

In monitoring programs associated with dredging campaigns it is often necessary to understand the underlying cause of any mortality events (e.g. of corals, seagrasses, filter feeders) that may be observed. The purpose is to determine whether dredging activities were (reasonably) considered to have caused or contributed to the impact, as opposed to natural events such as coral disease events, bleaching events, predator outbreaks etc. Sometimes called 'inference assessments', the approach involves reviewing all available evidence (a weight of

[2]The basis of the P_{50}–P_{80} approach is somewhat arbitrary and associated with a notion of the developers that a median value at an impact site above the 80th percentile of a baseline site represents a 'measurable perturbation' and thus worth investigating.

evidence approach) based on carefully structured arguments that support or rule out plausible alternative predictions. The turbidity modelling/overburden approach could be used as part of a weight of evidence approach to assess if the sites had received high sediment loads and attribute the source of the turbidity events (natural or dredge related). Sediment traps are often used in such inference assessments to identify sediment deposition events during dredging programs. Sediments traps are typically deployed by SCUBA divers, resolution is coarse (averaged per day over several weeks of deployment) and data on sediment trap accumulation rates are only available after drying and weighing the accumulated sediments which takes time. **In contrast the turbidity modelling/overburden technique can provide a rapid initial assessment of whether sites were potentially exposed to elevated turbidity that may have given rise to a deposition event.**

Residual Knowledge Gaps

The performance of the turbidity model needs to be further tested in a range of different environmental settings and ideally where there have been concurrent measurements of physical forcings such as waves and tidal currents coupled with near-sea bed turbidity and sediment deposition rates collected at high temporal frequency (such as with the deposition sensors described by Whinney et al. (2017)).

The underlying principle — that elevated SSCs created by a dredging plume in a low energy water column will result in elevated sediment deposition — has been demonstrated in this study. Using this principle it may be possible to assess a sediment 'overburden' by subtracting turbidity at control or reference sites located beyond the influence of plumes but still in the same geographic, hydrodynamic and sedimentary setting. Previous attempts to use an adjacent bay as a turbidity control site has not been successful (Orpin et al. 2004), but this avenue could be explored further using multiple control sites and temporal smoothing of data (e.g. using running means analysis).

1 Introduction

Dredging and dredge related activities such as dredge material placement (spoil disposal) can temporarily release sediment into the water column where it can have a range of environmental effects on sensitive benthic communities such as coral reefs (Rogers 1990, Foster et al. 2010, McCook et al. 2015, Jones et al. 2016). The settlement of the re-suspended sediment in particular is a well know hazard, requiring epi-benthic organisms to expend energy self-cleaning or become progressively smothered in sediments. In sensitive organisms such as corals, smothering is commonly observed in dredging projects close to reefs (Dodge & Vaisnys 1977, Bak 1978, Jones et al. 2016) and the reduction in gas (solute) exchange, under some circumstances, can quickly lead to local tissue mortality and lesion formation (Weber et al. 2012).

Environmental policy in Australia requires dredging proponents to make scientifically sound predictions of the likely areal extent of any environmental effects and to manage projects accordingly under a spatially defined zonation scheme (EPA 2011, 2016). The spatial and temporal patterns of suspended sediment concentrations (SSCs) and light reduction, and the relationship with distance from dredging, has recently been described for a number of large scale dredging projects (Fisher et al. 2015, Jones et al. 2015). However, establishing the same relationships for sedimentation has proved difficult, in part because of considerable difficulties measuring short term sedimentation rates at the appropriate scales (i.e. mg cm^{-2} per hour or day, reviewed in Thomas and Ridd (2004), and Jones et al. (2015)). Nevertheless, being able to predict the scale of potential impacts of sedimentation from dredging near coral reefs is important for dredging management, and establishing an evidence-based footprint is increasingly becoming important for public perception of the nature and scale of dredging projects (Fisher et al. 2015, Spearman 2015).

Measuring sediment deposition *in situ* with optical backscatter sensor (OBS) techniques during dredging projects was first described by Thomas et al. (2003). However, the flat measuring plates of the sediment accumulation sensors (SAS) can result in rapid resuspension and possibly saltation of sediments across the surface, giving low or sometimes spurious readings (Ridd, personal observation and see also below). Conventional techniques such as sediment traps cannot be used for estimating sedimentation in the shallow reef environment for reasons outlined in Reynolds et al. (1980), Ridd et al. (2001), Ogston et al. (2004), and most recently in Storlazzi et al. (2011), and so alternative, more novel techniques or approaches are needed.

One such approach is to identify conditions in the water column that are likely to result in high sediment deposition at the seabed during dredging. The underlying principle is based on identifying whether high turbidity is caused by natural resuspension events or by dredging, as they are likely to result in two different sedimentation regimes. Natural resuspension of sediments in the shallow reef environment is caused by tidal currents and especially wind-driven waves (Larcombe et al. 1995, Jing & Ridd 1996, Larcombe et al. 2001, Ogston et al. 2004, Presto et al. 2006, Verspecht & Pattiaratchi 2010). High SSCs can be generated but this typically occurs under energetic conditions where the water column hydrodynamics are sufficient to keep at least some of the sediments from settling. Sediment deposition occurs but during quiescent periods and following entrainment and dilution, and over a period where energy in the water column is gradually decreasing (Ogston et al. 2004). In contrast, dredging can create high SSCs in a low energy water column where the ambient hydrodynamics are insufficient to re-suspend deposited sediments and keep the sediment load in suspension. The sediments can rapidly fall out of suspension according to particle specific settling velocities. Sediment deposition generated under such conditions could exceed those during natural resuspension events and which nearby organisms are physiologically adapted to (Jones et al. 2016).

To use this technique it is necessary to estimate likely SSCs from information on waves and tidal current i.e. to develop a turbidity model. If the SSCs exceed the estimates predicted from the model, and in the absence of alternative explanations such as sediments within river plumes, then an assumption is made that the difference is caused by a dredging plume and could result in high levels of sedimentation. The greater the difference between the measured and the predicted (modelled) SSC value - hereafter referred to as the 'overburden' - the greater the probability of high sedimentation rates.

The turbidity modelling approach has not yet been experimentally tested, but the opportunity exists using data collected from a recent large scale capital dredging project on Australia's east coast (the Hay Point project) and west coast (the Barrow Island project). The state and federal regulatory conditions for the projects to occur were comprehensive, involving detailed water quality monitoring at multiple sites at different distances from the dredging, and including requirements to collect pre-dredging baseline data. During the Barrow Island project, which was conducted on a coral reef, a coral monitoring program was also undertaken involving regular *in situ* inspections and photographing hundreds of individually marked corals at multiple sites and at multiple distances from the primary dredging sites. In this study we examine and test some of the underlying assumptions of the turbidity modelling approach and the use of background (reference) sites to estimate sediment overburden and periods of enhanced deposition. We use this approach to calculate the potential spatial scale of sediment deposition zone around dredging, and compare it to information from SAS sensors.

2 Materials and Methods

2.1 Study sites

The studies were conducted near Hay Point, in the coastal nearshore environment of the central coast of Queensland, and around Barrow Island, a 'clear water' environment about 55 km offshore in the Pilbara region of NW Australia (Figure 1). Water quality and hydrodynamic data were collected every 10 min from 6 sites in the vicinity of Hay Point and at 12 sites on the eastern side of Barrow Island. Data were collected at Hay Point from July 2014–July 2015 and at Barrow Island from December 2007–December 2012. The Barrow Island study sites were positioned along a north to south transect from 0.2 km away from the main site of dredging to up 30 km away (Figure 1).

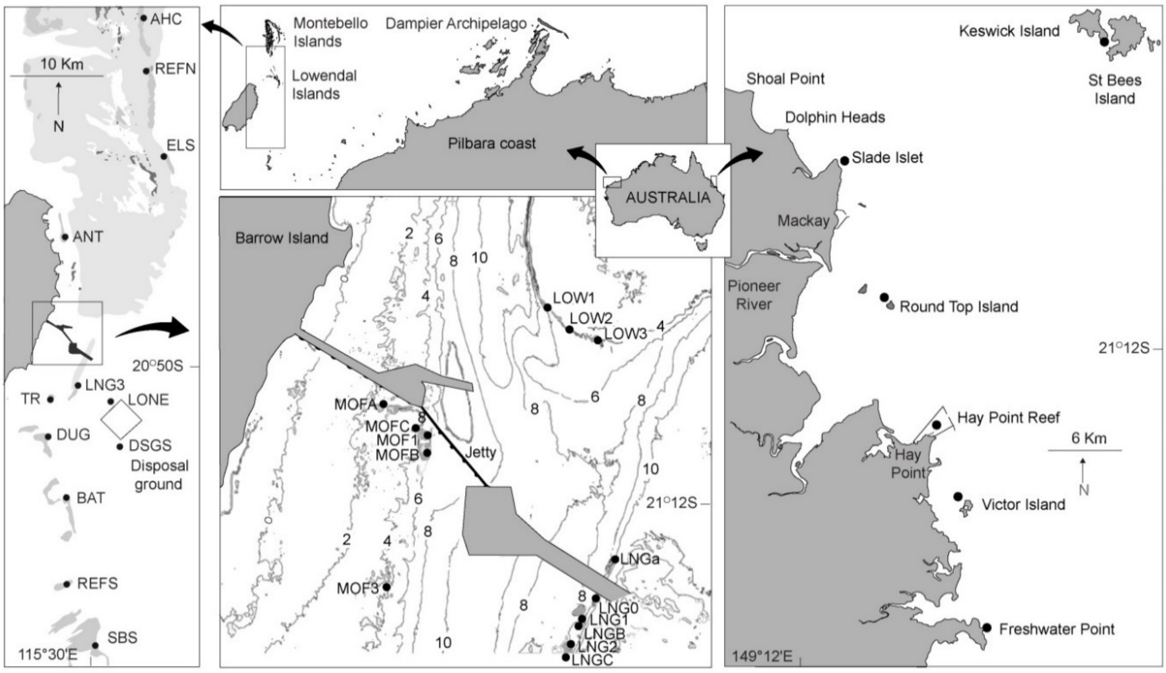

Figure 1 Location map showing Barrow Island situated in a clear-water environment 55 km offshore from the Pilbara coast in NW Australia, and Hay Point on the central coast of Queensland in NE Australia.

At each of the monitoring sites, measurements were taken every 10 min using sensors mounted on a steel framed platform ~40 cm from the seabed. Turbidity was measured with a sideways facing optical fibre backscatter (OBS) nephelometer (Macdonald et al. 2013) and sediment deposition measured using a sediment accumulation sensor (SAS) which also uses OBS (Ridd et al. 2001, Thomas & Ridd 2005). To prevent biofouling all optical sensors had a built-in wiper which cleaned the sensor surface every 2 h. Water pressure was measured with a water pressure sensor in units of m.

2.2 Turbidity model

Water column turbidity was modelled using hydrodynamic variables to simulate the primary natural resuspension processes of waves and tides. Model input parameters were derived from water pressure measurements.

$$\hat{T}(t) = a_0 X_{rms}^{b_0}(t) + a_1 X_{rms}^{b_1}(t-1) + a_2 X_{wh}^{b_2}(t) + a_3 X_{tc}^{b_3}(t) + a_4 X_{tr}^{b_4}(t) + a_5 X_{w}^{b_5}(t) + a_6 \quad (1)$$

where $\hat{T}\ (t)$ is the estimated turbidity at time t in units of days.

Pressure fluctuations at the seafloor, induced by surface gravity waves, were calculated by taking the root mean square (RMS) of the ten consecutive readings over ten seconds.

$$X_{rms}(t) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (2)$$

where X_{rms} is the RMS pressure fluctuation, n is the number of samples (ten), x_i is the i^{th} pressure sample, and $\bar{x}$ is the mean of the ten pressure samples. RMS data was averaged on a daily basis, using the arithmetic mean due to excessive noise present in the 10 min sampling of the raw data (Whinney 2007).

$$\bar{x_j} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i} \quad (3)$$

where $\bar{x_j}$ is the j^{th} mean data point, n is the number of samples averaged which was set to 144 for water quality logger data and 8 for wind data (i.e. 1 day), x_i is the i^{th} raw data point (once per ten minute sample).

The seafloor RMS pressure fluctuations from the previous day (*t-1*) were included in the model as X_{rms} *(t-1)* (equation 1) to account for any temporal lags. X_{wh} is the water depth and is the arithmetic mean of the ten consecutive 1 s pressure readings. X_{tc} refers to tidal current and was assumed to be related to the difference in water height between 20 min samples. The tidal range, X_{tr} is the RMS of the raw water depth, X_{wh} data using a 13 h window (to ensure each sample includes one peak and one trough of the semi-diurnal tidal changes). X_w is a wind parameter (tested during the Barrow Island project only) based on wind speed recorded every 3 h at the airport on Barrow Island (Bureau of Meteorology Station ID: 005094). All input variables were averaged over 1 day.

Model parameters, a_{0-5} and b_{0-5}, were optimised by training (fitting) the model input variables to the corresponding turbidity measurements using the first half of the baseline data (fit period) for each site. Turbidity was modelled only at sites that had turbidity peaks >5 NTU during the fit period to ensure there was sufficient information to fit the model. The success of the fit at these sites was tested using the second half of the baseline data (test period). The MATLAB non-linear least squares function ('lsqnonlin') (MathWorks® 2017) was used to optimise the model. A nonlinear method was used due to the number and complexity of the parameters being optimised, with five coefficients and five indices requiring optimisation, as well as the offset term, a_6.

Non-linear least squares optimisation estimates the model parameters that minimises the function:

$$\sum_{i=1}^{n}\left(T_i - \hat{T}_i\right)^2 \tag{4}$$

where $\hat{T}_i$ is the i^{th} modelled turbidity value at time t and T_i is the measured turbidity value at t.

The success of the model was tested by calculating the R^2 values between measured and modelled turbidity for the fit and test period, and by visually comparing concurrent measured and modelled turbidity events during the baseline period. Absolute residual errors between the modelled turbidity and measured turbidity (the overburden, or excess SSC attributable to dredging) were calculated at each site. Relative residual errors were also calculated by dividing the absolute residual by the daily measured value.

2.3 Surface sediment density (SSD)

Turbidity from the sideways facing OBS was subtracted from the upwards facing OBS to provide readings of sediment deposition (by removing water turbidity from the deposition sensor readings). The deposition readings were then converted to surface sediment density (SSD, in units of mg cm^{-2}) by laboratory calibration in a 3 m tall perspex settling tube. A sensor and weighing pan were placed at the bottom of the tower, and sediment from each site was mixed with water and placed in the tower. The weight of the sediment was converted to SSD, and the OBS readings were converted to SSD using an SSD–OBS curve (Ridd et al. 2001). The ten minute SSD measurements were daily averaged and reported as a relative sediment deposition index (see below).

3 Results

3.1 Turbidity model

In the nearshore coastal environment at Hay Point, average daily turbidity values in the fit and test (baseline) periods ranged from ~1 NTU to a maximum of 556 NTU (Table 1) and included numerous short-term turbidity peaks to >20 NTU, as shown for a representative site (Hay Point Reef) in Figure 2. In the offshore, clear-water, reefal environment at Barrow Island average daily turbidity values in the baseline period ranged from ~1 NTU to a maximum of 90 NTU (Table 2). Occasional turbidity increases were noted, but the turbidity only exceeded 5 NTU on a few occasions and only at site LONE (Table 2). During the dredging period, there were numerous dredge-related turbidity events exceeding 10 NTU (shown for representative site MOF1 in Figure 3), including maximum turbidity values exceeding 200 NTU at sites LNG0, LNG1 and MOF1 (which were <1 km from the dredging Figure 1, Table 2).

Table 1. Hay Point data. Summary table showing mean ± SD, maximum daily and maximum turbidity (NTU) during the baseline (fit and test period) and R^2 values in the fit, test and baseline period at Hay Point (see Figure 1).

	Turbidity (NTU)				R^2 Fit, test, baseline (fit + test) periods		
Sites	$\bar{x}$	SD	Max daily	Max	Fit period	Test period	Fit and test period
Hay Point/Reef	8.4	16.9	97.6	406	0.79	0.45	0.83
Freshwater Point	11.4	25.1	127.7	556	0.60	0.68	0.81
Keswick Island	1.1	1.3	6.1	30	0.61	0.57	0.75
Round Top Island	3.3	9.6	82.8	364	0.32	0.56	0.71
Slade Point	8.6	16.4	85.9	303	0.07	0.64	0.66
Victor Island	8.1	14.4	91.5	294	0.12	0.62	0.68

Table 2 Barrow Island data summary table showing mean ± SD, maximum daily and maximum turbidity (NTU) during the baseline (fit and test period) and R^2 values between daily measured and modelled turbidity in the fit, test and baseline period (see Figure 1). The 'overburden' (i.e. difference between measured and modelled turbidity during the dredge period – see text) is shown as an average daily turbidity value and maximum daily turbidity. The numbers associated with the Barrow Island sites are distances (km) either north or south from the primary excavation site (see Figure 1). Sites LONE and DSGS at Barrow Island were 4.2 and 9 km south of the primary site of dredging and also 0.1 km from the dredge material (spoil ground) placement site (Figure 1).

	Site	Distance (km)	Turbidity (NTU)								R^2 between measured and modelled turbidity			Daily overburden (NTU)	
			Baseline				Dredge								
			$\bar{x}$	SD	Max daily	Max	$\bar{x}$	SD	Max daily	Max	Fit	Test	Baseline	Max	Mean
Northern sites	AHC	32.8	1.6	2.0	18.5	74.9	1.3	2.0	13.1	122.9	0.42	0.60	0.48	6.29	-1.35
	REFN	28	0.8	0.3	1.5	3.4	1.5	2.2	28.5	76.5	0.60	0.65	0.59	2.13	-3.01
	ELS	21	1.3	0.4	2.1	16.2	1.0	1.3	18.9	49.8	0.49	0.46	0.43	0.04	-3.07
	ANT	8.8	1.2	0.8	13.3	91.2	1.4	1.5	13.9	94.1	0.24	0.35	0.31	9.44	0.15
	DIW	6.5	1.9	0.7	3.3	15.7	1.3	1.4	14.4	112.1	0.05	0.07	0.06	12.94	0.18
	LOW	1.9	1.4	1.2	11.8	32.7	1.4	1.7	21.4	66.0	0.27	0.38	0.31	7.35	-0.49
	LOW1	1.6	1.1	0.4	2.0	13.4	1.3	1.1	16.4	45.6	0.09	0.11	0.01	6.95	-1.10
	LNGA	0.3	1.3	0.2	2.2	9.3	6.4	8.7	74.3	294.0	0.08	0.19	0.18	48.77	3.14
Southern sites	LNG0	0.2	1.2	0.8	8.5	28.4	6.1	7.9	60.0	231.0	0.44	0.21	0.16	57.22	4.37
	LNG1	0.5	1.2	1.0	13.1	35.1	5.2	6.8	52.8	268.6	0.32	0.40	0.33	41.56	1.07
	LNGB	0.7	2.1	0.8	3.3	5.9	5.4	7.8	79.4	392.3	0.17	0.37	0.33	70.15	1.48
	LNG2	1.0	1.0	0.8	6.0	24.6	3.7	4.1	32.1	191.6	0.17	0.31	0.23	23.92	0.40
	LNGC	1.4	1.0	0.4	2.6	8.2	4.7	6.6	58.7	196.0	0.54	0.52	0.50	50.57	-0.30
	LNG3	4.0	1.4	1.4	18.4	38.3	3.2	5.4	59.9	114.1	0.58	0.65	0.62	32.04	1.40
	MOF1	0.8	1.3	1.0	9.4	39.8	4.9	7.2	74.0	259.8	0.23	0.28	0.23	70.63	3.29
	MOFB	1.0	1.5	0.5	3.9	15.3	4.1	5.8	68.6	233.2	0.08	0.27	0.24	64.82	2.19
	MOF3	1.5	1.4	1.2	11.6	45.0	3.2	4.4	50.0	148.1	0.20	0.19	0.23	29.38	1.57
	MOFA	0.6	1.8	0.6	5.6	27.6	7.0	14.4	153.0	547.2	0.13	0.48	0.41	134.11	4.81
	MOFC	0.7	2.1	0.8	6.4	24.5	6.5	11.0	120.2	415.4	0.12	0.25	0.21	116.39	4.84
	TR	5.0	1.3	0.7	8.2	23.4	3.7	6.4	70.6	132.9	0.69	0.72	0.71	32.70	1.55
	DUG	9.2	1.4	1.4	10.9	49.3	2.9	6.3	53.5	103.3	0.10	0.39	0.27	42.10	1.41
	BAT	15	1.4	1.2	9.3	37.2	1.5	2.8	32.5	92.3	0.22	0.62	0.37	12.14	-1.03
	REFS	24	2.2	1.4	5.2	14.1	1.5	2.3	20.0	43.2	0.26	0.77	0.62	4.97	-1.60
	SBS	30	2.7	4.6	26.9	84.2	1.6	2.3	30.5	67.7	0.42	0.53	0.36	3.10	-2.45
Spoil Ground	LONE	4.2	1.0	1.0	10.0	41.1	1.4	2.0	17.6	43.6	0.64	0.78	0.72	6.43	0.03
	DSGS	9.2	0.8	0.3	1.5	7.8	1.8	3.1	25.3	55.1	0.17	0.67	0.63	15.16	0.74

Waves influenced the turbidity model more than the other input variables at Hay Point and Barrow Island sites (Figure 2C, Figure 3C). At some of the Hay Point sites the waves on the previous day (RMS waves at time *t-1*) were also a significant component of the model (Figure 2D), whereas at Barrow Island the same parameter had a negligible influence (Figure 3C). Wind (measured at Barrow Island sites only) was minor compared to the influence of waves.

During the dredging phase at Barrow Island measured turbidity levels at the sites closest to the dredging (hence under the immediate influence of dredging plumes) were much higher than predicted by the turbidity model (Figure 3A).

The median daily overburden (up to ~5 NTU and maximum of up to ~70 NTU), was higher at sites close to dredging and decreased with increasing distance from dredging (hence under less influence from the plumes, Table 2, and Figure 4).

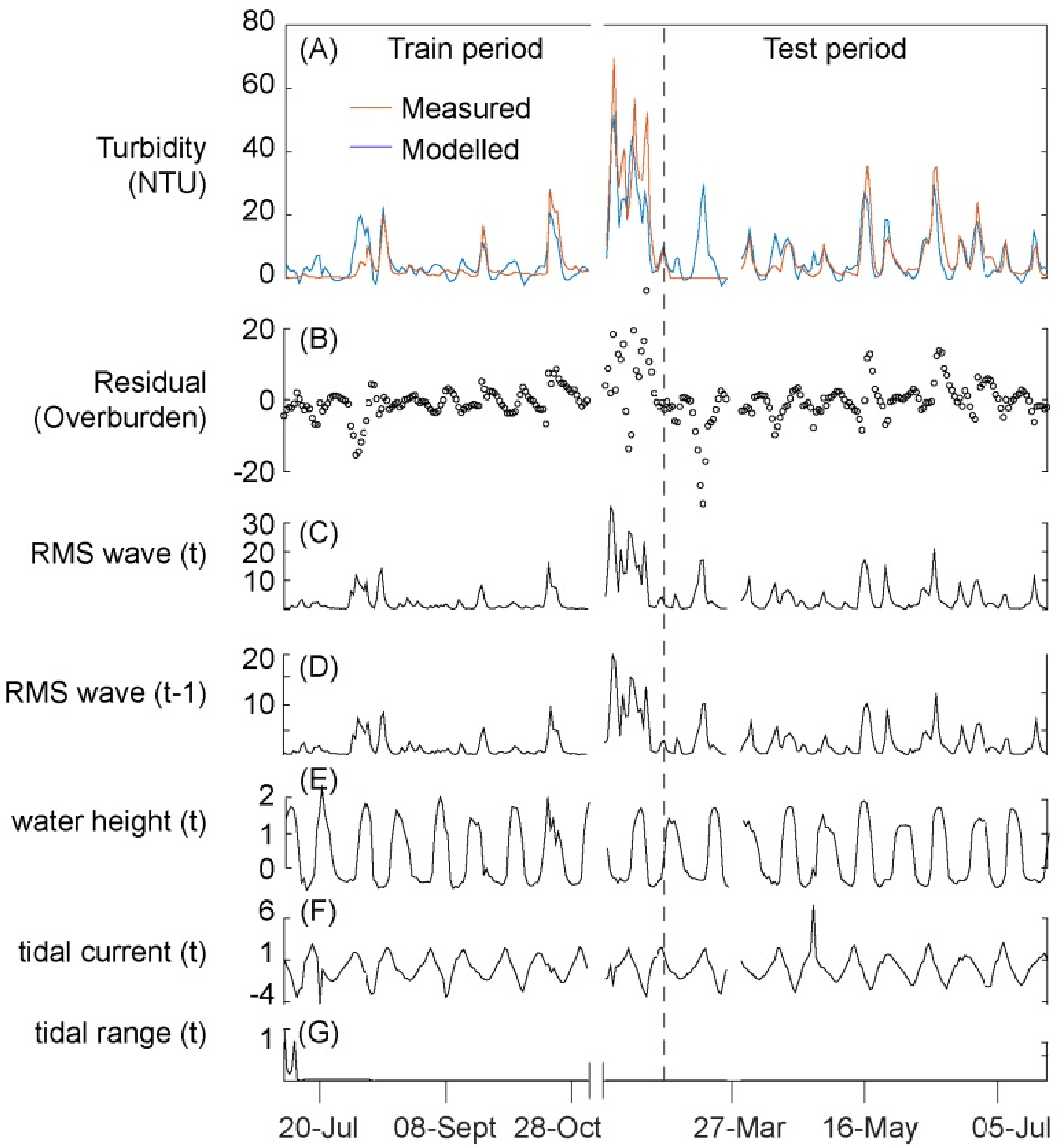

Figure 2. Hay Point project. Turbidity model (equation 1) performance at Hay Point Reef (see Figure 1) during the baseline fit and test periods showing the predicted NTU contribution attributable to each model parameter: (A) the modelled (blue line) and measured (orange line) turbidity levels, (B) the residual turbidity, or 'overburden', which is the difference between the measured and predicted turbidity. Figures C–H show the model terms (with model parameters applied) including: (C) waves at time t, (D) waves from the previous day (waves at t-1), (E) water height at time t, (F) tidal current at time t and (G) tidal range at time t (all in units of NTU).

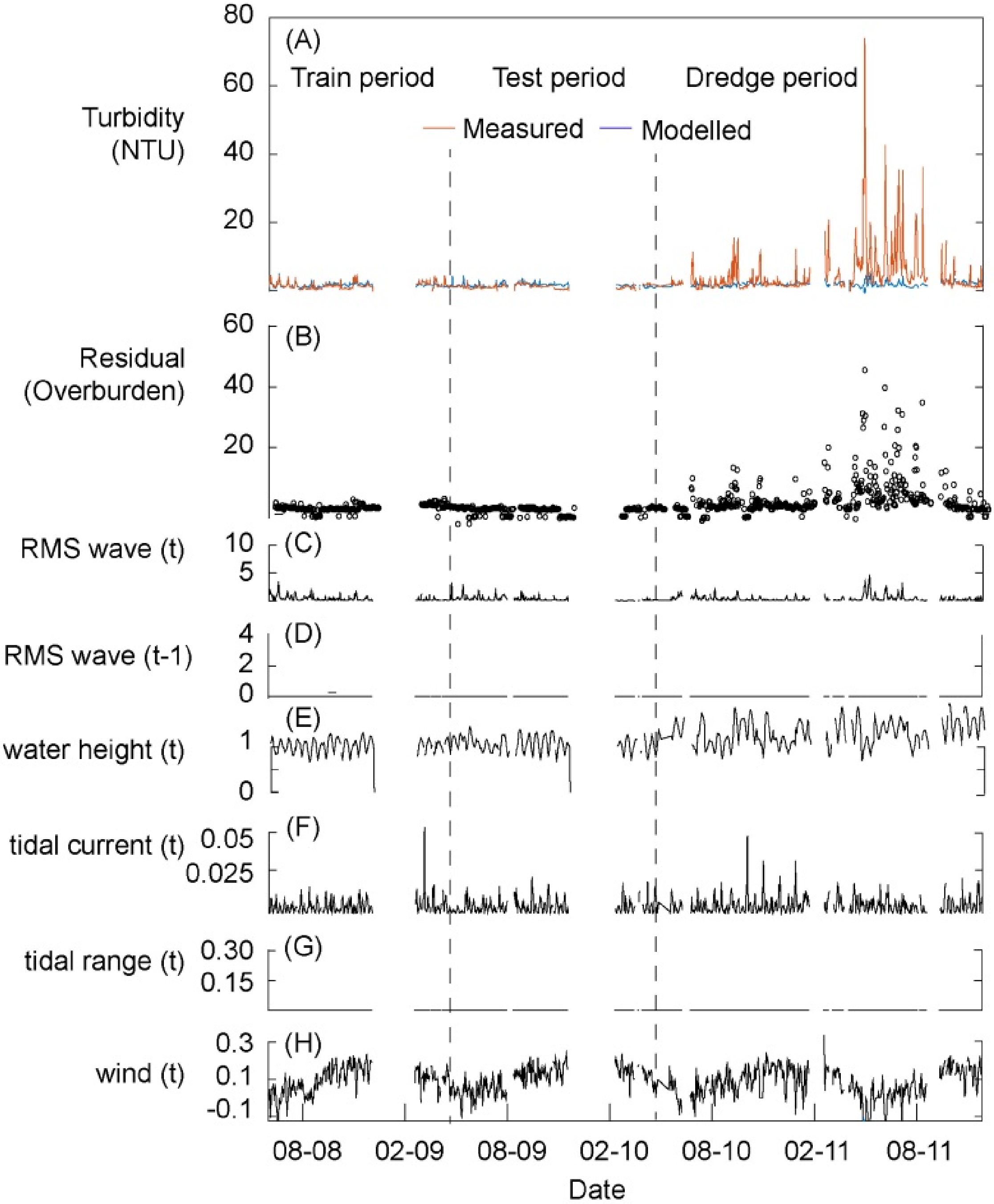

Figure 3. Barrow Island Project. Turbidity model (equation 1) performance at MOF1 (0.8 km south of the main dredging zone) during the baseline fit and test periods showing the predicted NTU contribution attributable to each model parameter: (A) the modelled (blue line) and measured (orange line) turbidity levels, (B) the residual turbidity, or 'overburden' (which is the difference between the measured and predicted turbidity). Figures C-H show the model terms (with model parameters applied) including (C) waves at time t, (D) waves from the previous day (waves at t-1), (E) water height at time t, (F) tidal current at time t, (G) tidal range at time t and (H) daily wind at time t (all in units of NTU).

Sites within a few hundred metres north and south of the dredge zone, such as LNG0 and LNGA, had higher and more frequent overburden events during dredging with average overburden between 3.1 and 4.4 NTU (Table 2), in contrast to northern sites and sites >10 km south (shown in Figure 4A in 2D and in 3D using time as an extra dimension in Figure 7A). Reference sites >10 km north and south of the dredging (Figure 1) had average dredge period overburden ≤ 0 NTU, equivalent to or less than typical baseline period overburden across all sites (≤ 0.5 NTU, Table 2). Site LONE, beside the dredge material placement site, had infrequent overburden events >2 NTU and low average overburden of 0.03 NTU (Table 2) similar to the most southern reference sites and all sites during the baseline period (Table 2).

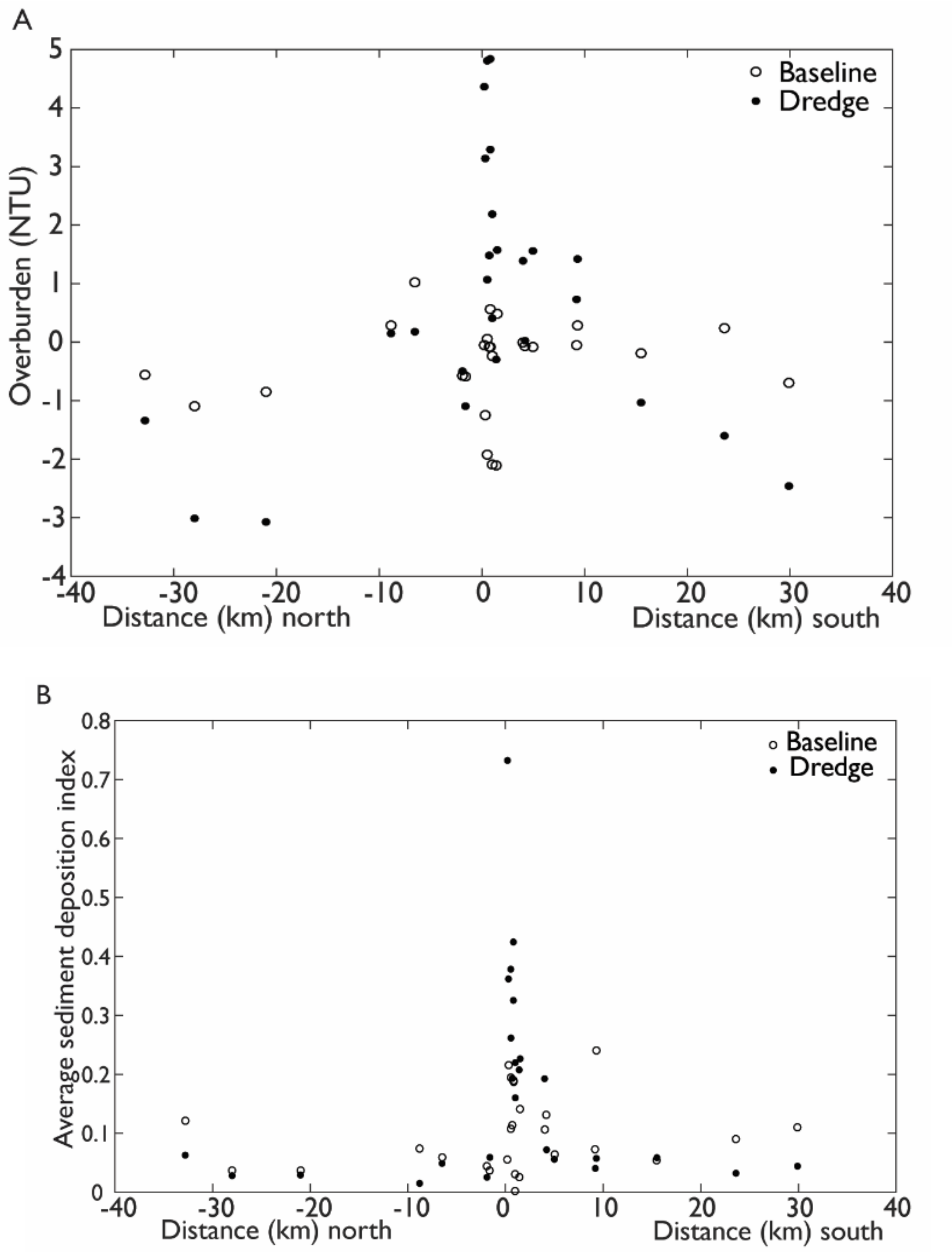

Figure 4. Distance to dredge effects for (A) median daily overburden (NTU) and (B) averages of SDI (sediment deposition index - daily averaged deposition values) during the Barrow Island project, calculated separately for the baseline (white circles) and dredge (black circles) periods, plotted according to the distance (km) of the sites from the dredge zone, with negative values north of the dredge zone (which is at the origin) and positive values to the south (see Figure 1).

3.2 Sediment deposition index (SDI)

The sediment deposition sensor is based on optical backscatter sensor (OBS) principles. The instrument uses fibre optic bundles set into a horizontal measuring surface and connected to an infra-red LED and a light sensor. The amount of light from the LED that is back-scattered into the sensor varies in proportion to the amount of sediment that has settled. Every two hours a wiper removes accumulated sediment, resetting the sensor reading to zero and ideally creating a 'sawtooth' pattern in the sensor output indicative of sediment accumulation. This sawtooth spectra is shown in Figure 5A for the site MOFC, with 5 × 2 h cycles over a 24 h period. Normally a sedimentation rate can be calculated from each accumulation/wiper episode based on the positive linear slope of the accumulation. However, such occurrences were rare and further inspection of the raw data showed that there were frequently periods when sediment accumulated on the flat sensor, moved off, and either resettled again or advected away from the sensor within the 2 h accumulation period, such as in Figure 5B. This resulted in no sawtooth pattern or dips in the sawtooth slope preventing the raw SSD data being used for high resolution analysis (e.g. sediment deposition rates); however, the repeated deposition of sediment did provide an opportunity for lower resolution analysis (e.g. daily averages of sediment deposition) to be used for detection of a dredging-related deposition zone (i.e. a zone of increased sediment deposition during dredging compared to ambient conditions and compared to far field sites presumably unaffected by dredging).

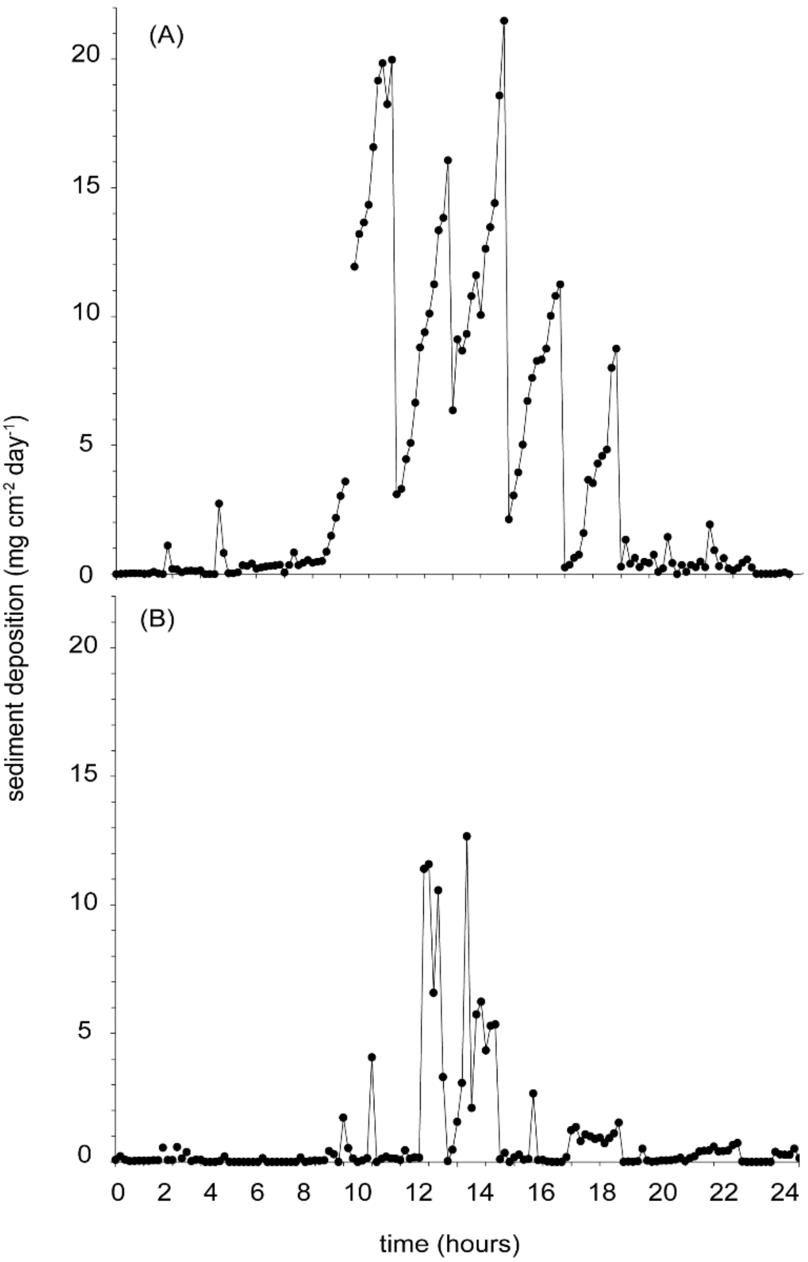

Figure 5. Deposition sensor data showing (A) the raw SSD data for (A) a well-defined 2 h periodic sawtooth pattern and (B) no sawtooth patterns in at site MOFC from 19-20 August and 19 -20 November 2010.

For this reason the SDI was calculated by averaging the 10 minute SSD measurements over each day, giving an index of sediment accumulation (i.e. a single daily measurement). Using the average daily sediment deposition value over the dredging period, there was a large gradient with SDI decreasing at increasing distances from the primary dredging sites (shown in Figure 4B in 2D and in 3D using time as an extra dimension in Figure 6B). SDI values within a few km south of the primary site of dredging area were ~7 times higher than the more distantly located sites tens of km away (Figure 4B, Figure 7B).

3.3 SDI compared to overburden

There was no relationship between SDI (daily averaged SSD) and daily overburden ($R^2 \approx 0$) across all Barrow Island sites, however there was a relationship at two sites (DUG and DSGS) when only higher overburden (>5 NTU) days were analysed (Figure 7). At site DUG, the R^2 increased from 0 to 0.5 and at site DSGS from 0 to 0.7 (Figure 7). The relationship remained weak at all other modelled sites. Sites > 10 km south and the two northern modelled sites (AHC and ANT) had <5 days when overburden >5 NTU while sites within 10 km south of dredging had between 0 and 117 d with overburden >5 NTU. There was no improvement in R^2 values when correlating daily overburden with the following day SDI.

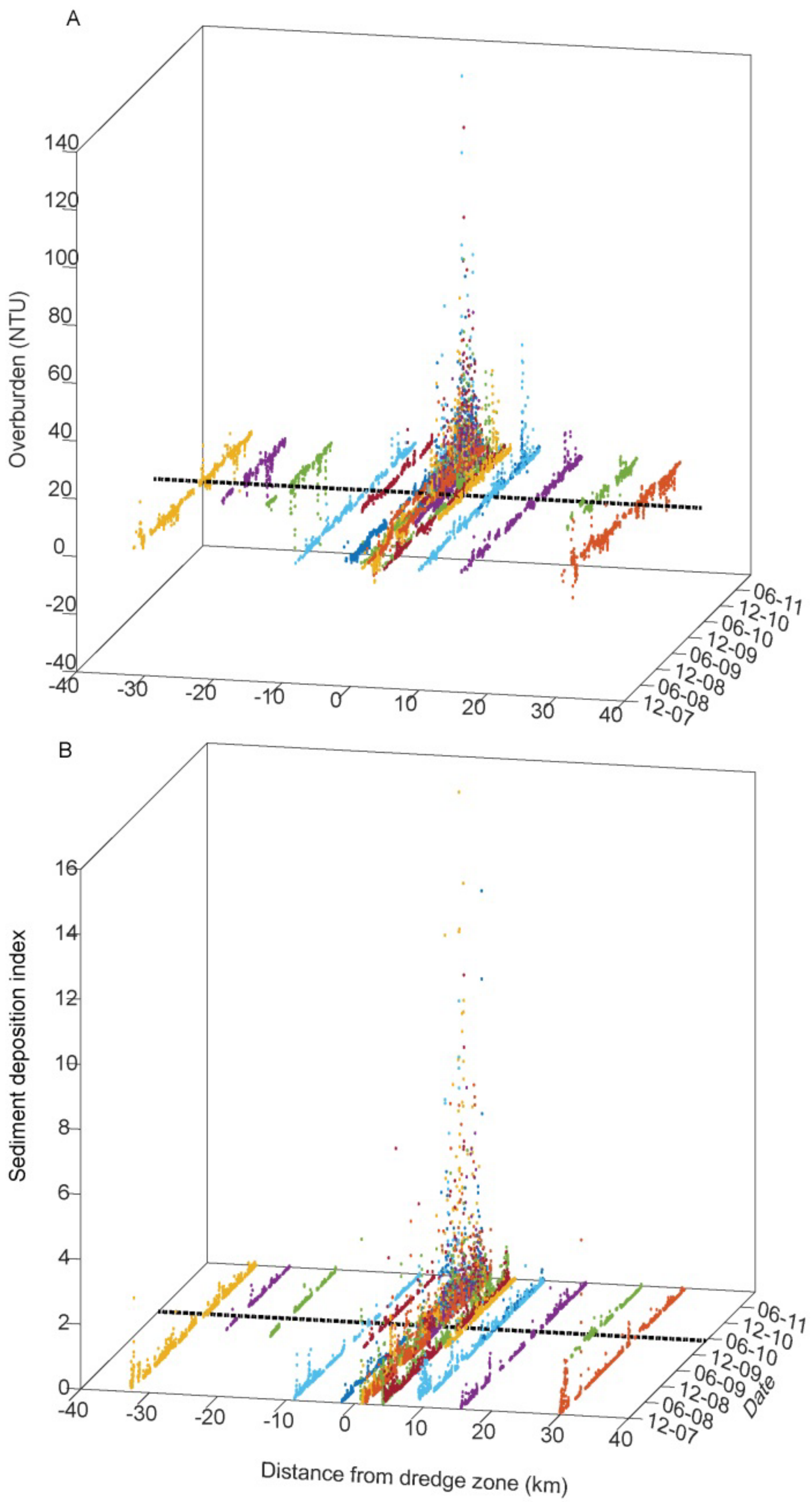

Figure 6. (A) Daily overburden (NTU) during the baseline period and dredge period (from May 2010 onwards) and (B) Daily sediment deposition index during the Barrow Island project plotted according to the distance (km) of the sites from the dredge zone with negative values north of the dredge zone (which is at the origin) and positive values to the south (see also Figure 1).

4 Discussion

In this study we examined a number of alternative approaches to assess the spatial scales of sediment deposition during a large scale capital dredging project in Western Australia, including a statistical turbidity model that can be used to estimate if sediment deposition is likely, and the use of optical back scatter deposition sensors (Ridd et al. 2001). There were a number of limitations and difficulties encountered with both techniques, but semi-quantitative estimates were made, suggesting a sediment deposition zone related to dredging activity occurred predominantly at sites located within 2 km south of the main dredging area. This deposition zone coincided with *in situ* observations of deposited sediment covering on corals and mucus sheet formation in massive *Porites* colonies, which is a useful indicator of elevated sediment deposition (Bessell-Browne et al. 2017).

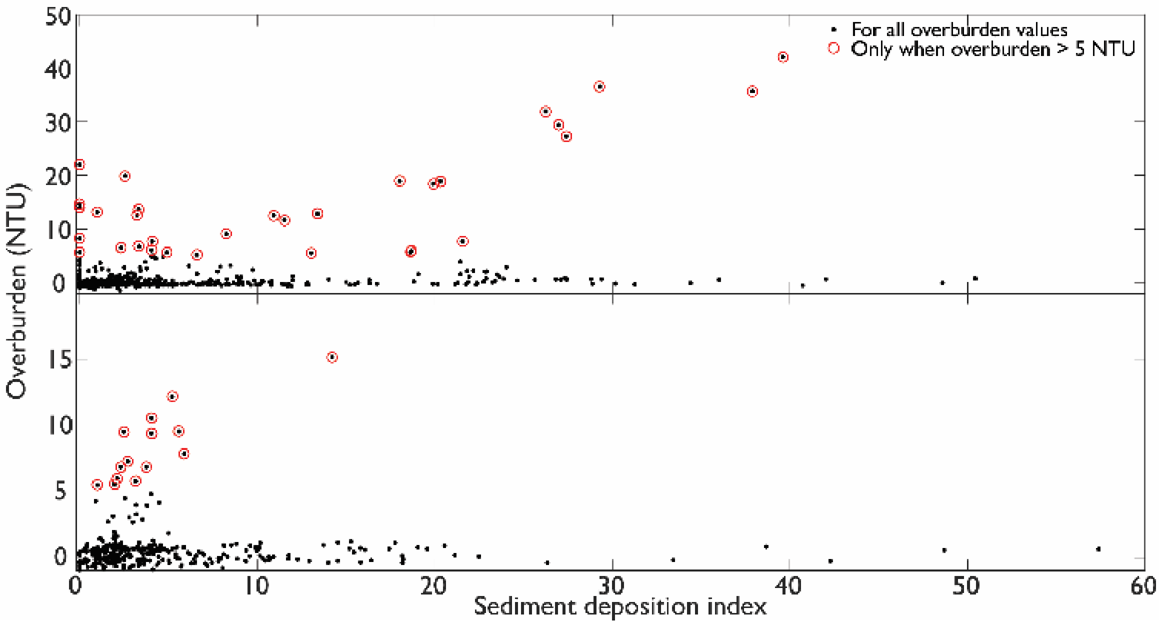

Figure 7. Overburden and daily averaged surface sediment density comparing all overburden values (black circles) and only days when overburden > 5 NTU (red circles) at sites DUG (A) and DSGS (B). The relationship improved significantly at both sites when comparing overburden and SDI only on days when overburden > 5 NTU, from $R^2 = 0$ (typical of all sites) to $R^2 = 0.5$ at DUG and $R^2 = 0.7$ at DSGS.

A simple statistical turbidity model, predicting background wave and tidally driven resuspension, was developed and tested for use during dredging operations to monitor dredge related turbidity and to identify potential sediment deposition events. A similar method of using a simple turbidity model to estimate the natural turbidity was developed for dredging activities in Darwin Harbour (van Senden et al. 2013). The difference between the turbidity model in this study and the turbidity model developed for Darwin Harbour is the form of the model and the dominant resuspension forcing mechanisms in the two regions. The model in this study is a power model where waves are the most significant forcing term while the Darwin Harbour model is an exponential tidal model due to the influence of tidal flows on sediment resuspension.

A feature of the models is the simplicity and in this study only 2 variables were required to be measured; turbidity and water pressure. Water quality modelling typically involves multi-dimensional complex coupled hydrodynamic and sediment transport models (e.g. DELFT3D) requiring multiple inputs such as currents, waves, tides, boundary layer dynamics and sediment type/particle size information (Swanson et al. 2007, van Rijn 1986, Luger et al. 1999, Luger & van Ballegooyen 2000, Erftemeijer et al. 2012). The model performance was strong in the turbid coastal environment at Hay Point where, during the test phase (2nd half of the baseline data), 83% of the sites had R^2 (between observed and predicted turbidity) of >0.5. In the offshore, clear water environment on the eastern side of Barrow Island the model performance was much weaker, with only 38% of the sites having an R^2 value of >0.5. Model parameter optimisation requires frequent natural turbidity events and these low R^2 values were most likely the result of insufficient turbidity events during the baseline period to adequately fit the model input variables to the measured turbidity. Hay Point is a naturally turbid environment with wind and waves frequently resulting in high turbidity (Chartrand et al. 2008, Macdonald et al. 2013). During the baseline period daily average turbidity was 8 NTU and the mean of the maximum daily turbidity per site was 82 NTU. However, during the baseline phase at Barrow Island daily average turbidity values were only 1.4 NTU and the mean of the maximum daily turbidity per site was 8 NTU. Barrow Island is located approximately 55 km offshore and less influenced by sea-breezes typical of the Queensland coast (Larcombe et al. 1995). The sites were located on the eastern lee of the island protected from waves and swell (Pearce et al. 2003, DEC 2007, Jones et al. 2015). Furthermore, the shallow bathymetry creates complex currents and inhibits the flood tide as it flows around the north and south of the island (Hubbert et al. 2005, Condie & Andrewartha 2008).

Estimates were also made of the sediment deposition field using *in situ* sediment deposition sensors based on optical backscatter principle (Ridd et al. 2001). These sensors, which are essentially upward facing nephelometers, produce a sawtooth pattern (see image in Thomas & Ridd 2005) as sediment settles on the sensor over a 2 h measuring period before being wiped away by a self-cleaning mechanism. The repeated wiping of sediment could be identified in the raw data as a 2 h cycle using a wavelet method, similar to a Fourier transform for examining periodicity. However obvious sawtooth patterns (indicating sediment deposition was occurring) were rarely seen in the data, and only at site MOFC. Closer inspection of the raw data and measurements taken between the sensor wipes suggested the presence of sediment on the sensor, but due to the flat, glassy sensor plate design water motion easily removed deposited sediment (Ridd et al. 2001). These observations prompted the design of a new deposition sensor with a more rugose sensor surface that more closely resembles coral. Details of the sensor surface re-design and calibration and testing of the new configuration are described in Whinney et al. (2017).

Despite the inability to detect a sedimentation rate over each 2 h period (due to a lack of clearly defined accumulation events during the project) it was possible to average all readings over the day, providing a relative index of sediment deposition in the baseline (pre-dredging) and dredging periods. Results showed strong evidence of dredge related sediment deposition occurring at sites within <2 km south of the main dredge area, and a decrease in sedimentation with increasing distance from the main dredge area. Sites < 2 km from the dredging had deposition levels that were 5–7× higher than reference sites. There was no evidence of sediment deposition north of the dredging area which had deposition and overburden levels similar to baseline (background) conditions. These results are consistent with the prediction of the deposition zone by the modelling approach.

The use of the model to predict dredge related deposition events was also tested at each Barrow Island site (no dredging occurred during the Hay Point study) by validating the model overburden with the daily *in-situ* SDI. The validation was inconclusive at most sites when using the entire range of overburden values; the model underperformed at most sites in the clear water Barrow Island environment (due to low wave activity and low turbidity events during model fitting), and the deposition sensor underestimated deposition events.

Although the relationship between overburden and SDI was weak when using all data points, the relationship improved significantly at 2 sites (DUG and DSGS, from $R^2 \sim 0$ to 0.5 and 0.7, respectively) when comparisons were made using only days with overburden >5 NTU. Both of these sites are located at the same latitude on the southern tip of Barrow Island (see Figure 1) and are probably more exposed to waves and tidal currents (see Hubbert et al. 2005) but are deep enough (with sensor depths of 5.5 m and 14 m, respectively – see Chevron Australia Pty 2011 for sensor depths) that wind driven water motion may not remove sediment from the deposition sensor plate as easily as the shallower sites further south (for example Wolanski et al. (2005) reported waves affecting only shallow sites < ~ 5.5 m on the leeward side of an island).

Despite data from the deposition sensor not being used throughout the project due to perceived doubts of its veracity, the data show a consistent pattern of higher deposition closer to the dredge area and compared to baseline conditions. Most of the sites within 0.5–5 km south of dredging had significantly higher SDI during dredging compared to all northern sites and sites >5 km south (which had similar conditions to all sites during the baseline study; median dredge period averages 0.15–0.7 during dredging compared to 0–0.2 during the baseline). Sediment accumulation levels may have been lower than expected, but overall there were strong similarities between SDI spatial trends during dredging and other analysis methods in this study by Fisher et al. (2015) and compared to other case studies into the impacts of dredging near coral reefs (see Erftemeijer et al. 2012). Sites within 0.5–2 km south of dredging had maximum SDI just over double the maximum SDI at sites > 2 km away. Similarly, Fisher et al. (2015) reported a 3 km zone of potential impact with elevated turbidity and decreased light levels due to dredging. Despite the deposition sensor underestimating deposition levels (evident by a lack of accumulation events), monitoring changes in deposition levels during dredging requires comparisons to reference sites and/or ambient conditions, therefore relative SDI (daily averaged SSD) levels between sites are sufficient for identifying a dredge related deposition zone (where sites close to dredging had higher average deposition levels during dredging compared to ambient conditions and compared to sites further afield).

To overcome problems with reduced sensitivity to absolute SSD levels, a new deposition sensor has since been developed (Whinney et al. 2017). The new sensor resolves these issues by using an indented surface to better mimic coral surfaces and by increasing the number of sensors.

In summary, this study provides detailed spatial analysis of a dredge related deposition zone during a large scale dredging operation using multiple techniques. A clear deposition zone, analysed using SDI and model overburden (i.e. dredge related turbidity), was confined to within 0.5–5 km south of dredging.

The turbidity model performed well in the turbid coastal environment of Hay Point but underperformed in the clearer water Barrow Island environment (due to low wave and turbidity levels during the model fit period). Model performance at the Hay Point sites demonstrates that the model can be used in more turbid environments to estimate natural turbidity and monitor dredge related turbidity threshold exceedance during future dredging operations. Although the use of the model overburden to also monitor dredge induced deposition events was inconclusive, improvement in the relationship between overburden and SDI at some sites on higher overburden days (>5 NTU, which are more likely to result in deposition events) demonstrates that the model has potential to be used to determine the impact of dredge related deposition on coral health. Further testing is recommended during a dredge operation in a more turbid environment; by assessing model performance to predict natural turbidity events and compare the model overburden to measured deposition levels.

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