

Port of Mackay and Hay Point Ambient Marine Water Quality Monitoring Program (July 2016 to July 2017)

Nathan Waltham, James Whinney, Rachael Macdonald, Peter Ridd

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A Report for North Queensland Bulk Ports Corporation

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SUMMARY POINTS

Background

1. North Queensland Bulk Ports has implemented an ambient marine water quality monitoring program surrounding the Ports of Mackay and Hay Point for the period July 2016 to July 2017 (building on the July 2014/15 and July 2015/16 ambient periods). The objective of the program is to progress a long term water quality dataset to characterise marine water quality conditions within the Mackay region, and to support future planned port activities.
2. This program has incorporated a combination of spot field measurements and high frequency continuous data loggers, laboratory analysis for a range of nutrient, herbicides and heavy metals.
3. The initial thirteen site networks that made up the 2014/15 monitoring period was reduced to seven sites for the 2015/16 and 2016/17 periods. Sites extend approximately 60km along the Mackay coastline, from Slade Islet to Freshwater Point, and offshore to Keswick Island. Sites in the network align with key sensitive receptor habitats (e.g. corals or seagrass), along with key features in the study region (e.g. river flow points).

Climatic conditions

1. The total 2016/17 wet season rainfall across the study was within the 90th percentile of the distribution of total annual wet season rainfall recorded in the region (1910 to 2017). For the entire ambient marine monitoring period, the total rainfall at Plane Creek Sugar Mill (17 km linear from Hay Point) was 1,536 mm, with 73 % recorded during March 2017. Generally rainfall in the region contributed to short flow pulse river flow that were generally not sufficient to create notable discharge to the marine environment. This contrasts the 2013/14 wet season where rainfall was within the 5th percentile of historical records.
2. The rainfall total across the 2016/17 wet season is much higher than previous years, and provided the first chance to characterise the upper range in marine water quality conditions within the study region. The data in this report therefore needs to be considered in this context.
3. The daily average wind speed and direction recorded at Mackay airport for the reporting period (2016/17) was predominantly from the south east and south west, with more than 45% of the days reaching more than 24km/hr, which is higher than previous years.

Water chemistry

1. Field water quality conditions were measured at all sites for water temperature, electrical conductivity, pH, dissolved oxygen, and secchi disk depth on a 6wkly basis, for three depth horizons (surface (0.2m), mid water and bottom).
2. Seasonal differences in water quality were minor, except for temperature which continues to be highest during the summer months.
3. Water column was well mixed during each survey, with little differences among the three horizons examined. Secchi disk to depth ratio (Zeu:Z) ranged between 9 and 100% of the water column at sites, suggesting that optical water clarity on survey days were generally good.

4. Particulate nutrient concentrations continue to exceed relevant guidelines for the region. Chlorophyll-*a* concentrations were also regularly elevated above the relevant guideline, particularly so during February/March 2017 – probably in response to elevated available nutrient concentrations during these months. Continuing elevated nutrients and chlorophyll-*a* concentrations in the region seem to highlight persistent local sources contributing to these concentrations (i.e. runoff from local farms or urban centres).
5. Ultra-trace heavy metals are non-detectable across the monitoring period, a factor probably reflecting the low rainfall. Previously, ultra-trace concentrations of copper detected in Mackay marina but were not detected in this reporting period.
6. Atrazine, Diuron, and Hexaninone were detected at several coastal sites, particularly during the wet season survey (March 2017).
7. An assessment of the plankton community (both phytoplankton and zooplankton) was completed during this reporting period. There was a clear separation in the plankton community between most surveys, suggesting seasonal and inter-annual variation, and a weak relationship with available nutrients.

Sediment deposition and turbidity

1. Continuous sediment deposition and turbidity logging data supports the pattern found more broadly in north Queensland coastal marine environments, that during dry periods with minimal rainfall, elevated turbidity along the coastline is driven by the re-suspension of sediment, and is most notable here given the links drawn between root mean square (RMS) water depth and turbidity/suspended sediment concentrations (NTUe/SSC). Large peaks in NTUe/SSC and RMS water depth were recorded over periods longer than a week.
2. Presenting NTUe/SSC with respect to RMS water depth using box plot distributions, it is shown that as RMS water depth increases so too do the values of NTUe/SSC and the variation of NTUe/SSC. In fact, values of SSC for all sites regularly exceed the relevant water quality guideline for SSC in coastal waters, simply as a function of increasing RMS water depth. With increasing RMS water depth, the variation also increases which is probably a function of a more dynamic environment and more wave energy.
3. Another important finding here was that deposition data did not indicate large deposits occurring at any of the monitored sites, and this is likely attributed to re-suspension of sediment by wave energy. This was the case at Keswick Island site (AMB 12) where deposition rates is highest.
4. Cyclone Debbie, a category 4 system, caused widespread wind damage and flooding in Mackay and surrounding areas in March 2017. Increased wave heights and suspended sediment levels were observed in response to this extreme weather event.
5. As part of this monitoring program, a multivariate predictive NTUe/SSC model has been developed at sites to forecast natural turbidity levels. The model utilised wave, water depth and tidal components from pressure sensor data as inputs. The predictive capacity of the model improved across the logging period.
6. The model developed here provides management with a powerful tool for use during dredging campaigns, for example, as the differentiation between natural turbidity and dredge related turbidity may be monitored. This means that during

port operations, that the difference in the measured turbidity compared to the predicted using this model, represents the contribution associated with the activity. This is a powerful management tool for NQBP.

7. Water current monitoring conducted during this monitoring year has provided further information on the hydrodynamics of the coastal system. These data highlight the natural variability in current speed and direction among sites. Future monitoring of current in this region will build a more thorough data index that may be used in active dredge monitoring in the future.
8. There was a small difference in RMS water height, SSC, deposition, and water temperature between the dry and wet season. However, daily total PAR and temperature values were generally higher during the wet season in comparison to the dry season.

Light attenuation (Photosynthetically active radiation; PAR)

1. High frequency continuous PAR logging data revealed fine-scale patterns of PAR are driven by tidal cycles with fortnightly increases in PAR coinciding with neap tides and lower tidal flows. Larger episodic events which lead to extended periods of low light conditions are driven by a combination of strong winds leading to increases in wave height and resuspension of particles, and rainfall events resulting from storms leading to increased catchment flows and an input of suspended solids. Such events did not occur during the current monitoring period.
2. Patterns of light were similar among all the coastal sites. Light penetration in water declines in an exponential relationship with depth as photons are absorbed and scattered by particulate matter. Therefore variation in depth at each location means benthic PAR was not directly comparable among sites as a measure of water quality. Generally, however, shallow inshore sites reached higher levels of benthic PAR, but were more variable than in comparison to deeper water coastal sites, and sites of closer proximity to one another were more similar than distant sites.
3. The Keswick Island site which is located 26km from the coast and sheltered on the leeward side of Keswick and St Bees Island, displayed patterns in PAR with the greatest dissimilarity to other sites. This site had a more stable light environment and did not show decreased PAR in response to Cyclone Debbie.
4. While turbidity is the main indicator of water quality used in monitoring of port related activities and benthic PAR is significantly correlated with suspended solid concentrations, the relationship between these two parameters is not always strong. At many of the sites where both turbidity and benthic light were measured, the concentration of suspended solids in the water column explained less than half of the variation in PAR. As PAR is more biologically relevant to the health of photosynthetic benthic habitats such as seagrass, algae and corals it is becoming more useful as a management response tool when used in conjunction with known thresholds for these habitats. For this reason, it is important to include PAR in the suite of water quality variables when capturing local baseline conditions of ambient water quality.

Recommendations

1. The program this reporting period included seven monitoring sites, which has allowed us to continue characterising water quality in the Mackay region. It is recommended that these same seven sites remain for the 2017/18 period, in order

to continue to capture local water quality conditions. This year rainfall was much higher than previous years, thereby providing an important return on the investment in this program. Program refinements are still under consideration.

2. Plankton assemblage sampling should continue. These data are beginning to illustrate some interesting patterns, namely some seasonal differences, particularly so during summer. Continuing this data collection will assist with understanding the spatial patterns in plankton community in the region.

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Acronyms used in this Report

Acronym	Description
BOM	Bureau of Meteorology
GIS	Geographical Information System
MODIS	Moderate-resolution Imaging Spectroradiometer
NQBP	North Queensland Bulk Ports
PAR	Photosynthetically active radiation
RMS water height	Root Mean Square water height is a calculation of the variance about the mean water depth
SSC	Suspended Solid Concentration (mg/L)
TropWATER	Centre for Tropical Aquatic Ecosystem and Water Quality Research

1 INTRODUCTION

1.1 Port operations

The Port of Mackay and the Port of Hay Point are situated on the central Queensland Coast (Figure 1.1). The Port of Mackay is located approximately four kilometres north of the Pioneer River, and is enclosed by large break walls that protect the port and marina property, while also allowing exchange of oceanic waters. The port has a series of operational and associated loading/unloading facilities, and an extensive marina operation and commercial fishing fleet. The port is operated by North Queensland Bulk Ports Corporation (NQBP).

The Port of Hay Point is situated approximately 40kms to the south of Pioneer River and Mackay City. Two coal terminals operate in the port: 1) Dalrymple Bay Coal Terminal; and 2) BMA Hay Point Coal Terminal. Similar to Port of Mackay, NQBP is the authority for the port.

In both ports, routine maintenance dredging is necessary to maintain declared navigational depths within the swing basin and berth areas, departure path and aprons, and Tug Harbour at the Port of Hay Point. For the Port of Mackay, the most recent dredging campaign was completed in 2013, while the last maintenance dredging campaign undertaken by NQBP at the Port of Hay Point was completed in 2010. Any dredging activity necessary in the operating ports in the region are undertaken in accordance with Commonwealth and State approvals with management objectives guided by the Port of Mackay Long Term Dredge Management Plan and the Port of Hay Point Dredge Management Plan.

1.2 Program outline

Routine maintenance dredging is periodically required at the Port of Mackay and Hay Point to maintain vessel navigational depths. NQBP are committed to complete a range of monitoring programs specific to each dredge campaign with the objective of identifying direct impacts of the dredging activity. In order to better define the potential impacts associated with port operations and to characterise the natural variability in key water quality parameters within the adjacent sensitive habitats, NQBP committed an ambient marine water quality monitoring program in and around the coastal waters of the Port of Hay Point and the Port of Mackay (Figure 1.1; Table 1.1). As part of this program, water quality parameters are being investigated at a range of sites, including a control site in the southern Whitsunday Islands (Keswick Island; AMB12). This monitoring program contains a range of ambient water quality components that collectively continue to characterise the natural variability in key water quality parameters, including those experienced at the nearest sensitive receiving habitats for both Ports.

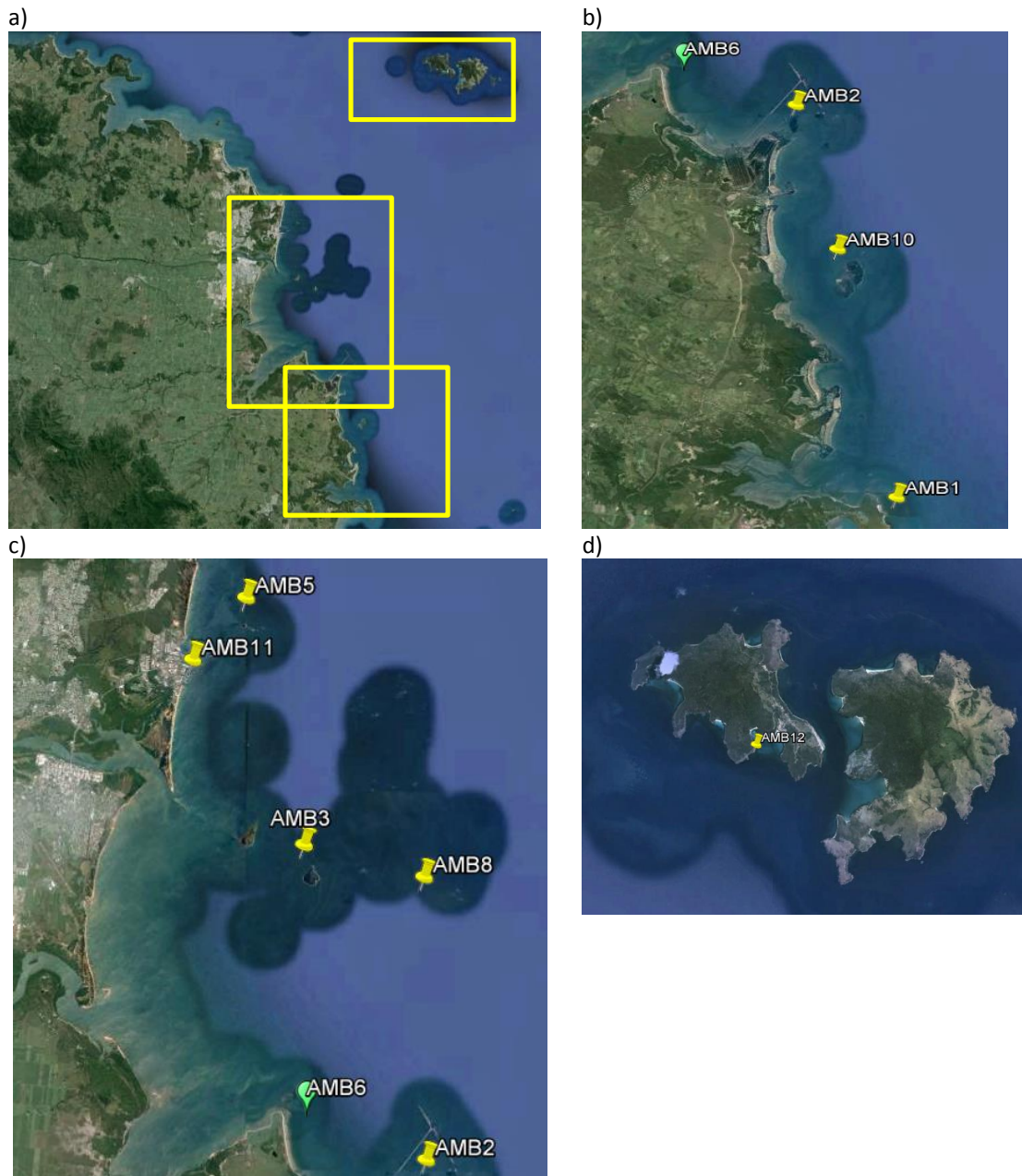


Figure 1.1 Locations of the marine water quality monitoring program sites during 2016/17 program. AMB6 is PAR logger only

Table 1.1 Locations of the ambient marine water quality monitoring program sites. (*) logger discontinued from station and relocated. Included below are decommissioned loggers following the 2014/15 reporting period

Location	AMB site no.	Lat.	Long.	Water quality	Deposition/PAR logger
Freshwater Point	1	-21.42	149.34	Yes	Yes
Hay Point/Reef	2	-21.26	149.30	Yes	Yes
Round Top Island*	3b	-21.17	149.26	Yes	Yes
Slade Island	5	-21.09	149.24	Yes	Yes
Dudgeon reef*	6b	-21.24	149.25	Yes	PAR only
Relocation ground (Spoil grounds)	8	-21.18	149.30	Yes	Yes
Victor Islet	10	-21.32	149.32	Yes	Yes
Mackay Harbour	11	-21.11	149.22	Yes	
Keswick Island	12	-20.93	149.42	Yes	Yes
Decommissioned following 2014/15 period					
Flat Top Island	4	-21.17	149.24	Yes	Yes
Slade Point	7	-21.18	149.30	Yes	Yes
East Cardinal marker	9	-21.10	149.26	Yes	

1.3 Rainfall and river flows

To date, the total wet season rainfall within the study area is low, within the 10th percentile of the distribution of total annual wet season rainfall recorded in the region (Figure 1.2). However, this year (2016/17) rainfall has been within the 5th percentile for wet season totals, mostly influenced by Tropical Cyclone Debbie, where over 1,100mm of rainfall was recorded in several days. For the entire ambient marine monitoring period the total rainfall at Plane Creek Sugar Mill (17km linear from Hay Point) is 2765 mm, with 47% of the total rainfall associated with Tropical Cyclone Debbie. It seems likely that this major weather system has contributed to catchment flows, the first experienced during this ambient program (back to July 2014).

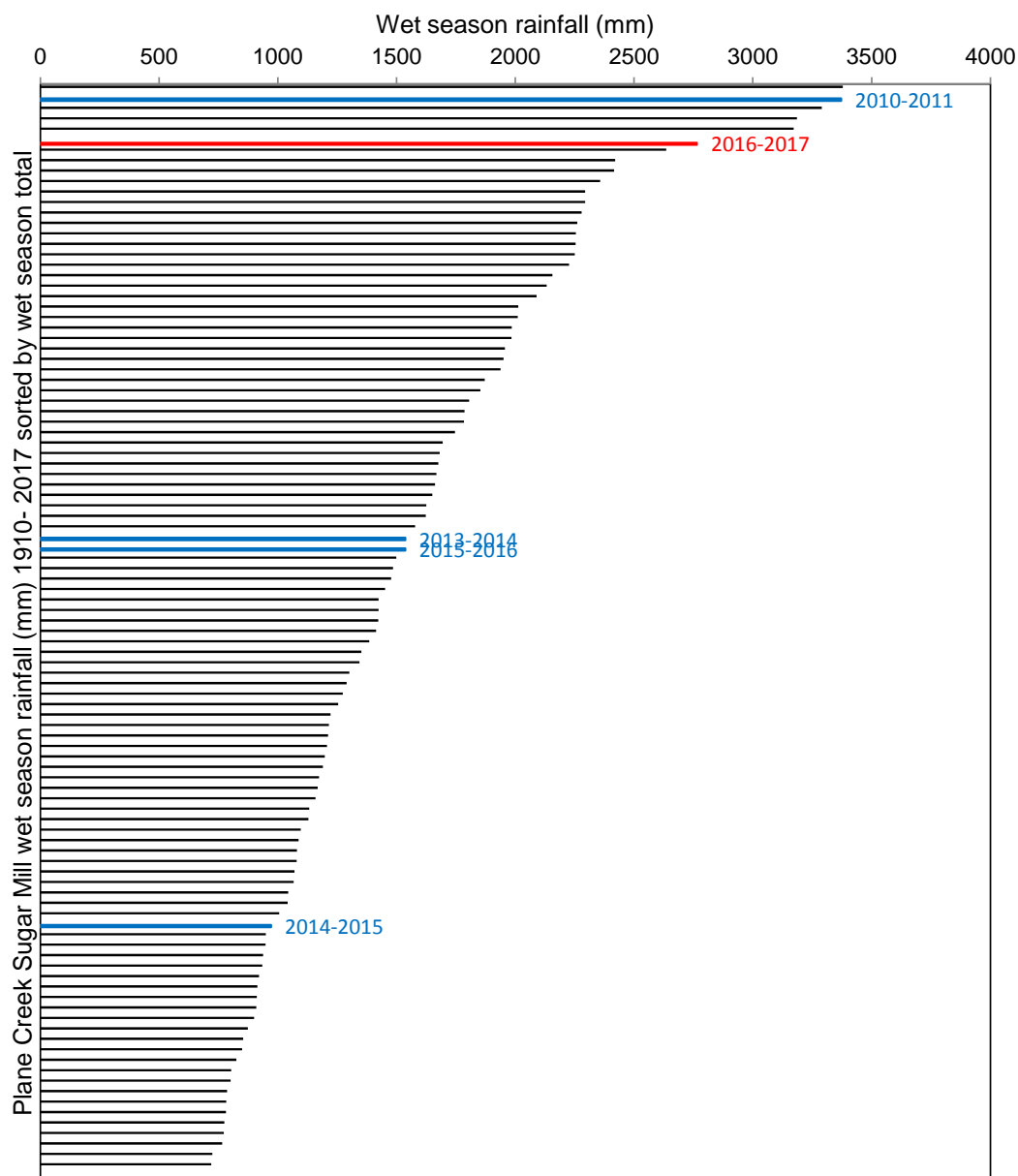


Figure 1.2 BOM wet season (Nov – March) rainfall data for Plane Creek Sugar Mill (station number: 33059) ranked in order of decreasing total rainfall (mm). Blue bars show total rainfall over the past few years, and the red bar represents the 2016/17 ambient marine water quality monitoring period

The example hydrograph for Pioneer River (Figure 1.3) shows more frequent rainfall events during 2016/17 in comparison to previous monitoring periods. In March 2017, tropical cyclone Debbie caused a large peak in river flow (Figure 1.4). Overall, while the total rainfall for in the region is proximal to the long term average, most of the rainfall was experienced in a few events.

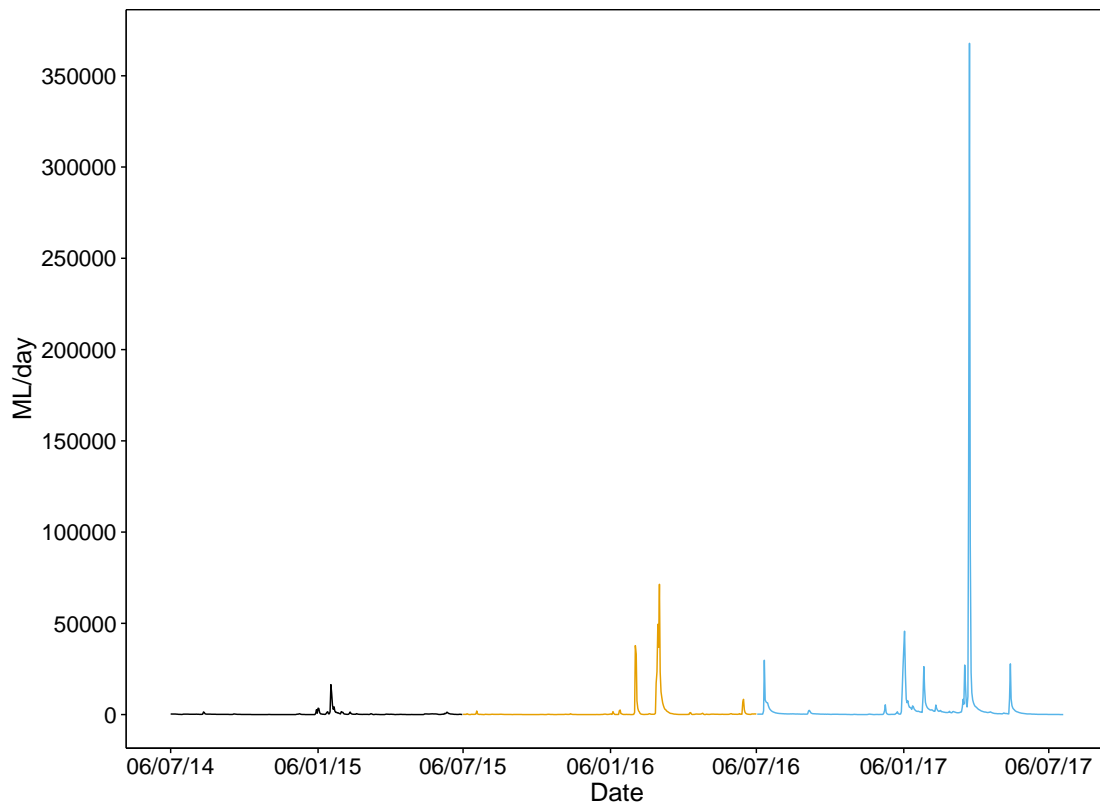


Figure 1.3 Flow recorded for Pioneer River. Line colour indicates monitoring period: black = July 2014 – July 2015, orange = July 2015 – July 2016, and blue = July 2016 – July 2017

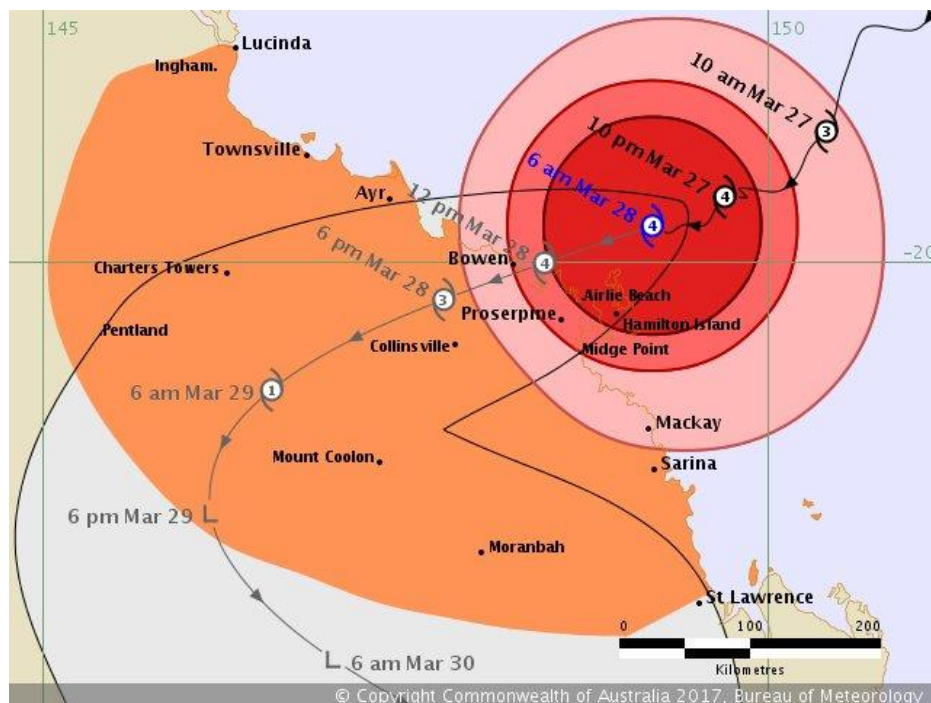


Figure 1.4 Tropical Cyclone Debbie crossed the coast on March 28th, 2017, making landfall just north of the study area

1.4 Wind for Mackay airport

The daily average wind speed and direction recorded at Mackay airport for the reporting period (2016/17) is predominantly from the south east and south west, with more than 45% of the days reaching more than 24km/hr (Figure 1.5). The higher percentage of days with winds greater than 24km/hr in 2016/17 compared to previous years may be linked to the passing of tropical cyclone Debbie. However, overall, the dominance of south east winds is consistent with previous monitoring periods, and wind rarely came from the north east direction during this reporting period (< 5% of the days in 2016/17).

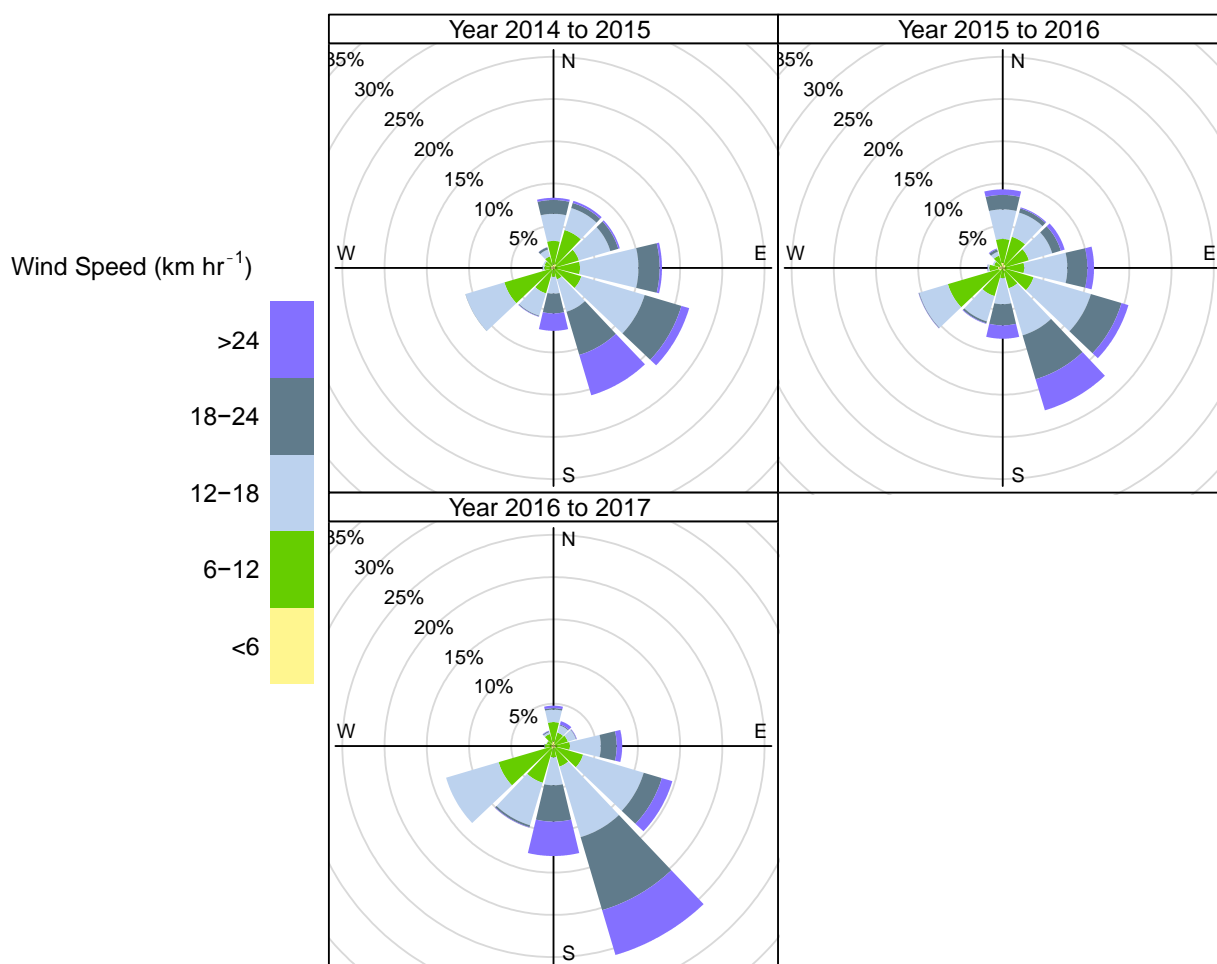


Figure 1.5 Daily average wind direction and strength recorded in Mackay airport for three monitoring periods throughout July 2014 to July 2017

1.5 Project objectives

This scope of works was formulated to fulfil “*Port of Mackay and Hay Point Ambient Marine Water Quality Monitoring Program Tender (Q13-032)*”. The goal of the program is to characterise the ambient marine water quality monitoring within the region within and adjacent to Port of Mackay and Hay Point. This report provides a review and analysis of the third year of monitoring (July 2016 to July 2017). These data are part of a longer term commitment to monitor and characterise receiving water quality conditions, in particular to support future planned asset management and protection for both these ports.

2 METHODOLOGY

2.1 Ambient water quality

Spot water quality samples were collected at all sites (Figure 1.1) approximately on a 6wk basis (Table 2.1) over the 12 month project from a research vessel. At each site, a calibrated multiprobe was used to measure water temperature, salinity, dissolved oxygen (%), pH, and turbidity (Figure 2.1). In addition to these spot measurements, secchi disk depth was recorded, as a measure of the optical clarity of the water column, along with light attenuation using a LiCor meter. These field *in-situ* measurements were recorded at three depth horizons: a) surface (0.25m); b) mid-depth; and c) bottom horizon. These measurements assisted in characterising water quality conditions within the water column, building on the previous 2014/2015 and 2015/2016 monitoring periods.

A review of available reports reveals that water quality conditions in the coastal region of Mackay and Hay Point are variable, and influenced by local activities and contributing catchment runoff during rainfall events. On this basis, and in considering key priority outcomes outlined in recently published Coastal Strategic Assessment and Marine Strategic Assessments for the Great Barrier Reef World Heritage area (DEHP, 2013; GBRMPA, 2013), the water quality program design below was completed. The list of parameters examined consisted:

- Ultra-trace dissolved metals : arsenic (As), cadmium (Cd), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn);
- Nutrients (particulate nitrogen and phosphorus);
- Chlorophyll-*a*; and
- Pesticides/herbicides (Low LOR suite (EP234(A-I)) including: diuron, ametryn, atrazine, terbutryn. Note that pesticides are suspected to be in low concentrations during periods of low rainfall runoff, and only detectable following rainfall. As a consequence sampling of only two events at all sites for pesticides, one during the dry (July 2015) and a wet (March 2016) season was deemed reasonable.



Figure 2.1 TropWATER staff conducting field water quality sampling

Table 2.1 Summary of instrument maintenance and water quality surveys completed during 2016/17 reporting period

Date	Nutrients, Chloro	Metals, herbicides	Plankton	Logger maintenance
July 2014	Yes	Yes		Yes
November 2014	Yes	Yes		Yes
March 2015	Yes	Yes		Yes
August 2015	Yes	Yes		Yes
August 2015	Yes			Yes
October 2015	Yes			Yes
November 2015	Yes	Yes	Yes	Yes
January 2016	Yes			Yes
February 2016	Yes			Yes
March 2016	Yes	Yes		
April 2016	Yes		Yes	Yes
May 2016	Yes			Yes
June 2016	Yes			Yes
July 2016	Yes			Yes
August 2016	Yes	Yes		Yes
September 2016	Yes			Yes
October 2016	Yes			Yes
December 2016	Yes			Yes
January 2017	Yes			Yes
February 2017	Yes			Yes
May 2017	Yes	Yes	Yes	Yes
July 2017	Yes			Yes
September 2017	Yes		Yes	Yes
October 2017	Yes		Yes	Yes

Sampling methodology, sample bottles, preservation techniques and analytical methodology (NATA accredited) were in accordance with standard methods (i.e., DERM 2009b; APHA 2005; Standards Australia 1998). Field collected water samples were stored on ice in eskies immediately during field trips aboard the vessel, and transported back to refrigeration, before delivery to the TropWATER laboratory. For chlorophyll analysis, water was placed into a 1L dark plastic bottle and placed on ice for transportation back to refrigeration. For dissolved metals and nutrients, water was passed through a 0.45 µm disposable membrane filter (Sartorius), fitted to a sterile 60 mL syringe (Livingstone), and placed into 60 mL bottles (metals) and 10 mL bottles (nutrients) for posterior analysis in the laboratory. (The use of these field sampling equipment and procedures have been previously shown to reduce the risk of contamination of samples, contributing to false positive results for reporting; TropWATER, 2015). Unfiltered sample for total nitrogen and total phosphorus analysis were frozen in a 60 mL tube. All samples were kept in the dark and cold until processing in the laboratory, except nutrients which were stored frozen until processing.

Water for chlorophyll determination was filtered through a Whatman 0.45 µm GF/F glass-fibre filter with the addition of approximately 0.2 mL of magnesium carbonate within (less than) 12 hours after collection. Filters were then wrapped in aluminium foil and frozen. Pigment determinations from acetone extracts of the filters were completed using spectrophotometry, method described in 'Standard Methods for the Examination of Water and Wastewater, 10200 H. Chlorophyll'.

Water samples were analysed using the defined analysis methods and detection limits outlined in Table 2.1. In summary, all nutrients were analysed using colorimetric method on OI Analytical Flow IV Segmented Flow Analysers. Total nitrogen and phosphorus and total filterable nitrogen and phosphorus were analysed simultaneously using nitrogen and phosphorous methods after alkaline persulphate digestion, following methods as presented in 'Standard Methods for the Examination of Water and Wastewater, 4500-NO₃- F. Automated Cadmium Reduction Method' and in 'Standard Methods for the Examination of Water and Wastewater, 4500-P F. Automated Ascorbic Acid Reduction Method'. Nitrate, Nitrite and Ammonia were analysed using the methods 'Standard Methods for the Examination of Water and Wastewater, 4500-NO₃- F. Automated Cadmium Reduction Method', 'Standard Methods for the Examination of Water and Wastewater, 4500-NO₂- B. Colorimetric Method', and 'Standard Methods for the Examination of Water and Wastewater, 4500-NH₃ G. Automated Phenate Method', respectively. Filterable Reactive Phosphorous was analysed following the method presented in 'Standard Methods for the Examination of Water and Wastewater, 4500-P F. Automated Ascorbic Acid Reduction Method'. Filterable heavy metals, and herbicides were analysed by Australian Laboratory Service (ALS).

Table 2.2 Water analyses performed during the program

Parameter	APHA method number	Reporting limit
Routine water quality analyses		
pH	4500-H ⁺ B	-
Conductivity (EC)	2510 B	5 µS/cm
Total Suspended Solids (TSS)	2540 D @ 103 - 105°C	0.2 mg/L
Turbidity	2130 B	0.1 NTU
Salinity		
Dissolved Oxygen		
Light Attenuation		
Pesticides/herbicides		
<i>Organophosphate pesticides</i>	In house LC/MS method: EP234A	0.0002-0.001 µg/L
<i>Thiocarbamates and Carbamates</i>	In house LC/MS method: EP234B	0.0002 µg/L
Thiobencarb		
<i>Dinitroanilines</i>	In house LC/MS method: EP234C	0.001 µg/L
Pendimethalin		
<i>Triazinone Herbicides</i>	In house LC/MS method: EP234D	0.0002 µg/L
Hexazinone		
<i>Conazole and Aminopyrimidine Fungicides</i>	In house LC/MS method: EP234E	0.0002 µg/L
Propiconazole, Hexaconazole, Difenconazole, Flusilazole, Penconazole		
<i>Phenylurea Thizdiazolurea Uracil and Sulfonyleurea Herbicides</i>	In house LC/MS method: EP234F	0.0002 µg/L
Diuron, Ametryn, Atrazine, Cyanazine, Prometryn, Propazine, Simazine, Terbutylazine, Terbutryn		
Nutrients		
Total Nitrogen and Phosphorus (TN/TP)	Simultaneous 4500-NO ₃ ⁻ F and 4500-P F analyses after alkaline persulphate digestion	25 µg N/L 5 µg P/L
Filterable nutrients (nitrate, nitrite, ammonia, Nox)	4500-NO ₃ ⁻ F	1 µg N/L
Ammonia	4500- NH ₃ G	1 mg N/L
Filterable Reactive Phosphorus (FRP)	4500-P F	1 µg P/L
Chlorophyll	10200-H	0.1 µg/L
Trace Metals		
Arsenic, Cadmium, Copper, Lead, Nickel, Silver, Zinc, Mercury	3125B ORC/ICP/MS	0.05 to 100 µg/L

2.2 Plankton community

Plankton community was examined during November 2015, April 2016, May 2017, July 2017, September 2017, and October 2017. At all sites, a 60µm plankton net (for phytoplankton) and a 500µm plankton net (for zooplankton) was towed behind the survey vessel for approximately 100m. The boat speed was reduced to approximately 6kts, with a GPS point taken at the start and end of each plankton tow. At the end of each plankton tow, the nets were retrieved, and the contents retained in the plastic jar attached to the net was immediately transferred to preservation containers. Samples were identified to the lowest possible taxon.



Figure 2.2 Plankton sample during November 2015 survey. a) Trichodesmium bloom on sea surface; b) phytoplankton (60µm) tow behind the survey vessel; and c) AMB 11 (Mackay Harbour) yellow dot ambient marine water quality site, black dots start and end of plankton tow

2.3 Multiparameter water quality logger

Sediment deposition, turbidity, Photosynthetically Available Radiation (PAR), water depth, Root Mean Squared (RMS) water depth and water temperature were measured at seven sites (AMB 1, AMB 2, AMB 3B, AMB 5, AMB 8, AMB 10 and AMB 12) using multiparameter water quality instruments manufactured at the Marine Geophysics Laboratory, School of Engineering and Physical Sciences, James Cook University (Figure 2.2). These instruments are based on a Campbell's Scientific 1000 data logger that has been programmed to measure and store these marine physical parameters using specifically designed sensors.

2.3.1 Turbidity

The turbidity sensor provides data in Nephelometric Turbidity Unit's equivalent (NTUe) and can be calibrated to Suspended Sediment Concentration (SSC) in mg/L (Larcombe et al., 1995). The sensor is located on the side of the logger, pointing parallel light-emitting diodes (LED) and transmitted through a fibre optic bundle. The backscatter probe takes 250 samples in an eight second period to attain an accurate turbidity value. The logger has been programmed to take these measurements at 10 minute intervals. The sensor interface is cleaned by a mechanical wiper at a two hour interval allowing for long deployment periods where bio-fouling would otherwise seriously affect readings.

It must be noted the international turbidity standard ISO7027 defines NTU only for 90 degree scatter, however, the Marine Geophysics Laboratory instruments obtain an NTUe value using 180 degree backscatter as it allows for much more effective cleaning. Because particle size influences the angular scattering functions of incident light (Ludwig and Hanes 1990; Conner and De Visser 1992; Wolanski et al., 1994; Bunt et al., 1999), instruments using different scattering angles can give different measurements of turbidity (in NTU). This has to be acknowledged if later comparison between instruments collecting NTUe and NTU are to be made. To enhance the data, all sites were calibrated to provide a measure of SSC (mg/L) and enable for the accurate comparison between 90 degree backscatter and 180 degree backscatter measurements.

2.3.2 Sediment deposition

Deposition is recorded in Accumulated Suspended Sediment Deposition (ASSD) (mg/cm²). The sensor is wiped clean of deposited sediment at a 2 hour interval to reduce bio-fouling and enable sensor sensitivity to remain high. The deposition sensor is positioned inside a small cup shape (16mm diameter x 18mm deep) located on the flat plate surface of the instrument facing towards the water surface. Deposited sediment produces a backscatter of light that is detected by the sensor. Deposited sediment is calculated by subtracting, from the measured data point, the value taken after the sensor was last wiped clean. This removes influence of turbidity from the value and re-zeros the deposition sensor every 2 hours.

If a major deposition event is in progress, the sensor reading will increase rapidly and will be considerably above the turbidity sensor response. Gross deposition will appear as irregular spikes in the data where the sediment is not removed by the wiper but by re-suspension due to wave or current stress. When a major net deposition event is in progress the deposited sediment will be removed by the wiper and the deposition sensor reading should fall back to a value similar to the turbidity sensor. The data will have a characteristic zigzag response as it rises, perhaps quite gently, and falls dramatically after the wipe (see Ridd et al., 2001).

Deposition data is provided as a measurement of deposited sediment in mg/cm² and as a deposition rate in mg/cm²/day. The deposition rate is calculated over the 2 hour interval between sensor wipes and averaged over the day for a daily deposition rate. The deposition rate is useful in deposition analysis as it describes more accurately the net deposition of sediment by smoothing spikes resulting from gross deposition events.

2.3.3 Pressure

A pressure sensor is located on the horizontal surface of the water quality logging instrument. The pressure sensor is used to determine changes in water depth due to tide and produce a proxy for wave action. Each time a pressure measurement is made the pressure sensor takes 10 measurements over a period of 10 seconds. From these 10 measurements, average water depth (m) and Root Mean Square (RMS) water height are calculated. RMS water height, D_{rms} , is calculated as follows:

$$D_{rms} = \sqrt{\sum_{n=1}^{10} (D_n - \bar{D})^2 / n}$$

Equation 1 : where D_n is the n th of the 10 readings and \bar{D} is the mean water depth of the n readings.

The average water depth and RMS water depth can be used to analyse the influence that tide and water depth may have on turbidity, deposition and light levels at an instrument location. The RMS water height is a measure of short term variation in pressure at the sensor. Changes in pressure over a 10 second time period at the sensor are caused by wave energy. RMS water height can be used to analyse the link between wave re-suspension and SSC. It is important to clearly establish that RMS water height is not a measurement of wave height at the sea surface. What it does provide is a relative indication of wave shear stress at the sea floor that is directly comparable between sites of different depths. For example, two sites both have the same surface wave height, site one is 10m deep and has a measurement of 0.01 RMS water height and site two is 1m deep and has a measurement of 0.08 RMS water height. Even though the surface wave height is the same at both sites, the RMS water height is greater at the shallower site and we would expect more re-suspension due to wave shear stress at this site.

2.3.4 Water temperature

Water temperature values are obtained with a thermistor that records every 10 minutes. The sensor is installed in a bolt that protrudes from the instrument and gives sensitive temperature measurements.

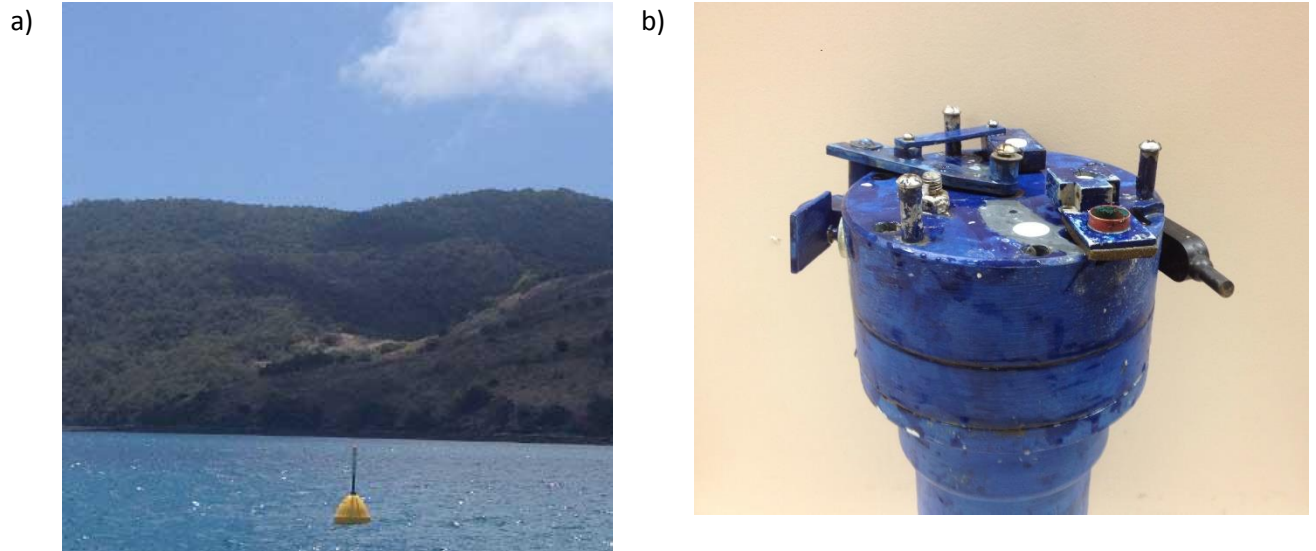


Figure 2.3 Example coastal multiparameter water quality instrument: a) site navigation beacon for safety and instrument retrieval; b) instrument showing sensors and wiping mechanisms

2.3.5 Photosynthetically Active Radiation (PAR)

A PAR sensor, positioned on the horizontal surface of the water quality logging instrument, takes a PAR measurement at ten (10) minute intervals for a one second period. To determine total daily PAR (mol photons m^2/day) the values recorded are multiplied by 600 to provide of PAR for a 10 minute period and then summed for each day.

2.4 Marotte current meter

The Marotte HS (High Sampling Rate) is a drag-tilt current meter invented at the Marine Geophysics Laboratory (Figure 2.4). The instrument records current speed and direction with an inbuilt accelerometer and magnetometer. The current speed and direction data are smoothed over a 10-minute period. The instruments are deployed attached the nephelometer frames and data is download when the instruments are retrieved.



b)



Figure 2.4 a) Basic schematic of Marotte HS current meter; and b) Marotte HS alongside Marotte at Moore Reef. Image courtesy of Eric Fisher

2.4.1 Measuring environmental controls on SSC

Stepwise regression analysis was used to investigate the environmental controls on SSC at the ambient sites, with data selected including:

(a) Ambient sites:

- | | |
|------------------------|----------------------|
| [1] "Freshwater Point" | [2] "Hay Point Reef" |
| [3] "Keswick Is" | [4] "Round Top Is" |
| [5] "Slade Is" | [6] "Victor Is" |

(b) River Gauge Station:

- | | |
|-------------|---------------|
| [1] "Sandy" | [2] "Pioneer" |
|-------------|---------------|

(c) Wind Station:

- | |
|------------------------------|
| [1] "Station 33119 – Mackay" |
|------------------------------|

(d) Tide Gauge Station:

- | |
|----------------------|
| [1] "Port of Mackay" |
|----------------------|

In this assessment, the environmental parameters with control on SSC were analysed by stepwise regression analysis followed by relative importance analysis (Grömping, 2006) using R language (R Core Team, 2015). The stepwise analysis allowed the selection of the environmental variables that explain the SSC variability in the water column. The relative importance analysis allowed these selected variables to be ranked based on their overall explanation of the SSC variability. In order to visualize the effect of each environmental parameter selected in the stepwise analysis, a partial plot analysis (Crawley, 2007) was carried

out. These partial plots indicate the dependence between SSC and each selected variable when all the other variables in the model are kept constant (Crawley, 2007). The data set used in the stepwise analysis was log-transformed, if needed, in order to satisfy requirements for regression analysis. For each site, all the following variables were tested in an initial model against SSC: RMS of water depth, mean daily wind, maximum tide amplitude and the Pioneer and Sandy River discharges. These rivers were selected due to their proximity to the sampling sites. The Rocky River gauge station was ceased in November, 2014, so it was not include in the analysis. Mean daily wind was calculated from 8 daily readings decomposed into NE-SW and NW-SE components. Maximum tide amplitude was calculated as the maximum absolute difference between two consecutive maximum or minimum tide readings. Wind components were calculated as the mean value of 8 daily measurements decomposed to in two diagonals, NE-SW and NW-SE. Variables presenting autocorrelation were excluded based on a variance inflation test (Fox and Monett, 1992) > 4 and outliers were removed based on Bonferroni Outlier Test (Cook and Weisberg 1982).

3 RESULTS AND DISCUSSION

3.1 Ambient water quality

3.1.1 Spot water quality physico-chemical

For the reporting period between July 2016 and July 2017 water temperature ranged between 20 and 30°C, which is consistent with previous reporting periods (Figure 3.1). There continues to be a strong seasonal effect on water temperatures in the region, with the highest water temperatures observed during surveys in the summer months (October, November, December), and cool water temperatures observed during the winter months (July, August, September). These patterns are consistent throughout the water column, indicating that the water column profile is not stratified and therefore well mixed. There are no guidelines for water temperature in coastal areas, however, temperature is an essential interpretative aid for ecological assessment in environments. For example, species such as fish and other animals have thermal stress point which causes discomfort and could be misconstrued as being a toxicological impact. There were no observed or known impacts on aquatic species in the region during this monitoring period.

Electrical conductivity (EC) was stable across all sites, with little evidence of changing conditions through the water column (Figure 3.2). Overall EC has remained between 51 mS/cm and 57 mS/cm, generally indicating oceanic conditions. However, in July 2014 and May/July 2017 EC decreased, ranging between 40 mS/cm and 55 mS/cm. The decrease in EC during May and July 2017 follows the large amount of rainfall associated with tropical cyclone Debbie in March 2017.

Dissolved oxygen saturation levels ranged between 80 to 112% (Figure 3.3). There was some local variability among sites, with the lowest levels recorded at AMB11 (Mackay Marina) at the bottom horizon. The reason for the lower dissolved oxygen in the marina is possibly due to the enclosed nature of this facility, with reduced tidal exchange and therefore circulation of waters, and a small wind fetch which may assist in re-oxygenating the water column profile. Despite slightly lower available oxygen at AMB11, during each survey fish are continually present suggesting that conditions are not critical or require management intervention. If conditions were to become critical, then it seems fish could easily swim out of the marina facility. For all other sites, the water column continues to be well mixed with dissolved oxygen levels similar along the depth profile.

Field pH measurements were stable across sites and depths primarily ranging between 8.0 and 8.3 (Figure 3.4). However, samples collected in August 2015 and April 2016 were more acidic (< 7.9) and samples collected in May and July 2016 were more alkaline (> 8.3), although still within expected range for marine waters (ANZECC, 2000). Throughout the 2016-2017 monitoring period pH levels were relatively stable.

Field turbidity measurements typically ranged between <1 to 55 NTU, with notable exceptions in November 2014 where turbidity was higher (Figure 3.5). Turbidity was similar among sites and relatively consistent throughout the water column (Figure 3.5b). Secchi disk depth (m) is a vertical measure of the optical clarity of water column and ranged between 1 and 16m (Figure 3.6a). The range measured is a response to localised variation in water quality, most likely a difference in tidal stage among sites during a survey – some sites may have been

surveyed on an ebbing or flooding tide where water depth was lower or higher, short term localised changes in turbidity that is associated with tide (see section 3.2) or algal blooms that reduce vertical clarity. The secchi disk depth to depth ratio (Zeu:Z, Figure 3.6b) was calculated for each site and survey. This ratio corrects the secchi disk depth for water depth. This ratio ranged between 9 and 100% of the water column, which means that water clarity ranged between 9% of the water through to the entire water column.

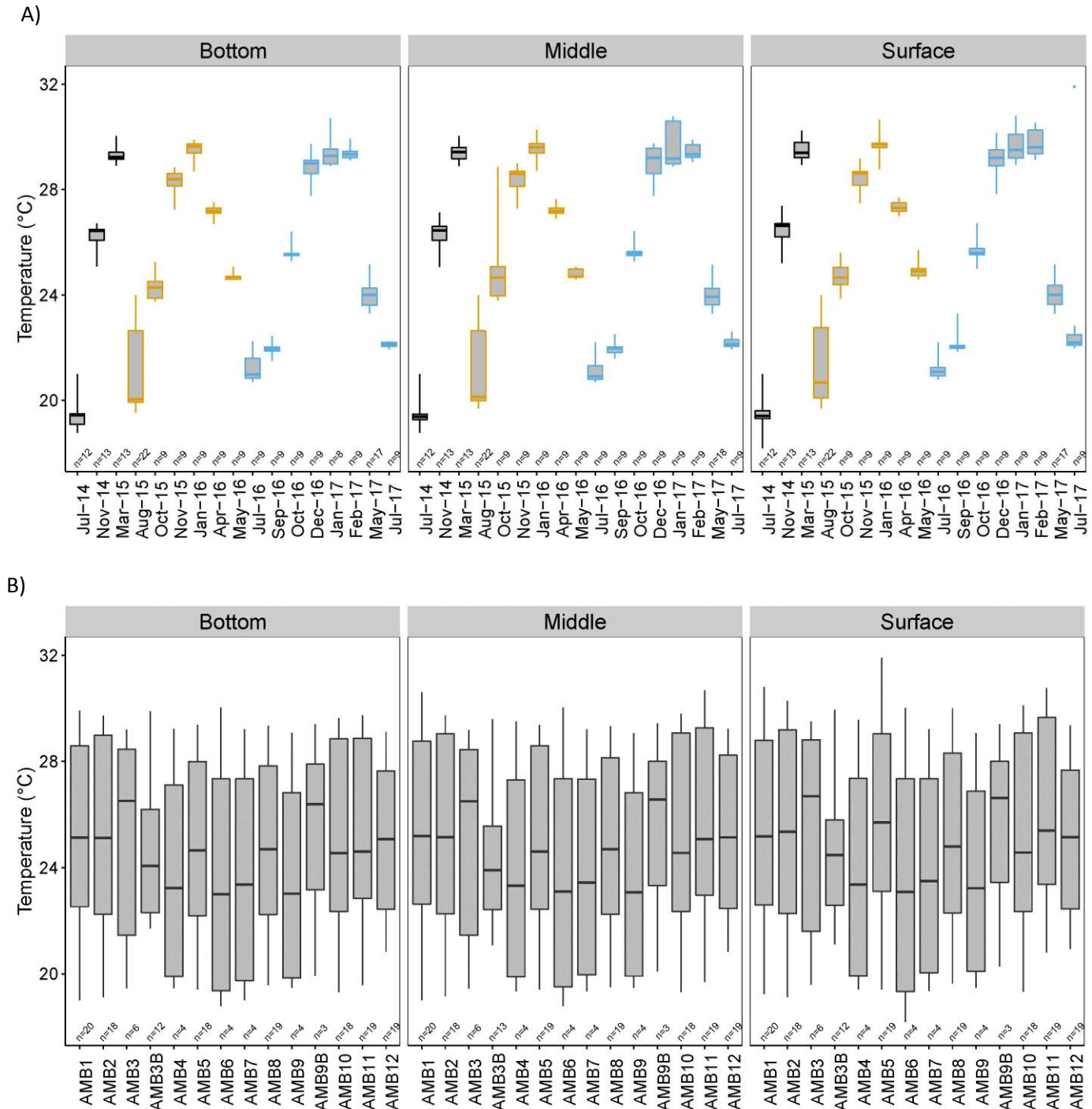


Figure 3.1

Water temperature box plots recorded: (a) the three depth horizons during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) the three depth horizons for each site (pooled across all three sampling periods during 2014-2017)

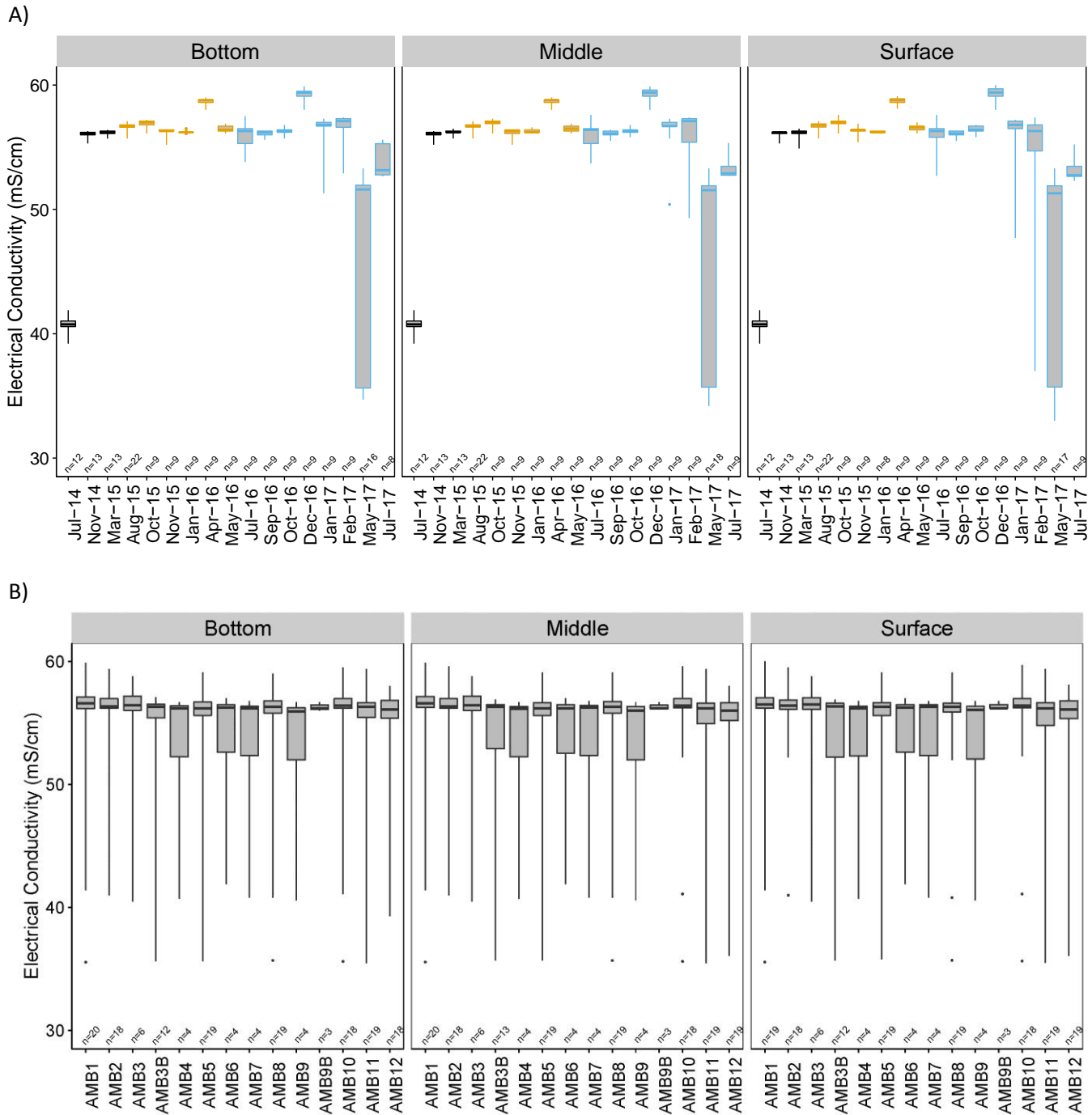
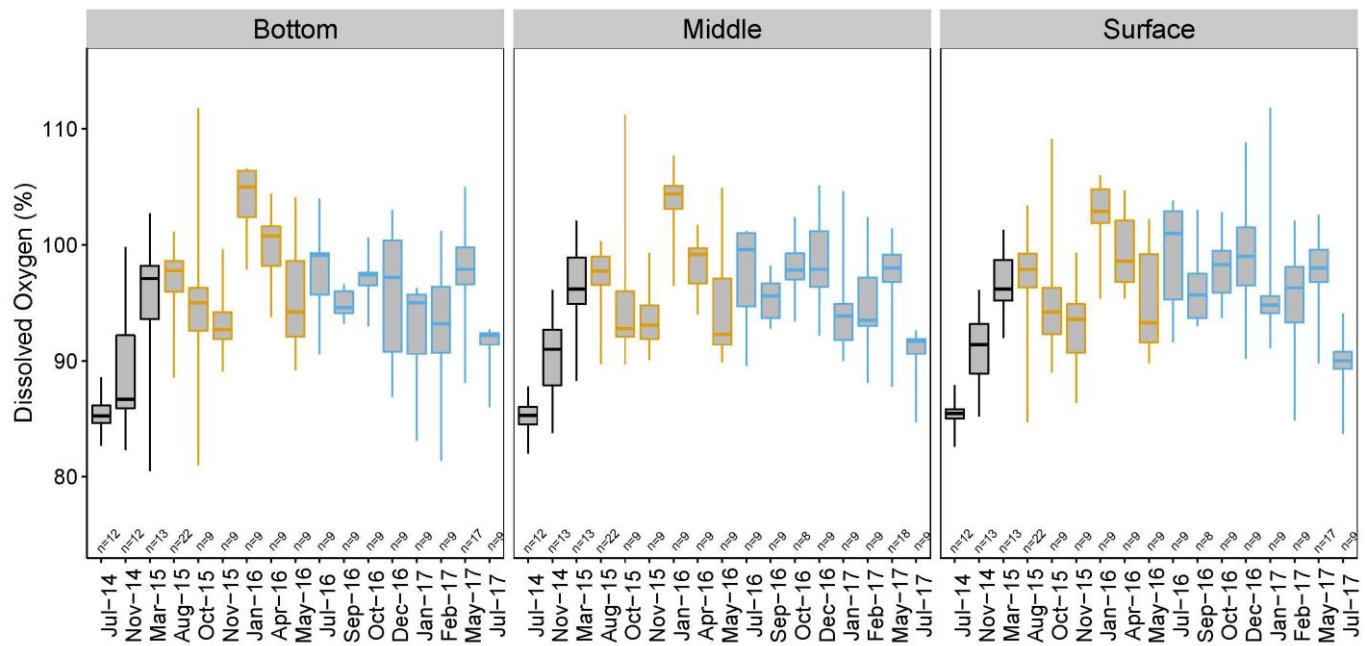


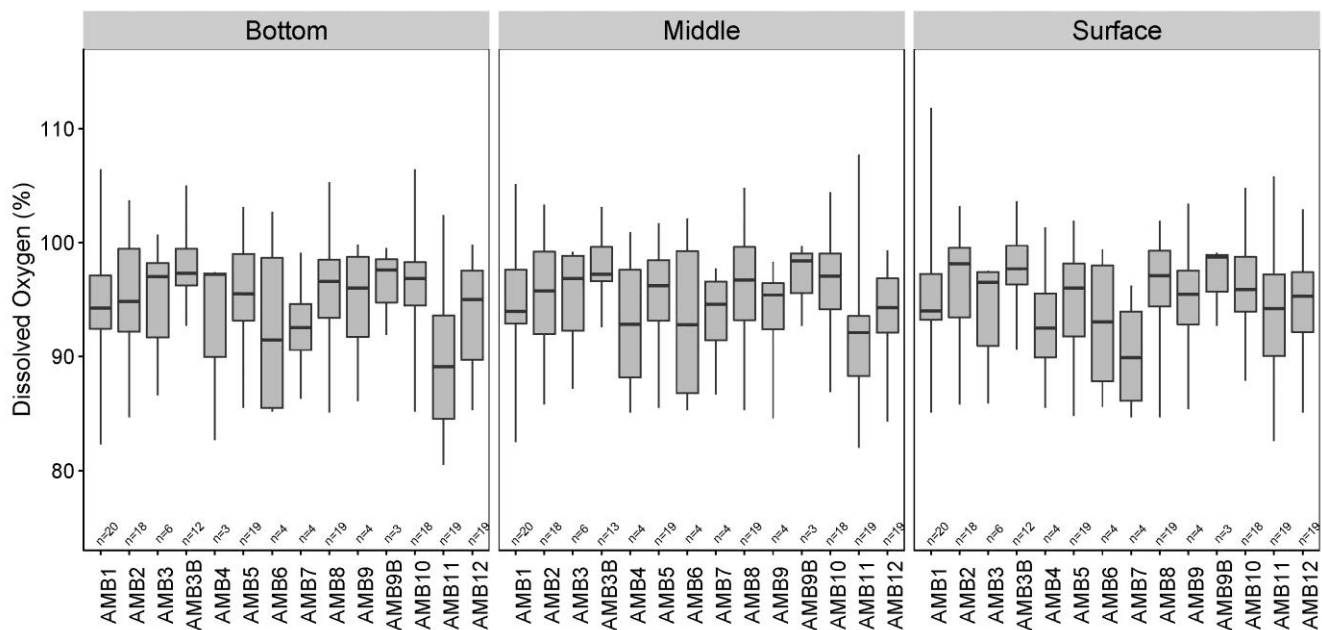
Figure 3.2

Salinity box plots recorded: (a) three depth horizons during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) the three depth horizons for each site (pooled across all three sampling periods during 2014-2017)

A)

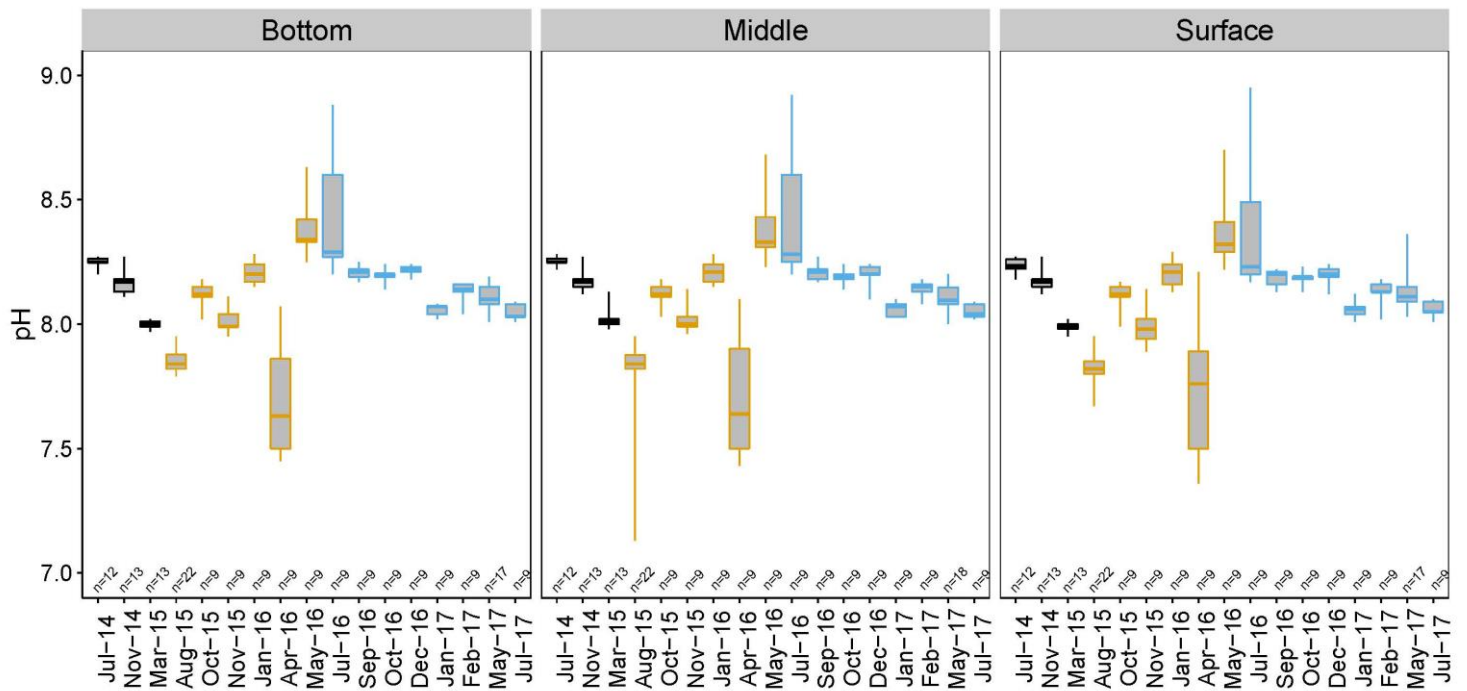


B)

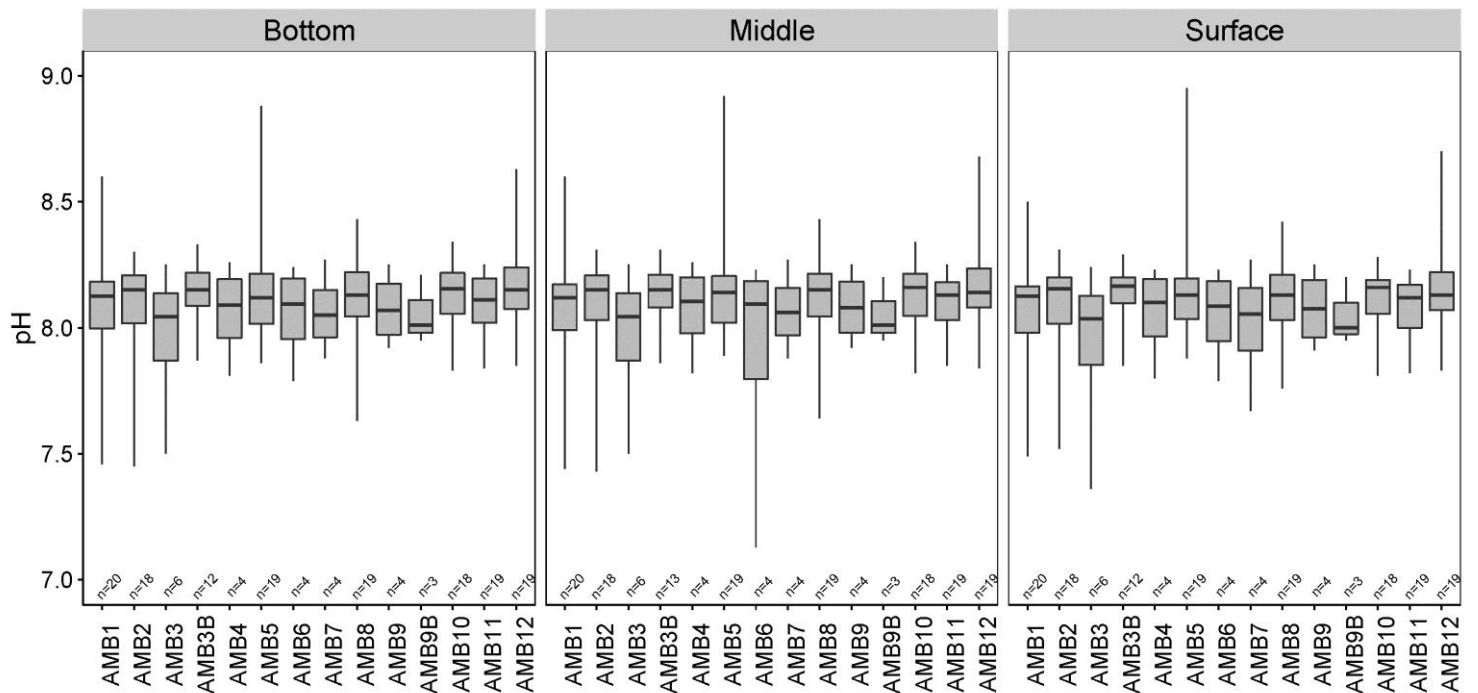

Figure 3.3

Dissolved oxygen box plots recorded: (a) three depth horizons during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) the three depth horizons for each site (pooled across all three sampling periods during 2014-2017)

A)



B)


Figure 3.4

pH box plots recorded: (a) three depth horizons during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) the three depth horizons for each site (pooled across all three sampling periods during 2014-2017)

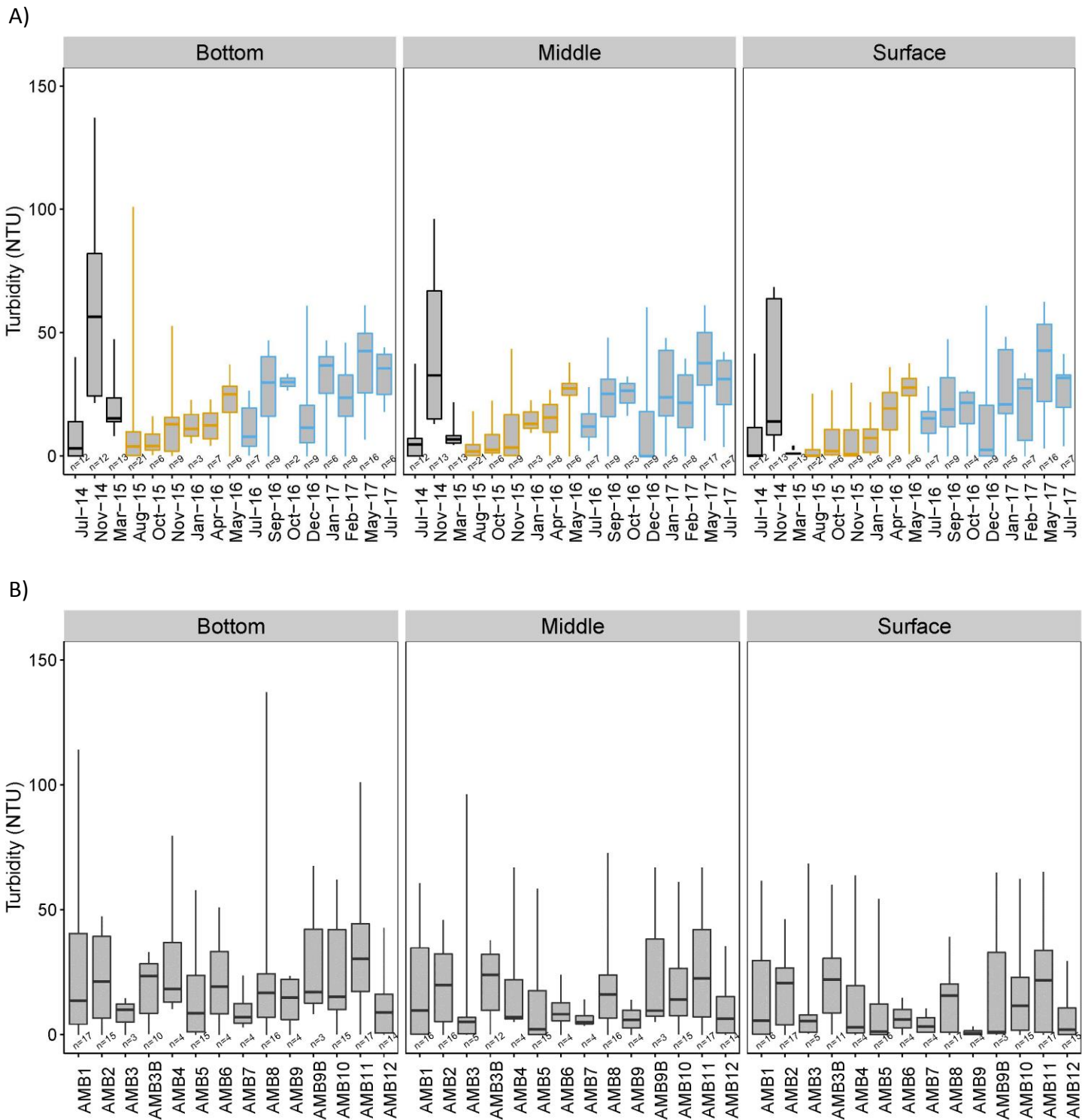
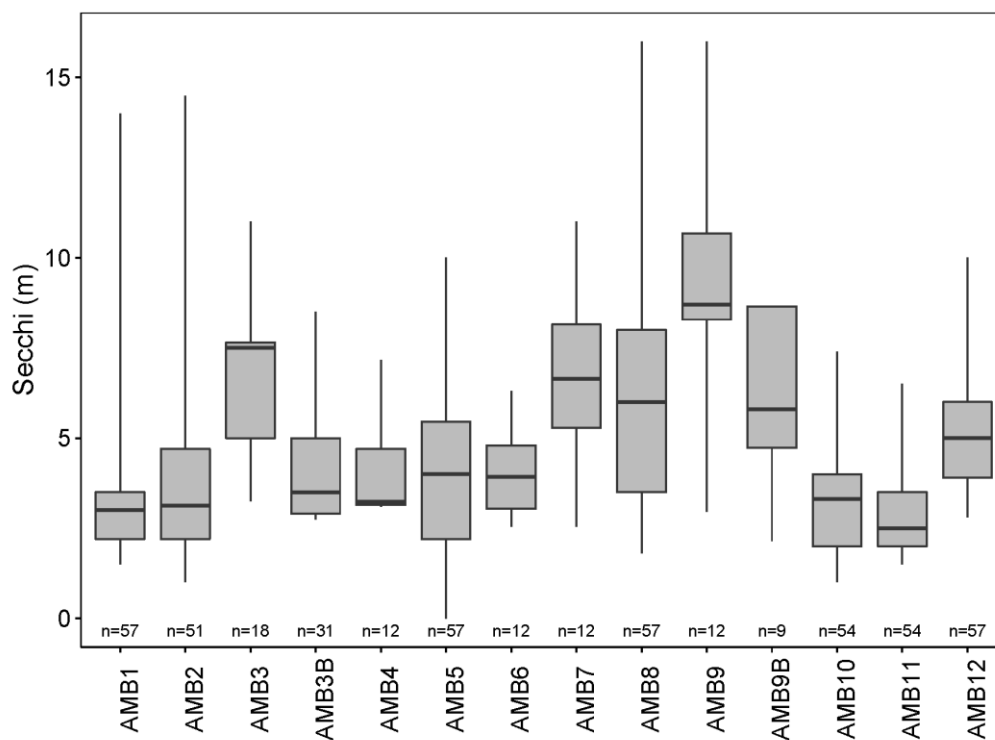


Figure 3.5

Turbidity box plots recorded: (a) three depth horizons during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) the three depth horizons for each site (pooled across all three sampling periods during 2014-2017)

A)



B)

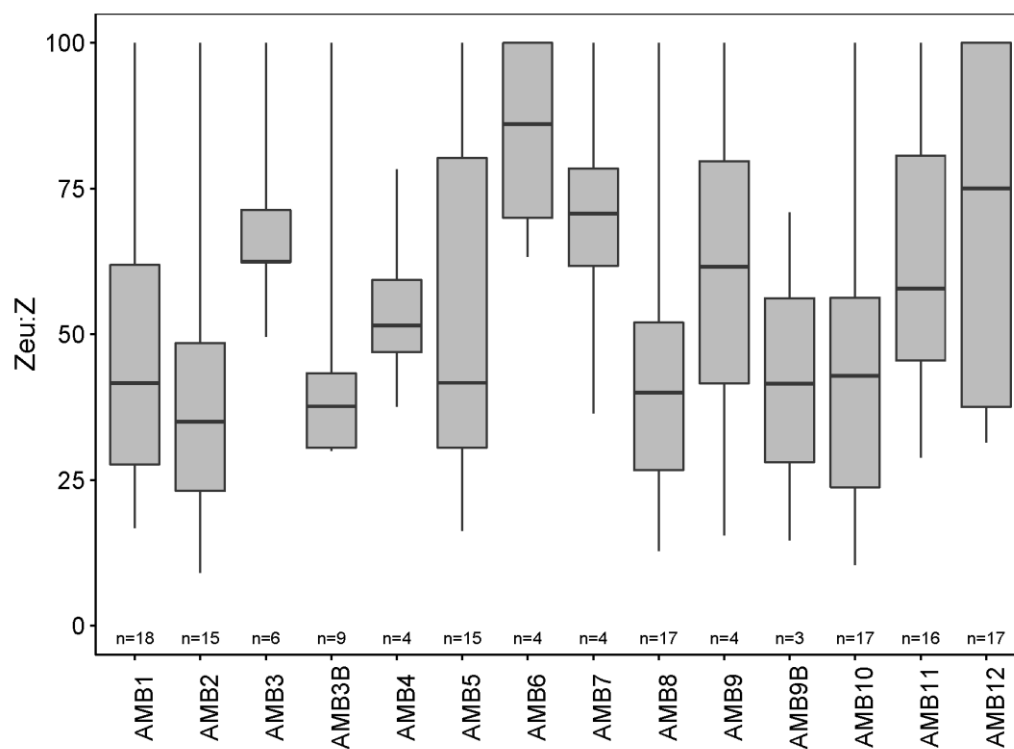


Figure 3.6 (A) Water secchi disk depth for all sites (surveys pooled for all monitoring periods 2014-2017); and (b) light attenuation depth to depth ratio (Zeu:Z) for sites (surveys pooled for all monitoring periods 2014-2017)

3.1.2 Nutrients and chlorophyll-*a*

Particulate nitrogen (PN) and phosphorus (PP) concentrations were compared to local water quality guidelines for the Mackay-Whitsunday Water Quality Improvement Plan (Folker et al. 2014; Drewry et al. 2008), the Water Quality Guidelines for the Great Barrier Marine Park Authority (GBRMPA, 2010) and the Queensland Water Quality Guidelines (DEHP, 2009). Particulate nitrogen concentrations exceeded the guideline during July 2014, October – November 2015, and in January 2017 (Figure 3.7a). Despite high concentrations during certain months, PN was similar across all sites, with concentrations exceeding guidelines at the following sites: AMB1, AMB4, AMB6, AMB7, and AMB9B (Figure 3.7b).

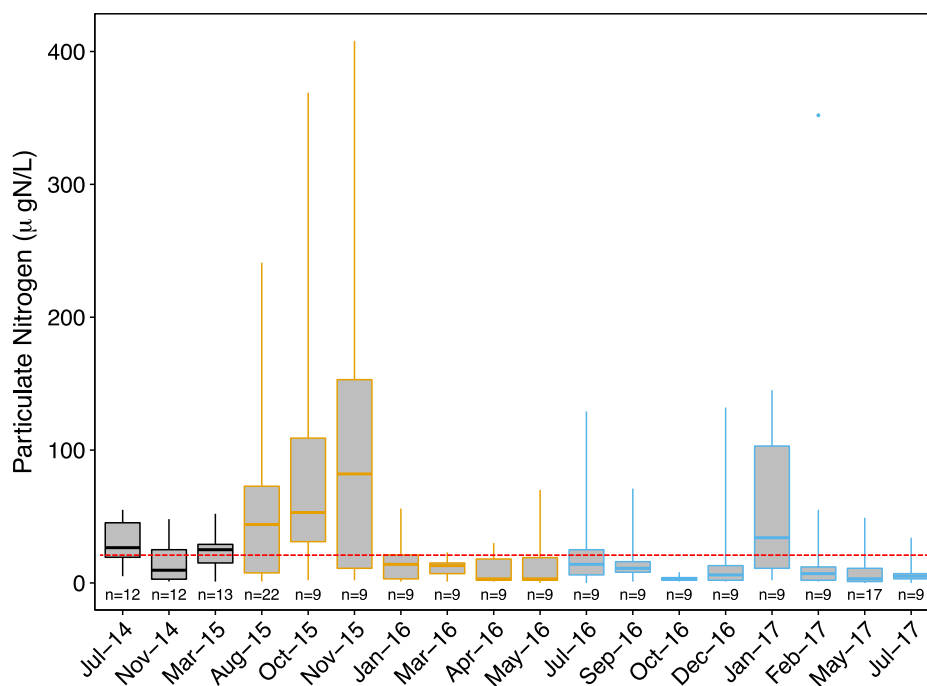
High concentrations of PN might be associated with contribution from local land use, whereby despite low rainfall (see Figure 1.3), there would be still some base flow from rivers and local rainfall that is known to contribute to nutrient loadings to coastal regions (Brodie et al. 2012; Kroon et al. 2012; Schaffelke et al. 2012; Logan et al. 2014). In addition, other sources of the nutrients might be through remobilisation of coastal sediments and release of available nutrients adsorbed to coastal sediments (Devlin et al. 2012). In addition, elevated nutrients might also be related to reprocessing of nutrients with algal blooms, where there has been an obvious trichodesmium (a marine cyanobacteria; Capone et al. 1997) bloom across the region during most surveys, but most notably during late spring and early summer.

Particulate phosphorus concentrations continue to be variable from survey to survey and site to site with no apparent seasonal pattern (Figure 3.8). February 2017 showed the highest concentration of PP over the entire monitoring period, exceeding the Mackay-Whitsunday water quality objective values (Folker et al., 2014). Sites AMB1, AMB2 and AMB11 also exceeded water quality objective values over all three monitoring periods during 2014 – 2017. AMB11 is located in the Mackay Marina, and therefore may be influenced by local stormwater runoff.

Chlorophyll-*a* concentrations were generally close to, or elevated above the guidelines (Figure 3.9). The highest concentrations were recorded during October 2015, but were not elevated in October 2016 (Figure 3.9a). Therefore this is likely not a seasonal pattern, but rather due to the inherent variability of local water quality conditions. Over the all three monitoring periods (2014-2017) Chlorophyll-*a* concentrations were highest at AMB7 and AMB11.

Relationships between nutrient levels (i.e. PN, PP, Chlor-*a*, and Phaeophytin-*a*) across all sites and sampling periods were positive but weak (correlation coefficients (*r*) ranged between 0.12 – 0.28; Figure 3.9a). Principal components analysis was used to further explore patterns in nutrient levels among sites, showing that most coastal sites have higher chlorophyll-*a* and phaeophytin-*a* levels in comparison to offshore sites (Figure 3.9b). However, AMB1 is a coastal site with relatively low levels of chlorophyll-*a* and phaeophytin-*a*, yet has the highest concentrations of particulate nitrogen and phosphorus (Figure 3.9b).

A)



B)

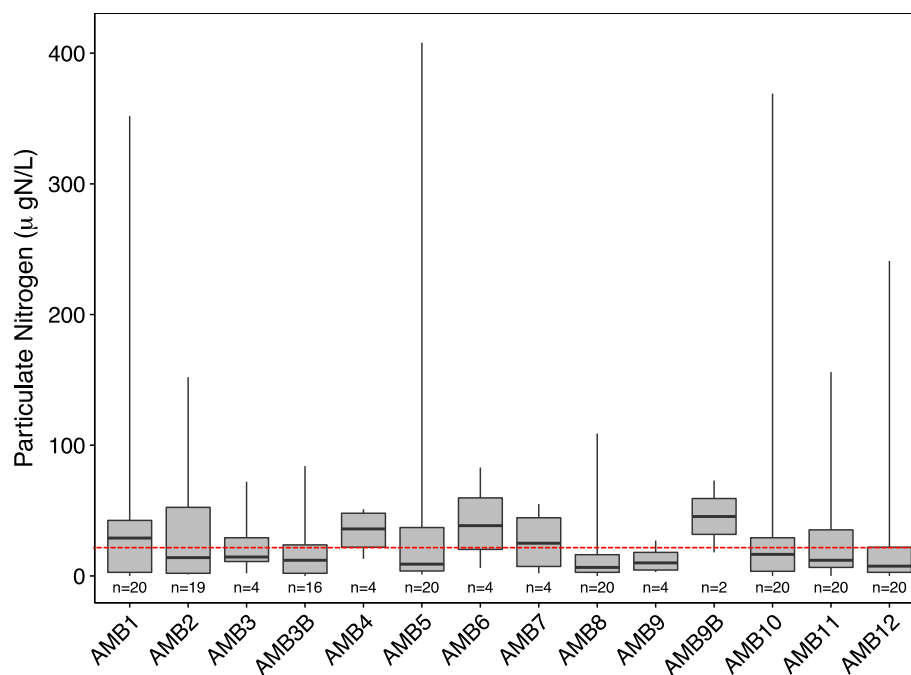
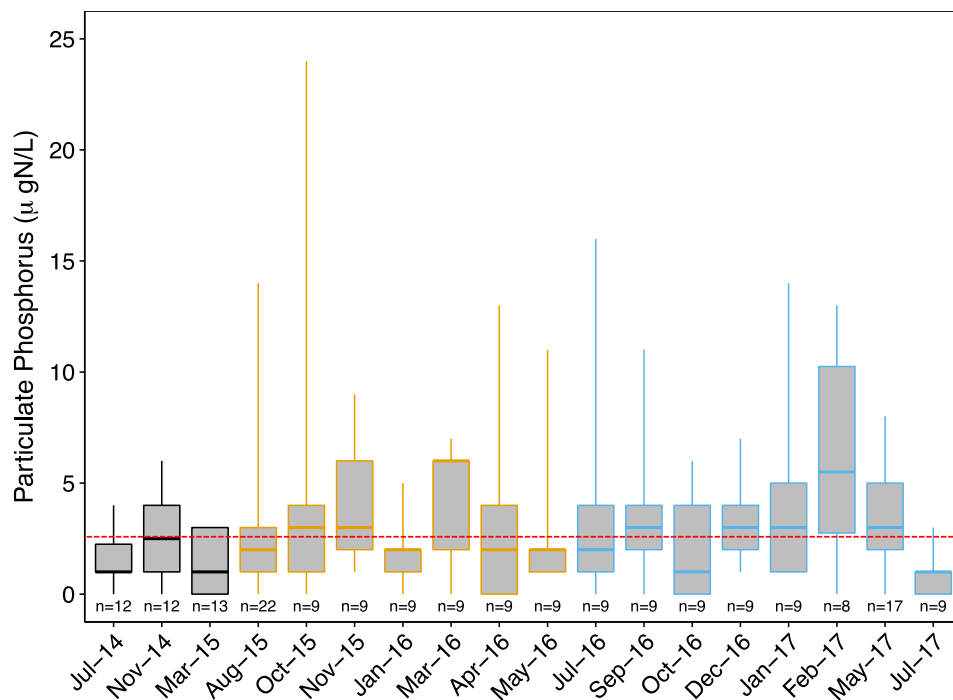


Figure 3.7 Particulate nitrogen box plots: (a) during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) at each site over this same survey period (surveys pooled)

A)



B)

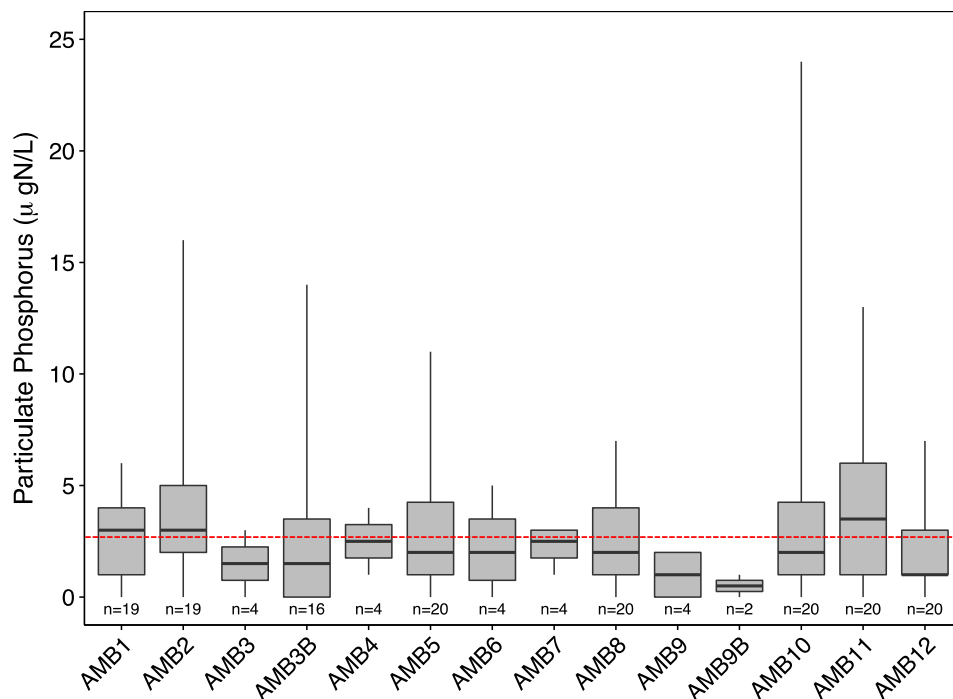
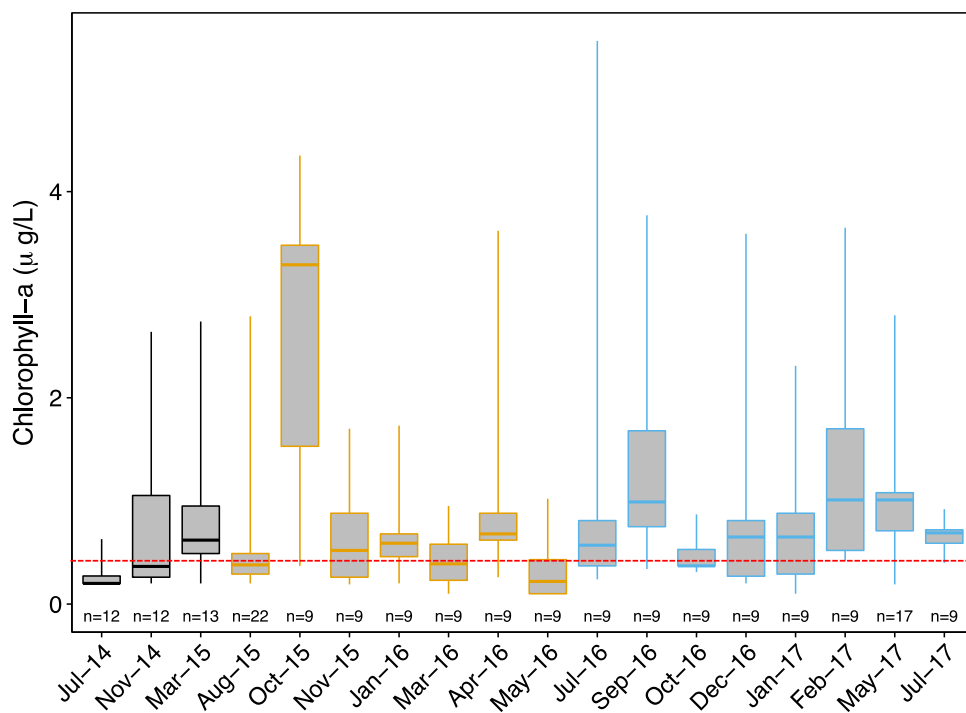


Figure 3.8

Particulate phosphorus box plots: a) during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) at each site over this same survey period (surveys pooled)

A)



B)

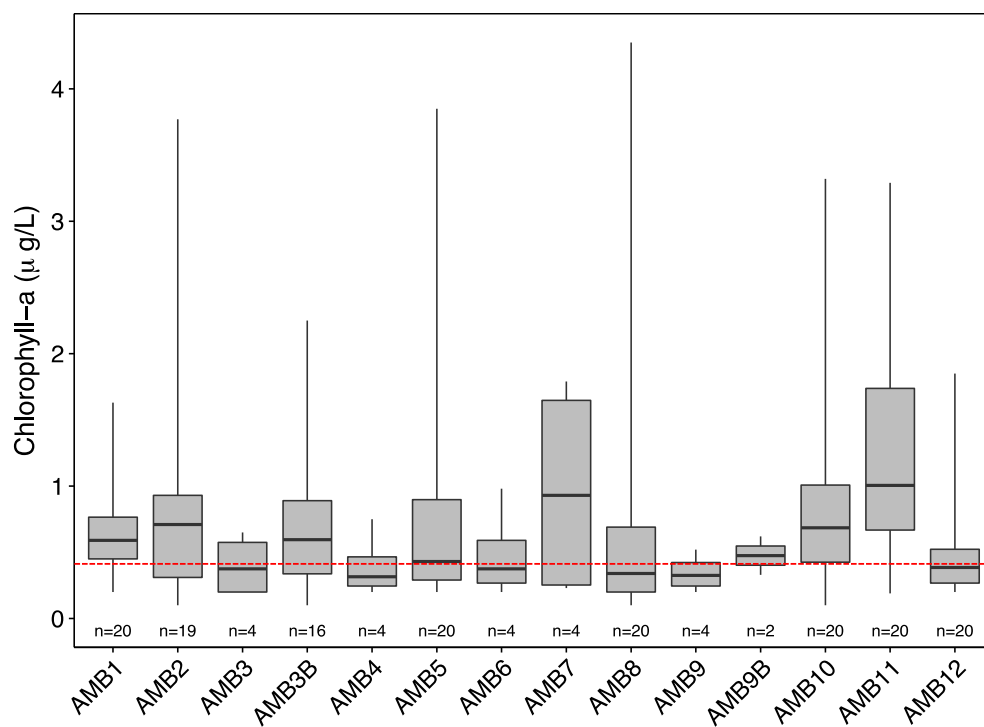


Figure 3.9 Chlorophyll-a box plots: a) during each survey (sites pooled) where colour indicates monitoring period: black = 2014/2015, orange = 2015/2016, and blue = 2016/2017; and (b) at each site over this same survey period (surveys pooled)

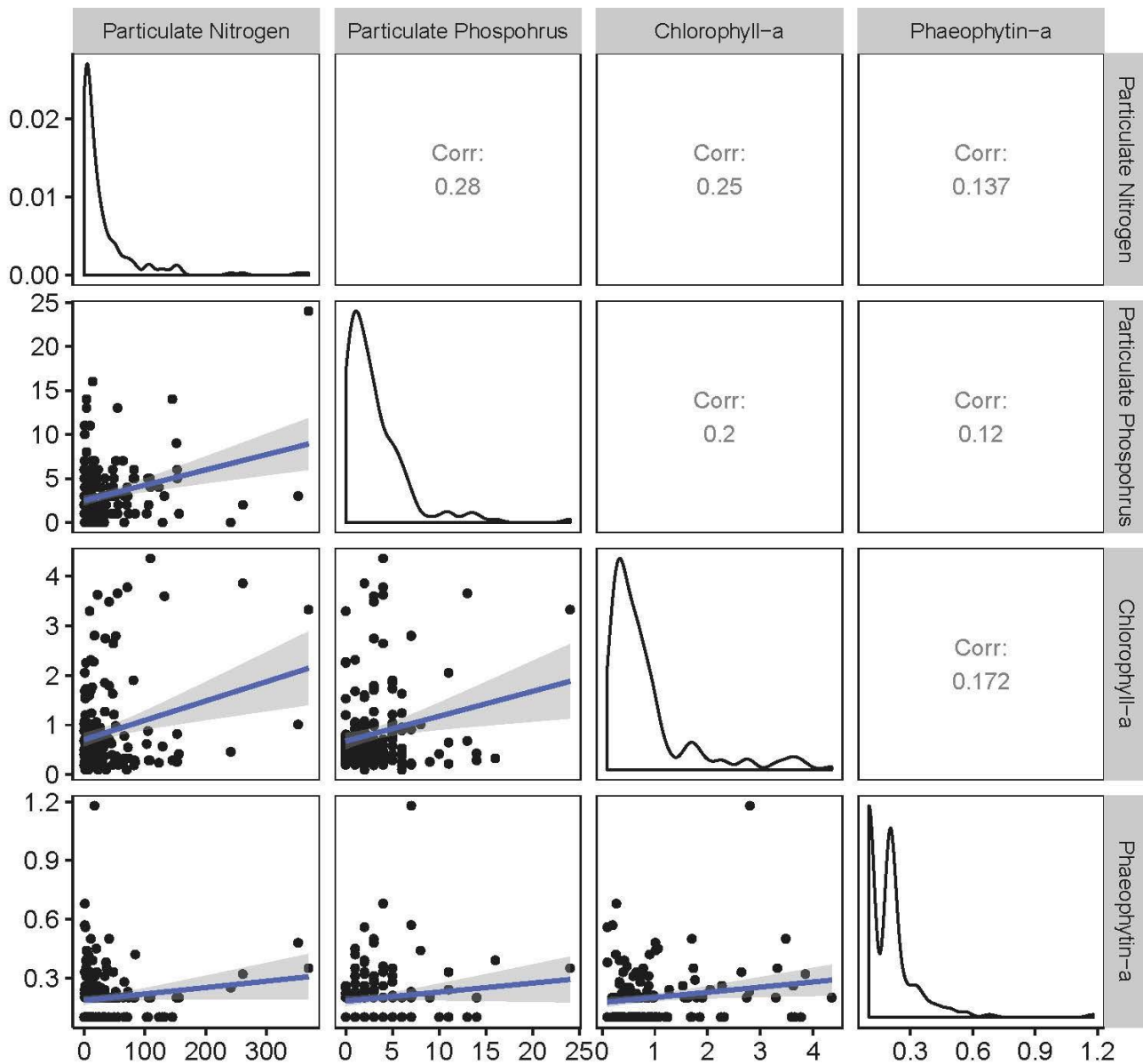


Figure 3.9a Scatterplot of nutrient relationships at pooled across all sites and surveys. Lines of best fit with 95% confidence intervals are displayed in blue, and correlation coefficients are shown in corresponding plots. Density plots show the distribution of the data

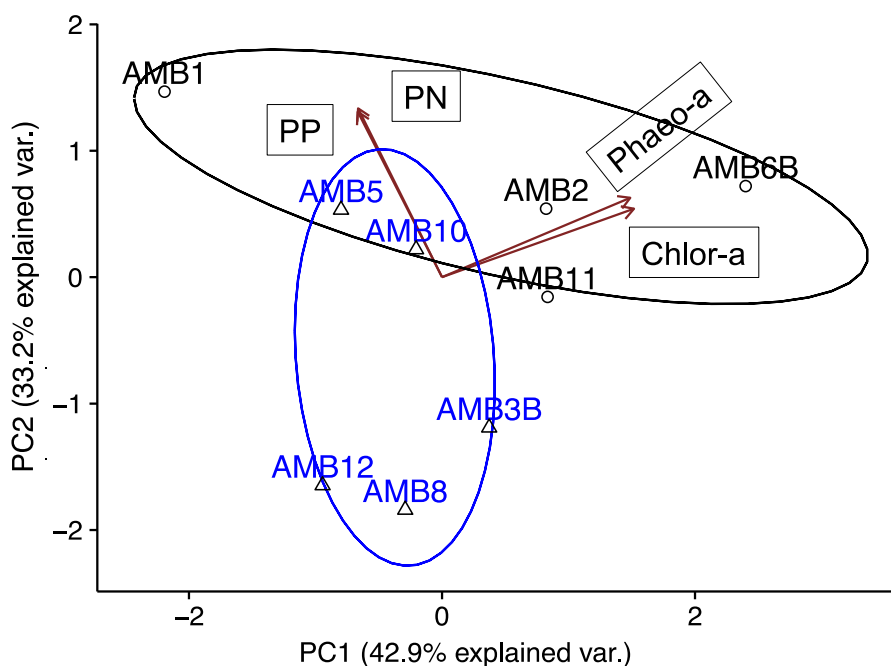


Figure 3.9b Principal components analysis (PCA) exploring relationships between nutrients (red vectors) and sites (blue = offshore, black = coastal) with 95% confidence interval ellipses surrounding offshore and coastal groups. Nutrient labels are abbreviated as follows: PP = Particulate Phosphorus, PN = Particulate Nitrogen, Chlor-*a* = Chlorophyll-*a*, Phaeo-*a* = Phaeophytin-*a*. Total variance explained by PC1 and PC2 = 76.1%

3.1.3 Ultra-trace water heavy metals

Ultra-trace heavy metal concentrations were compared to the ANZECC and ARMCANZ 2000 water quality guidelines (ANZECC, 2000). Most of the filterable metals were not detected above the Limit of Reporting (LOR), the exception to this was arsenic (Table 3.1). No ANZECC guideline exists has been established for arsenic. Arsenic is released into the environment naturally by weathering of arsenic-containing rocks and volcanic activity. It can be in the form of As (III) or As (V), which can be toxic to marine aquatic life. A low reliability marine guideline trigger value of 4.5 µg/L for As (V) and 2.3 µg/L for As (III) has been derived (ANZECC, 2000), however, these trigger guidelines are only an indicative interim working level. Measured concentrations seem to be below these low reliability guidelines.

Copper has been previously detected in the Mackay Harbour site (AMB 11) during the 2014/15 reporting period (Waltham et al. 2015), exceeding the ANZECC 95% protection limit. Lead was also previously detected (survey 1; July 2014), but was below the 95% protection value. Both lead and copper have not been recorded above the LOR during the current reporting period.

Table 3.1 Summary statistics for metals data recorded at all sites during the program. Values are pooled across sites. Values are compared to the ANZECC 95% protection guideline values (2000). Values in blue represent exceedances. (-) sample not collected

		Arsenic	Cadmium	Copper	Lead	Nickel	Silver	Zinc	Mercury	Tributyltin
Unit		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	ug/L	mg/L	ngSn/L
LOR			0.2	1	0.2	0.5	0.1	5	0.001	2
ANZECC		ID	5.5	1.3	4.4	70	1.4	15	0.4	0.006
Jul-14	Mean	1.45	<0.2	<1	0.25	<0.5	<0.1	<5	<0.0001	-
	Min	1.3	<0.2	<1	0.2	<0.5	<0.1	<5	<0.0001	-
	Max	1.6	<0.2	2	0.3	<0.5	<0.1	<5	<0.0001	-
Nov-14	Mean	1.28	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Min	0.8	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.5	<0.2	1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Mar-15	Mean	1.68	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Min	1.50	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.90	<0.2	2	<0.2	<0.5	<0.1	<5	<0.0001	<2
Aug-15	Mean	1.22	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Min	1.10	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.30	<0.2	1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Nov-15	Mean	1.74	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Min	1.60	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.90	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Mar-16	Mean	1.67	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Min	1.40	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.70	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Dec-16	Mean	1.72	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Min	1.60	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.90	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
May-17	Mean	1.58	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Min	1.50	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.80	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Overall	Mean	1.41	<0.2	2	0.25	<0.5	<0.1	<5	<0.0001	<2
	Min	0.8	<0.2	<1	0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.9	<0.2	2	0.3	<0.5	<0.1	<5	<0.0001	<2

3.1.4 Water pesticides and herbicides

The majority of pesticide and herbicide concentrations were not detected above the limit of reporting (Table 3.2). Where possible, these concentrations were compared to the water quality improvement guidelines for the Great Barrier Reef Marine Park (GBRMPA, 2010) and all detected concentrations were well below the 95% protection values. The Mackay-Whitsunday Water Quality Improvement Plan's water quality objectives (2014), however, use a region wide guideline of 0.01 µg/L (LOD unchanged since 2008). During this reporting period, Hexaninone, Diuron and Atrazine have been detected following commencement of this program (particularly at AMB1, AMB2 and AMB6B, which are all coastal sites located near to river systems) though results are a signal for the catchment land use in the local area, which is predominately sugar cane. Interestingly, during the wet season survey (March 2016) all pesticide and herbicide concentrations were below the limit of reporting. Similar to the first year of reporting (Waltham et al. 2015), it should be noted that although all detected

pesticide levels were below 95% protection guidelines, the period of study is focused on post wet and late dry season conditions.

Table 3.2 Summary (average) statistics for pesticides/herbicides recorded at all sites during the program (all values are µg/L). Values are pooled across sites for each survey and compared to the Water Quality Guidelines for the Great Barrier Reef Marine Park (GBRMPA, 2010) 95% protection level. Mackay-Whitsunday Water Quality Improvement Plan 2014-2021 Water Quality Objectives (WQO's) are also included to assess tracking. Overall concentrations are pooled for the program 2014 – 2017

Survey	Guideline	Atrazine	Ametyn	Diuron	Hexazinone	Tebutryn
	GBRMPA (2010)	1.4	1.0	1.6	1.2	-
	WQO (WQIP 2014)	0.01	0.01	0.01	0.01	0.01
July 2014		0.0006	<0.0004	0.0069	0.0005	0.0009
March 2015		0.0004	<0.0002	0.0045	0.0003	<0.0002
November 2015		0.0004	0.0002	0.0097	0.003	<0.0002
March 2016		<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
December 2016		0.0003	<0.0002	0.0002	0.0003	<0.0002
May 2017		0.0002	<0.0002	<0.0002	0.0005	<0.0002

3.1.5 Ordination of data

Spot water quality measurements have been collected at all sites for water temperature, electrical conductivity, dissolved oxygen (%), pH, turbidity, and light attenuation. In addition to these spot measurements, secchi depth has also been recorded, as a measure of the optical clarity of the water column. Field in-situ measurements have been recorded at three depth horizons; surface (0.25m), middle, and the bottom horizon. These measurements continue to assist in characterising water quality conditions within the water column, among sites and surveys. Exploratory statistical examination of the data collected to date using multidimensional scaling (nMDS) reveals a significant difference (ANOSIM, Global R <0.01) in water quality conditions from year to year (Figure 3.10).

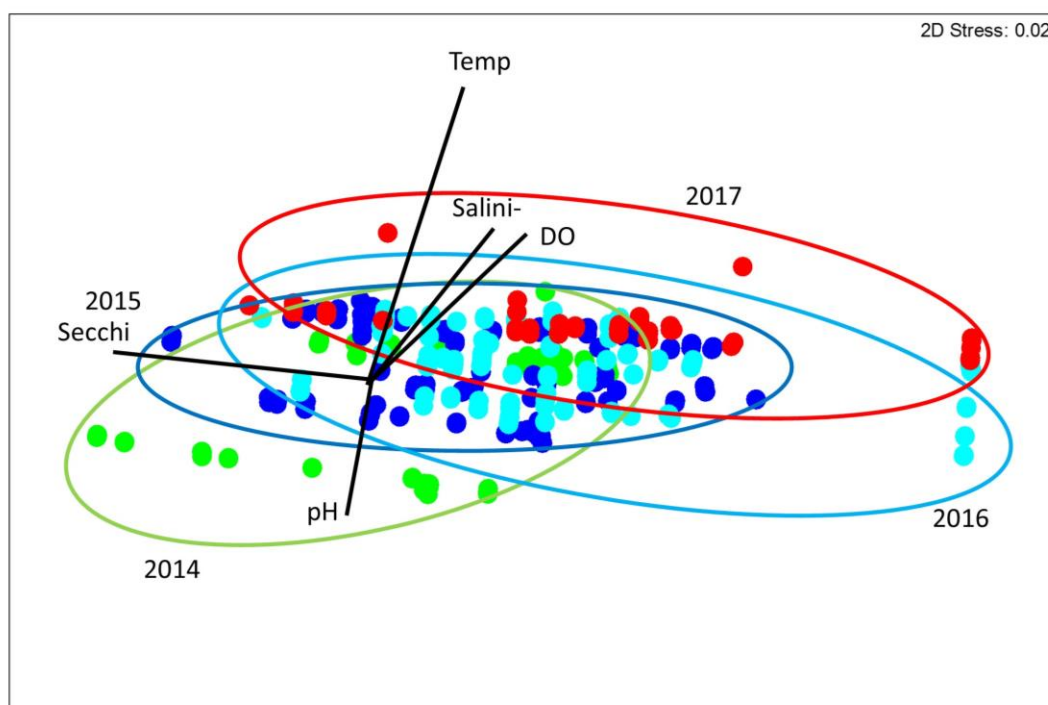


Figure 3.10 Non-dimensional ordination plot using field in-situ measurements recorded by year. Data has been Log x transformed on the Euclidean distance matrix (Clarke & Gorley 2006). Trajectory lines illustrate direction of influencing water quality parameter

3.2 Plankton communities

Plankton samples have been collected on six occasions across the study area: November 2015, April 2016, May 2017, July 2017, September 2017, and October 2017. A total of 77 phytoplankton species have been identified, comprising cyanobacteria, diatoms, flagellates and green algae taxa. Several species were recorded at all sites, including *Rhizosolenia spp*, *Chaetoceros spp*, *Chaetoceros simplex*, *Bacteriastrum delicatulum*, and *Navicula spp*. Freshwater Point (AMB 1) had the highest phytoplankton species richness in May 2017 (28 species), and the lowest species richness in September 2017 (4 species) (Figure 3.11a). Of the cyanobacteria species, *Trichodesmium spp* was the most widespread species, and was regularly recorded during field trips to the region. Furthermore, the large increases in phytoplankton abundance at Victor Islet (AMB10), Slade Island (AMB5) and Round Top Island (AMB3B) in September 2017 were driven primarily by *Trichodesmium spp* (Figure 3.11b).

A total of 50 different species of zooplankton were recorded during all surveys. Several species were recorded at all sites, including *Flaccisagitta enflata*, *Favella serrata*, and Siphonophorae. Dudgeon Point (AMB 6B) had the highest diversity of zooplankton species in November 2015 (19 species), while Hay Point (AMB 2) and Keswick island (AMB 12) both had the lowest zooplankton species diversity (4 species) in July 2017 and April 2016, respectively (Figure 3.12a). The total abundance of zooplankton peaked at different times of the year at each site, and was highest at Dudgeon reef (AMB6B) in April 2016 (Figure 3.12b).

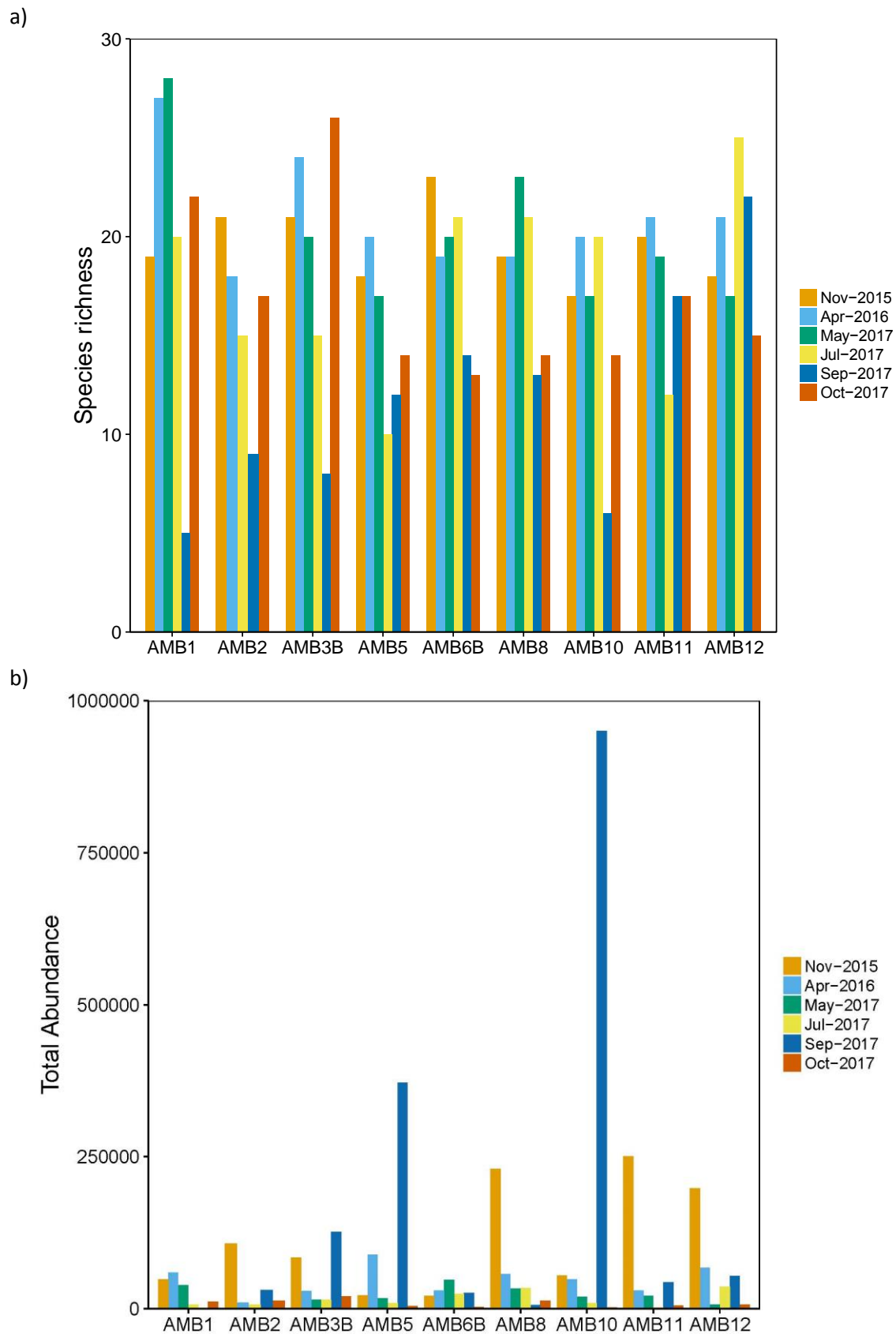


Figure 3.11 a) Species richness of phytoplankton; and b) total species count of phytoplankton at each site during the following survey periods: November 2015, April 2016, May 2017, July 2017, September 2017, and October 2017

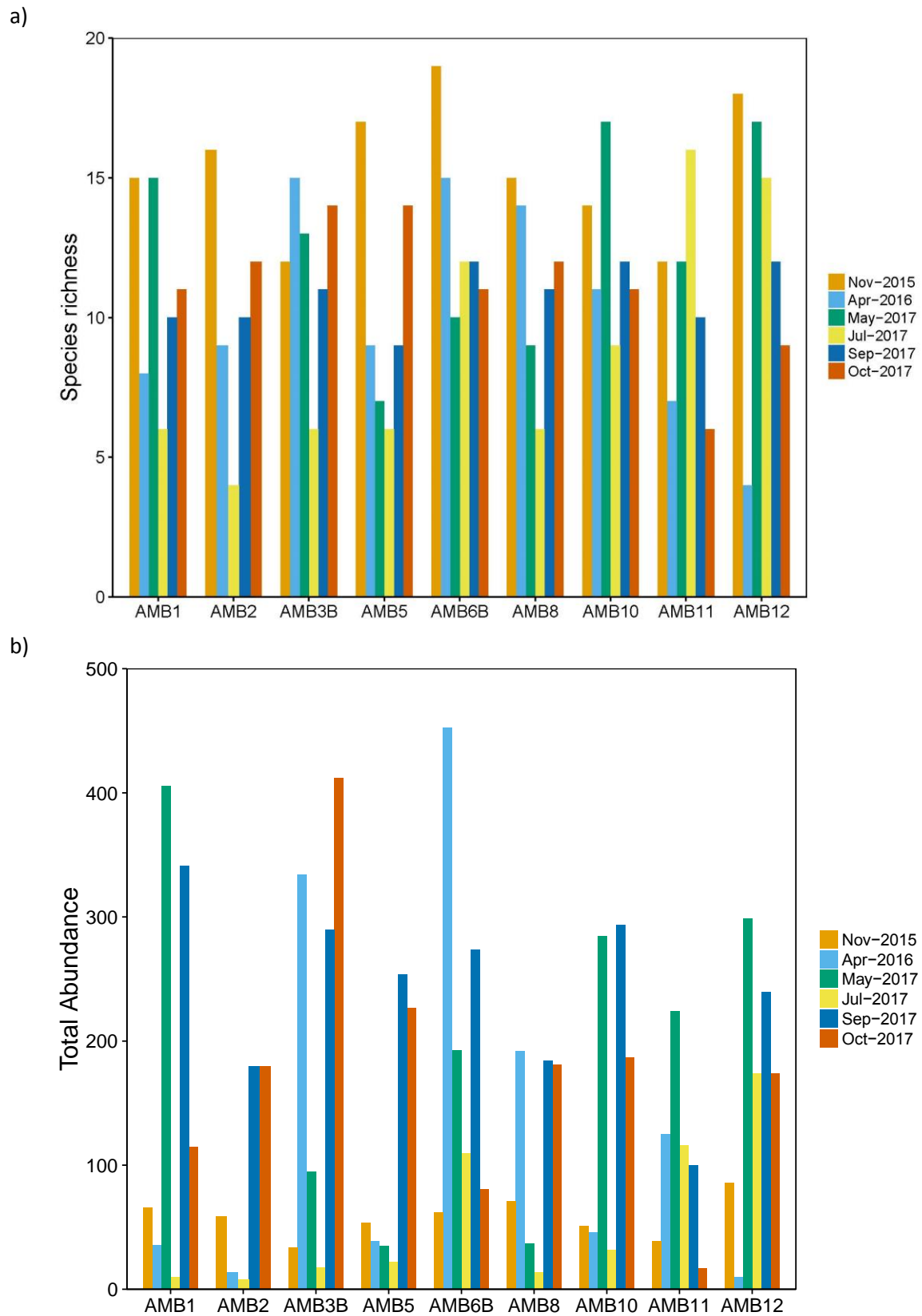


Figure 3.12 a) Species richness of zooplankton and b) total species count of zooplankton at each site during the following survey periods: November 2015, April 2016, May 2017, July 2017, September 2017, and October 2017

3.2.1 Plankton ordinations

Exploratory statistical analysis of the plankton using non-dimensional scaling (nMDS) revealed differences in species composition of phytoplankton (Figure 3.13) and zooplankton (Figure 3.14) between survey periods. Phytoplankton species composition at Freshwater Point (AMB1) in September 2017 was particularly distinct relative to other sites, corresponding to its low species richness and abundance at this time. Overlap of 95% confidence interval ellipses suggests that phytoplankton and zooplankton communities were most similar in their species composition during May, July, and September 2017.

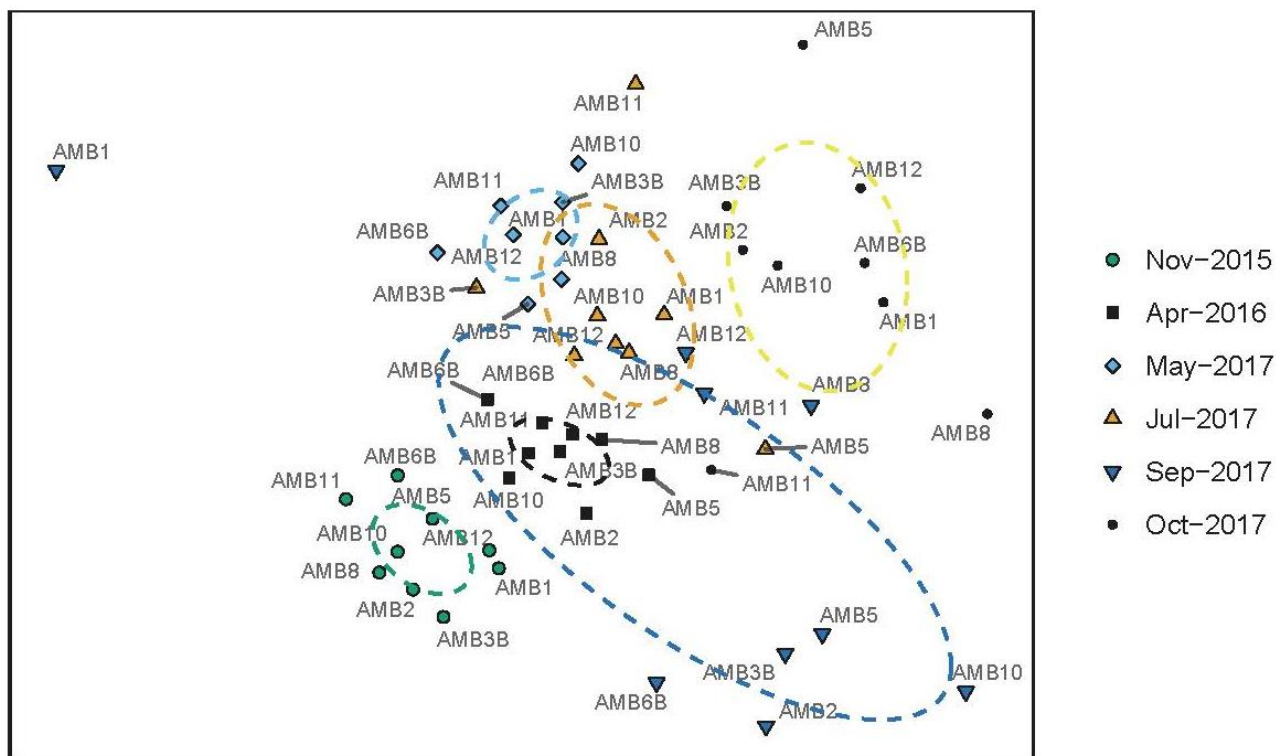


Figure 3.13 Non-dimensional ordination plot for phytoplankton collected during six survey periods throughout 2015-2017. Dashed lines represent 95% confidence interval ellipses for each survey period. Data has been squared root transformed on the Bray Curtis distance matrix (stress = 0.22, Clarke and Gorley 2006)

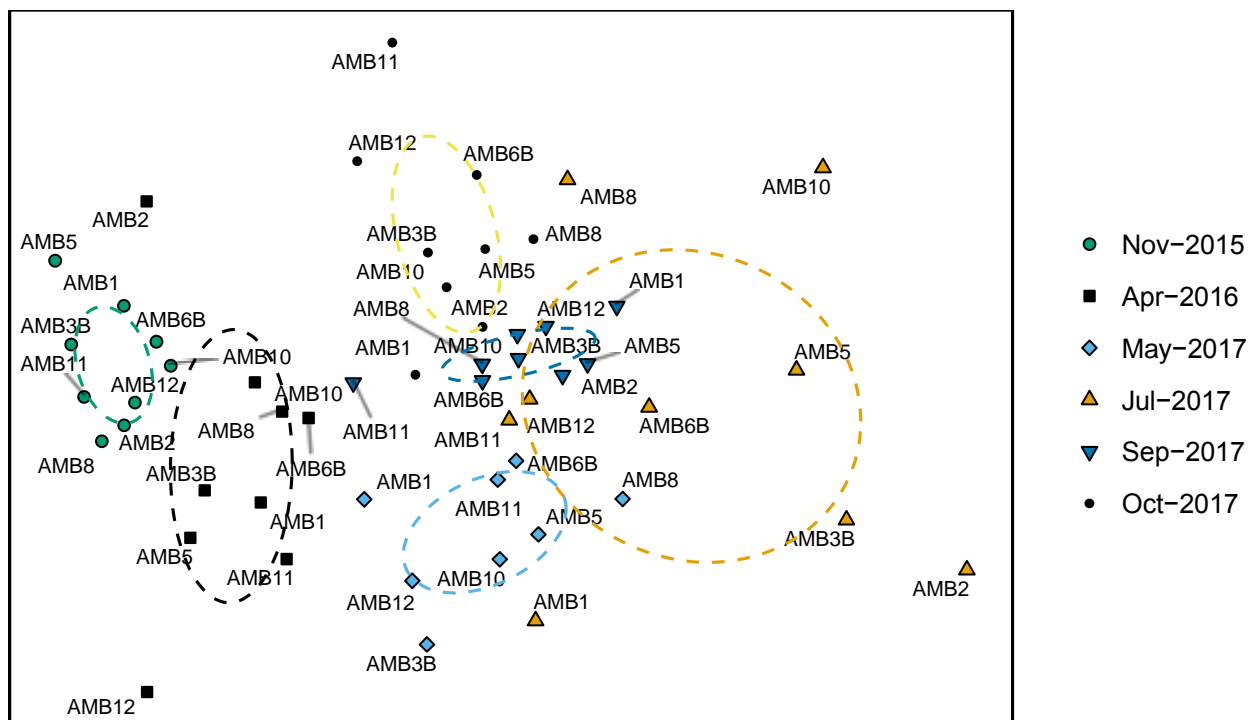


Figure 3.14 Non-dimensional ordination plot for phytoplankton collected during six survey periods throughout 2015-2017. Dashed lines represent 95% confidence interval ellipses for each survey period. Data has been squared root transformed on the Bray Curtis distance matrix (stress = 0.19, Clarke and Gorley 2006)

3.3 Multi-parameter water quality logger

Instruments were deployed at seven sites, AMB 1, 2, 3, 5, 8, 10 and 12 from July 2016 to July 2017 (see Table 1.1). Using standard statistics we describe observed trends, differences between sites and discuss driving forces in these environments.

Data is presented throughout the text, in a time series format, monthly and yearly statistical summaries. The box plots provide a visual representation of the descriptive statistics for Suspended Sediment Concentration (SSC), deposition rate ($\text{mg}/\text{cm}^2/\text{day}$), water temperature ($^{\circ}\text{C}$), RMS water height and PAR. In the box plots the central diamonds represent the mean value, the central line represents the median value and the central box represents the range of the middle two quartiles. The vertical bars represent the range of the 90th percentile and 10th percentile data points.

3.3.1 RMS water height

RMS water height values are mostly driven by weather events and this is clearly evident in the data as peaks in RMS water heights are observed at the same times at all sites over the survey year. Variation in the magnitude of RMS water height values during peak events and during non-event periods differs among sites due to differences in water depth and site exposure to wave energy. The RMS water height data from this survey year shows the sites can be categorised into three groups. Figure 3.15 provides a box plot of the yearly statistics

of RMS at sites and this offers an effective visual representation of the three categories described below.

The lowest value RMS category consisted only of Keswick Island (AMB 12). This site had much lower RMS values than all other sites with a median RMS water height of 0.01 and the lowest variance in RMS values (10th percentile = 0.00, 90th percentile = 0.03). These results are due to the site being positioned in the lee of Keswick and St Bees Islands that shelter it from wind and waves.

Freshwater Point (AMB 1), Hay Point (AMB 2), Relocation grounds (AMB 8), and Victor Islet (AMB 10) can be categorised in the middle RMS water height group, with median RMS values ranging from 0.02 to 0.03. As mentioned in the methodology, RMS water height is a proxy for wave energy or wave shear stress at the ocean floor (Macdonald 2015). This is important to note as the Hay Reef (AMB 2) Hay Reef and Relocation grounds (AMB 8) are more exposed locations than Freshwater Point (AMB 1) and Victor Islet (AMB 10) yet because these locations are deeper the wave shear stress on the ocean floor is very similar to the more protected, yet much shallower Freshwater Point (AMB 1) and Victor Islet (AMB 10). This information illustrates that these sites are directly influenced by very similar wave shear stress and therefore differences between sites needs to be attributed to other parameters such as current, depth and benthic geology.

Round Top Island (AMB 3) and Slade Islet (AMB 5) had relatively high median RMS values (AMB 3: RMS = 0.03, AMB 5: RMS = 0.04) than the five other sites. AMB 3 Round Top Island had the second deepest mean depth of 11 meters yet because this site was so exposed to wave energy it had the second highest median RMS water height values. Similarly, Slade Islet (AMB 5) was not a very shallow site (mean depth of 8.95m) yet because of its exposure to wave energy it had the highest RMS water height values.

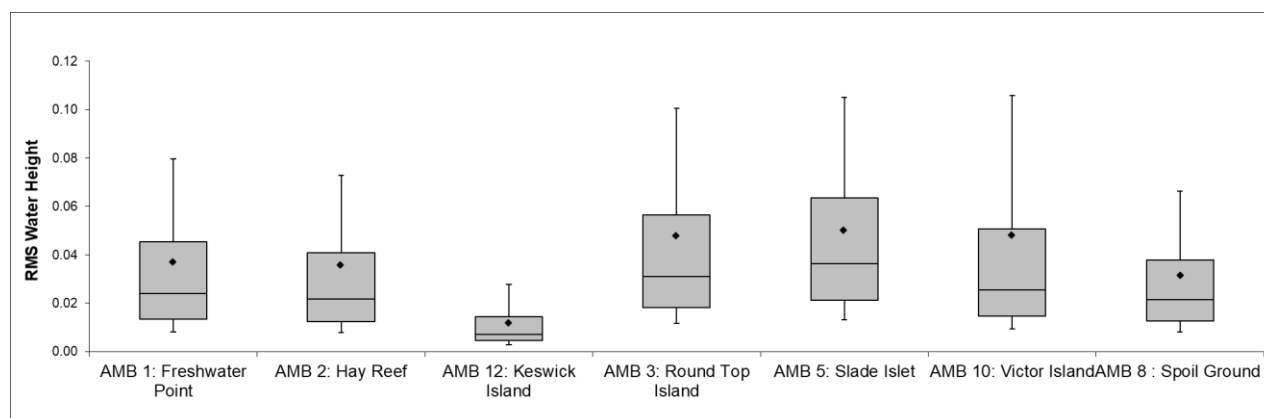


Figure 3.15 Box plot of RMS water depth (m) at 7 sites for the year deployment commencing in July 2016 through to July 2017

Table 3.3 RMS water depth statistics at sites for the monitoring period between July 2016 and July 2017

RMS Water Height Statistics							
Site	AMB 1: Freshwater Point	AMB 2: Hay Reef	AMB 12: Keswick Island	AMB 3: Round Top Island	AMB 5: Slade Islet	AMB 10: Victor Island	AMB 8 : Spoil Ground
Mean	0.037	0.036	0.012	0.048	0.050	0.048	0.03
median	0.024	0.022	0.007	0.031	0.036	0.025	0.02
min	0.000	0.000	0.000	0.000	0.000	0.000	0.00
lower quartile	0.013	0.012	0.004	0.018	0.021	0.015	0.01
upper quartile	0.045	0.041	0.014	0.056	0.064	0.051	0.04
max	0.723	2.269	0.216	1.111	0.450	2.452	0.52
90 th percentile	0.080	0.073	0.028	0.101	0.105	0.106	0.07
10 th percentile	0.008	0.008	0.003	0.012	0.013	0.009	0.01
n	49834	43705	49948	37852	47682	45706	38705
St. Dev	0.043	0.052	0.014	0.056	0.044	0.073	0.03
St. Error	0.000	0.000	0.000	0.000	0.000	0.000	0.00

The RMS water height time series data shows that large peaks occur throughout the year. Comparing sites in this enables these peaks to be identified to occur at the same times at all sites. This is due to weather driven wave events being the primary driver of wave shear stress on the ocean floor. Different sites show weather driven wave events at different magnitudes in the RMS data due to variations in site exposure and water depth.

In the 2014/2015 Port of Hay Point and Mackay ambient marine water quality monitoring report (Waltham et al. 2015), recurring high RMS water height values at approximately 12 and 24 hours, and 7, 14 and 30 day periods were identified using wavelet and Fourier analysis. The recurring periods of approximately 14 and 30 days were attributed to the synoptic weather systems that drive the wave events discussed above. The 12 and 24 hour period signal in RMS water height were attributed to changes in water depth due to tide which can change the wave dynamics of a site. Figures 3.16 and 3.17 provide an example of when weather driven wave energy in combination with tide are evident in the RMS data. Figure 3.16 shows a large spike in RMS water height at the start of the displayed period. This spike is the result of a weather driven wave event and is followed by a period where RMS water height falls to its background value as the weather event passes. Figure 3.17 enables the RMS water height data to be studied more closely during the spike. Comparing the 12 point averaged trend line with the water depth data shows a similar periodicity in the RMS water height and water depth data. This 12 hour signal is the tidal influence identified using wavelet and Fourier analysis in the previous reporting period (Waltham et al. 2015). It is interesting to note that a reduction in water depth does align with the periodic peaks in RMS water height and it is thought that other factors such as current and changes in the sites exposure at different tides alters the wave dynamics of the site.

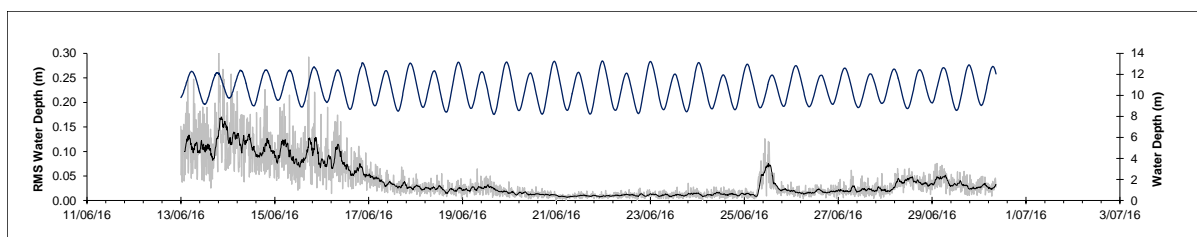


Figure 3.16 Hay Point (AMB 2) RMS water depth (grey), 12 point averaged RMS trend line (black) and water depth (blue). Data shows a wave event followed by a calmer period

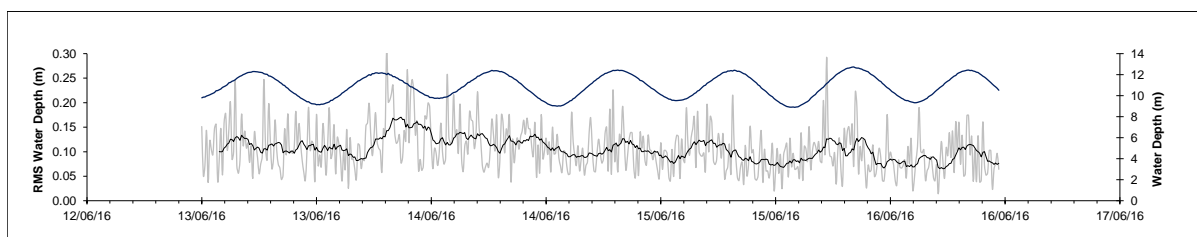


Figure 3.17 Hay Point (AMB 2) RMS water depth (grey), 12 point averaged RMS trend line (black) and water depth (blue). A closer inspection of data from wave event shown in Figure 3.16

3.3.2 NTUe/SSC data

The NTUe/SSC time series data at each site follows a typical pattern of low background values with recurring peak events. These peak events occurred at the same times at each site and coincide with peaks in RMS water height. This is a typical pattern as identified in the 2014/2015 and 2015/2016 reports (Waltham et al. 2015 and 2016), and similar to data collected in coastal locations in north Queensland by the James Cook University Marine Geophysics group (see Ridd et al., 2001). Yearly statistical values and individual peak values differ between sites. These differences are the result of variation in influencing factors such as RMS water height, site depth, benthic geology, hydrodynamics and proximity to river mouths.

Of the seven sites, two (Keswick Island AMB 12 and Round Top AMB 3) had median SSC values below 2mg/L and the least variance in NTUe/SSC. Site specific factors such as sediment size and type as well as wave shear stress (RMS water height) are major influences on NTUe/SSC and this is the likely attributing feature. Site AMB 12 Keswick Island showed the lowest median (0.89 mg/L) and lowest variance (SD = 4.33, 10th percentile = 0.29 mg/L, 90th percentile = 3.20 mg/L) values in NTUe/SSC. This is due to: a) the site being sheltered from the trade south east weather systems (see Figure 3.15 RMS water height) which results in less re-suspension of sediments by wave energy; b) coarser sediment at this site being less easily resuspended, and c) the sites position on the mid-shelf GBR exposes it to cleaner oceanic water. Although Round Top Island (AMB 3) had the second highest RMS water height data from the survey year, which would suggest high re-suspension of local sediment, the sediment at this site is coarse and not easily resuspended.

The inshore sites, Freshwater Point (AMB 1), Hay Reef (AMB 2), Slade Islet (AMB 5) and Victor Islet (AMB 10) had higher median NTUe/SSC with greater variance (Figure 3.18). These sites are considered open ocean sites, however, in contrast inshore coastal currents are high in suspended solids from surrounding shallow water where re-suspension of sediment dominates the environment (Macdonald et al. 2013). High variance in NTUe/SSC is the result

of large spikes in suspended sediment driven by the re-suspension of sediment due to weather driven wave events.

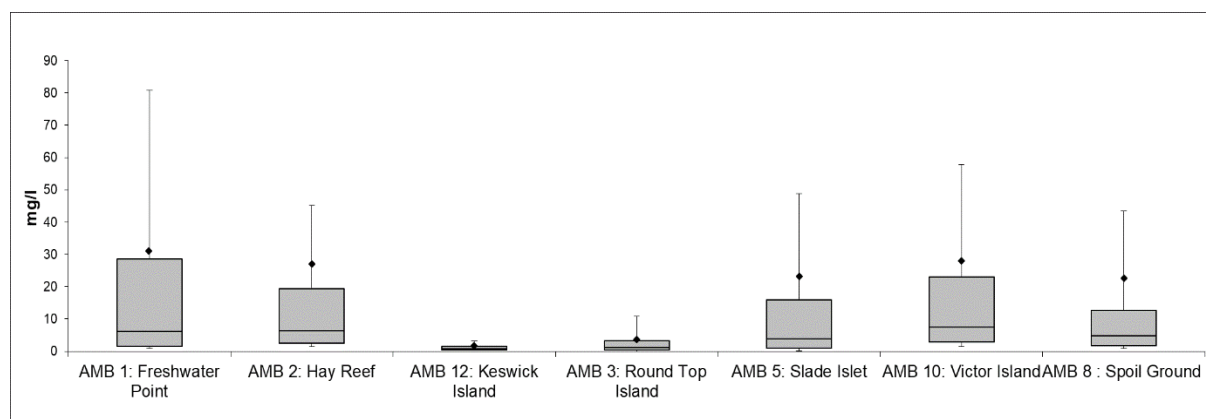


Figure 3.18 Box plot of SSC sites for the period July 2016 to September 2017

Table 3.4 Summary statistics for SSC at sites for the period July 2016 to July 2017

SSC Statistics							
Site	AMB 1: Freshwater Point	AMB 2: Hay Reef	AMB 12: Keswick Island	AMB 3: Round Top Island	AMB 5: Slade Islet	AMB 10: Victor Island	AMB 8 : Spoil Ground
Mean	31.13	27.04	1.80	3.63	23.26	28.05	22.74
median	6.09	6.26	0.89	1.16	3.79	7.49	4.83
min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
lower quartile	1.66	2.56	0.50	0.39	0.93	2.97	1.73
upper quartile	28.55	19.40	1.63	3.32	16.02	23.08	12.74
max	3264.95	2653.01	114.01	185.05	1600.35	2122.95	1266.99
90 th percentile	80.84	45.08	3.20	10.92	48.86	57.75	43.35
10 th percentile	0.88	1.55	0.29	0.00	0.17	1.48	0.81
n	46292	35685	49404	29488	37986	44561	34371
St. Dev	97.10	103.62	4.33	6.82	70.04	71.81	62.58
St. Error	0.45	0.55	0.02	0.04	0.36	0.34	0.34

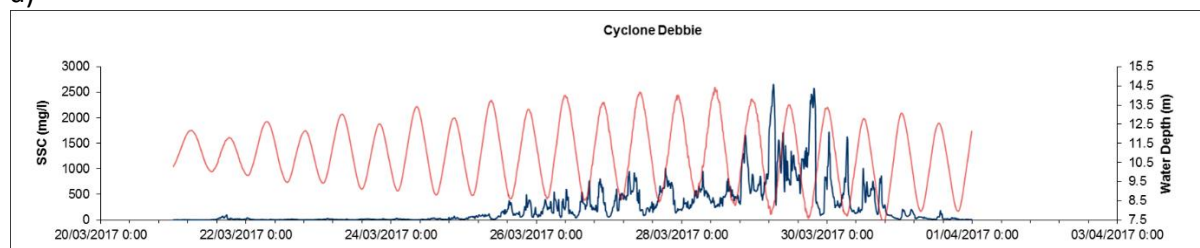
CYLCONE DEBBIE

Severe Tropical Cyclone Debbie occurred during 25-29 March 2017 (Figure 1.4), making landfall north of Proserpine (50km southeast of Bowen) on the 28 March 2017. The category 4 system travelled south throughout Queensland, causing widespread damage to the Whitsunday Islands, Airlie Beach, Proserpine and Bowen. Debbie also caused disastrous flooding in Central and Southeast Queensland and Northeast New South Wales, where several lives were lost. The peak wind gust of 263 km/h was recorded at Hamilton Island and is the highest recorded gust in Queensland. A 2.6 m storm surge was recorded at Laguna Quays, exceeding the Highest Astronomical Tide by 0.9 m. Torrential rainfall was recorded across the region. The highest being at, Clarke Range, west of Mackay, which received 986mm in the first 48 hours. The flooding led to an increased input of sediment from the rivers into the marine environment and high winds caused increased wave heights leading to greater levels of resuspended sediment.

To demonstrate the connection between increases in wave energy and increases in suspended sediment Figure 3.19a presents RMS water height and SSC data from the inshore site Hay Reef (AMB 2) in a time series format, during Tropical Cyclone Debbie. Figure 3.19b

shows depth and SSC for the same site. It is clear in this figure that weather events, represented by peaks in RMS water height data, correspond to peaks in NTUe/SSC. This is a pattern seen consistently across all sites where instruments were located (Figure 3.20). At Hay Reef the RMS water height peaks first followed by SSC a few hours later, river discharge peaks about 8 hours after that. At Hay Reef there was also a second peak about 13 hours after the first, it is possible that this is due to the river discharge, but it is more likely that it is due to tidal changes. Both SSC peaks occur just after low tide during the first half of the rising tide and so could be related to the movement of sediment on the tidal currents.

a)



b)

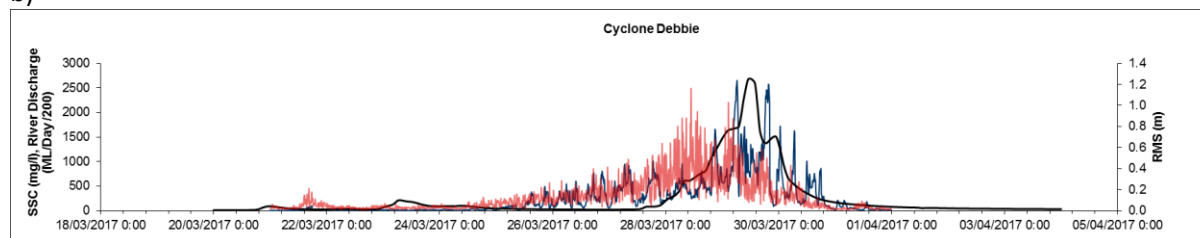
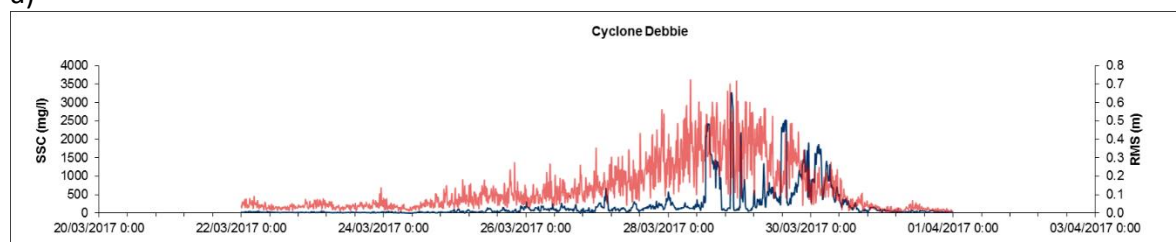
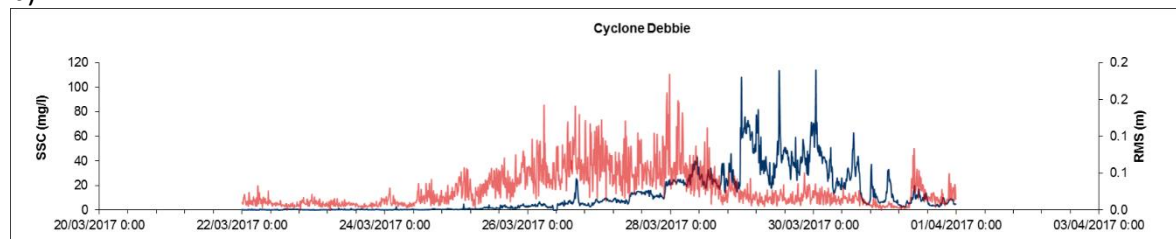


Figure 3.19 Spikes in SSC (blue), Pioneer River Discharge (black) and RMS water height (red) at Hay Reef during Cyclone Debbie (AMB 2)

a)



b)



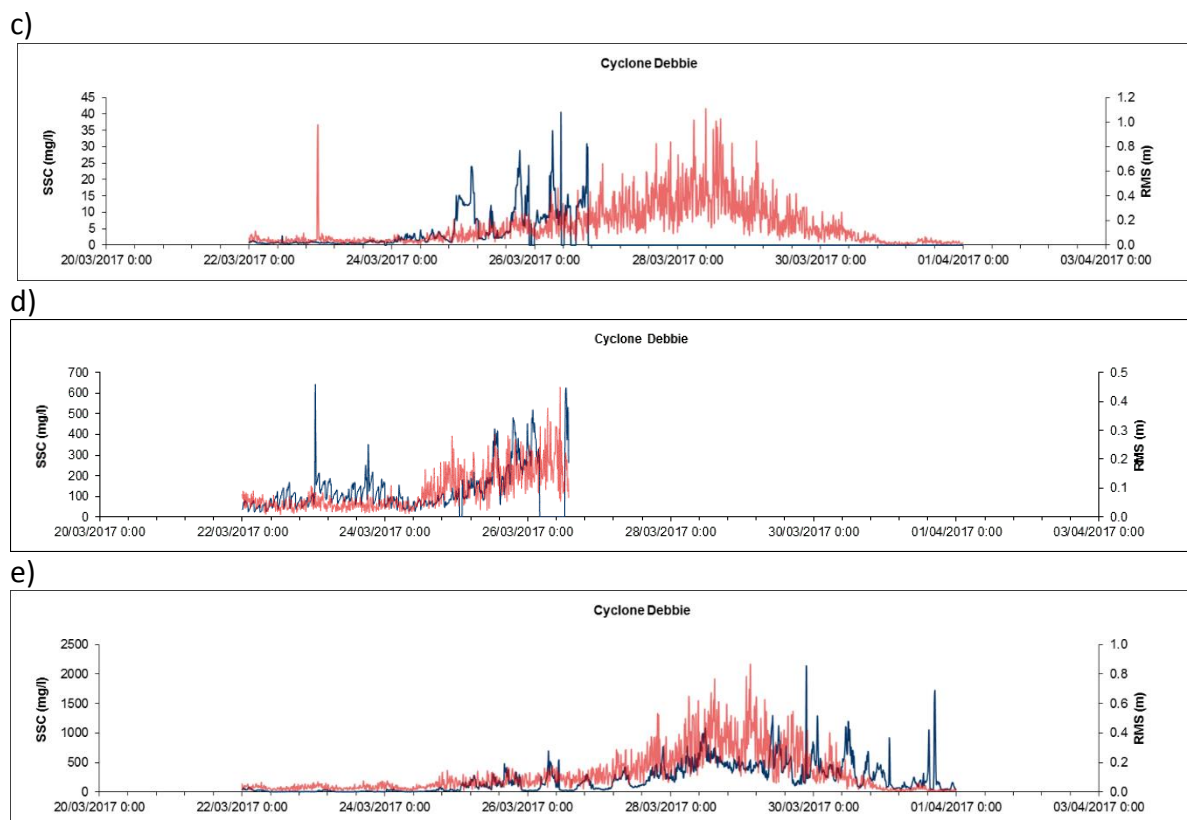


Figure 3.20 Time series of SSC (mg/L; in blue) and RMS water height (m; in red) during Tropical Cyclone Debbie from the following sites: a) Freshwater Point (AMB 1), b) Keswick Island (AMB 12), c) Round Top Island (AMB 3b), d) Slade Island (AMB 5), and e) Victor Island (AMB 10)

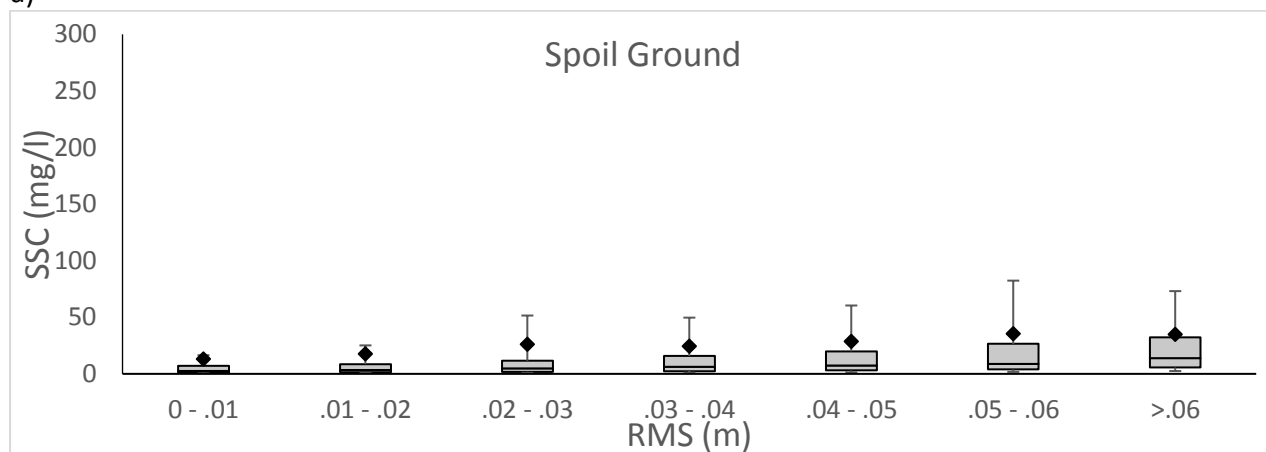
Figure 3.21 provides box plot distributions of NTUe/SSC at increasing RMS water height categories, and shows NTUe/SSC median values increasing with increases in RMS water height. With increasing RMS water depth, the variation in NTUe/SSC also increases which is likely a function of a more dynamic environment. This pattern is similar for all sites in the program, and supports the emerging conclusion that wave stress on the sea floor resulting from weather events is one of the primary drivers of measured NTUe/SSC in the data set.

Though it is evident in the data that natural variation in suspended sediment concentration is present between sites and over time, this variation is not represented in the Water Quality Guidelines for the Great Barrier Reef Marine Park (2010). The Water Quality Guidelines for the Great Barrier Reef Marine Park (2010) lists the annual mean trigger limits for suspended sediment as 5-15 mg/L for enclosed coastal waters, 2mg/L for open coastal and mid-shelf waters, and 0.7 mg/L for offshore waters (GBRMPA, 2010). In accordance to the water category definitions (GBRMPA, 2010), sites AMB 1, 2, 3, 5, 8 and 10 are open coastal sites and AMB 12 is a mid-shelf site. Only Keswick Island (AMB 12) had an annual mean suspended sediment concentration lower than the trigger limits defined in the GBRMPA (2010) water quality guidelines. It is suggested that the median, rather the mean, results are considered for analysis as they provide a more accurate representation of suspended sediment water values (less influence from outlier values) in a data set (Macdonald 2015).

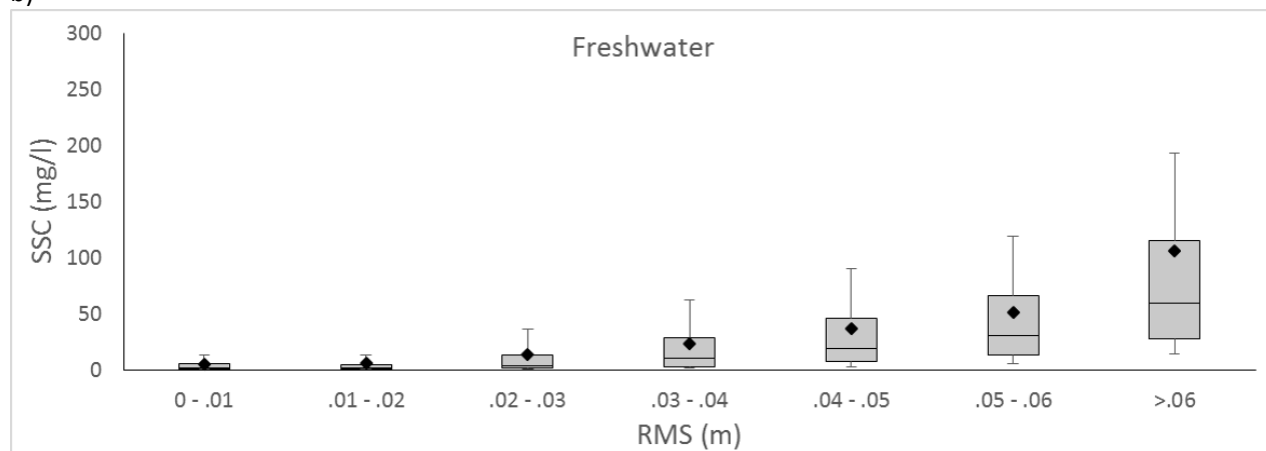
Understanding that coastal waters are complex hydrodynamic systems is important in understanding SSC results from different sites in this area. The SSC data highlights that there

exists large variability in suspended sediment concentration among coastal sites and it is necessary to note two points when analysing results: 1) mean yearly values are often skewed whilst a median yearly value provides a more accurate representation of typical suspended sediment values; and 2) large variation exists in the hydrodynamics and sedimentology between sites and in turn there exists variation in SSC. Use of site-specific data to develop trigger limits is a far more accurate method through which changes to the environment can be monitored.

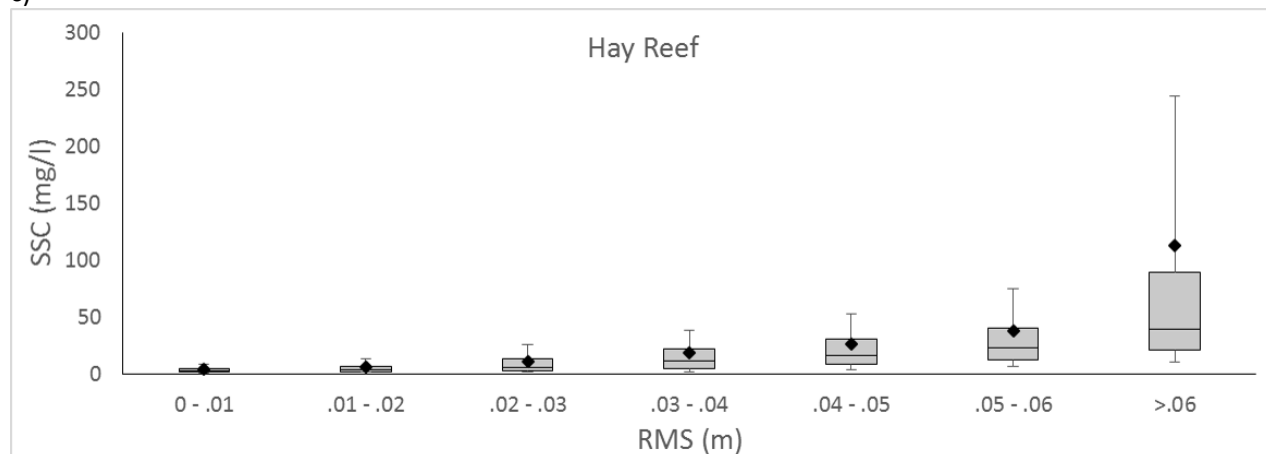
a)



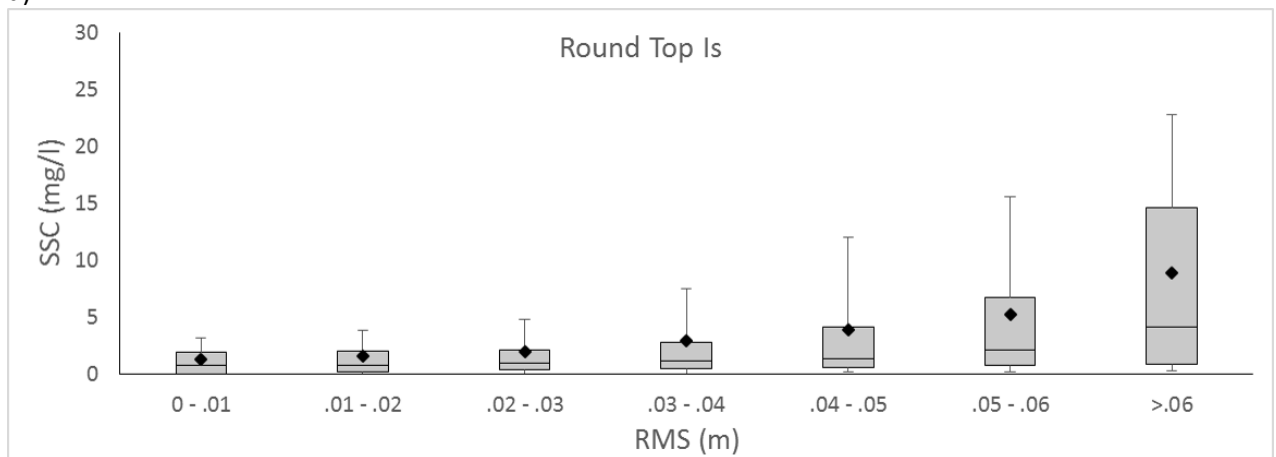
b)



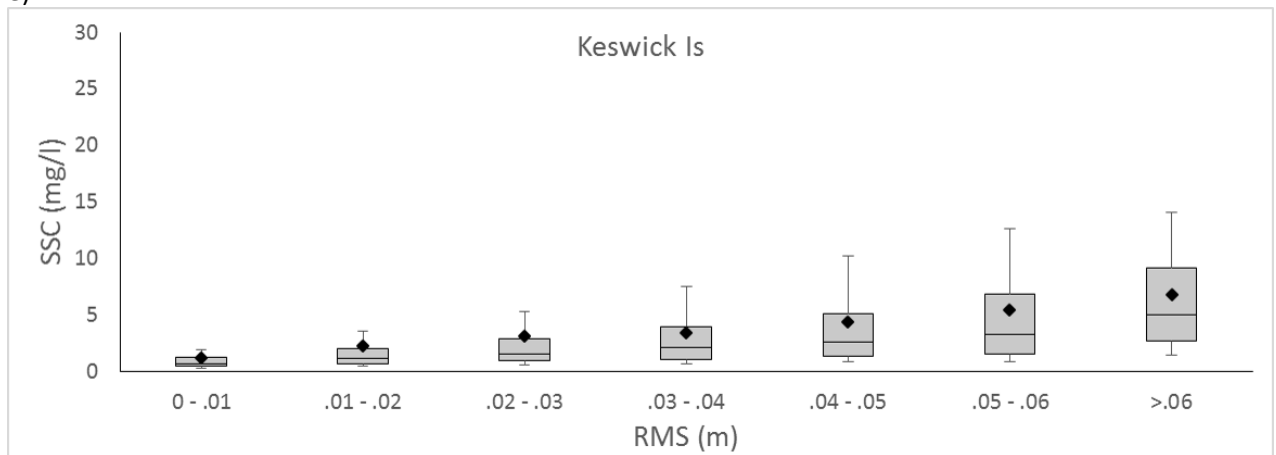
c)



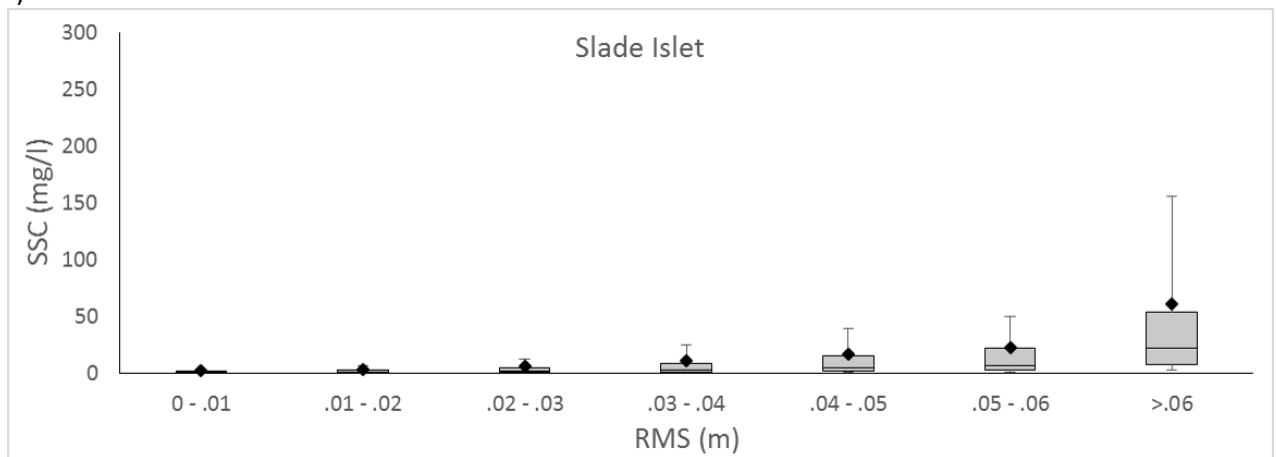
d)



e)



f)



g)

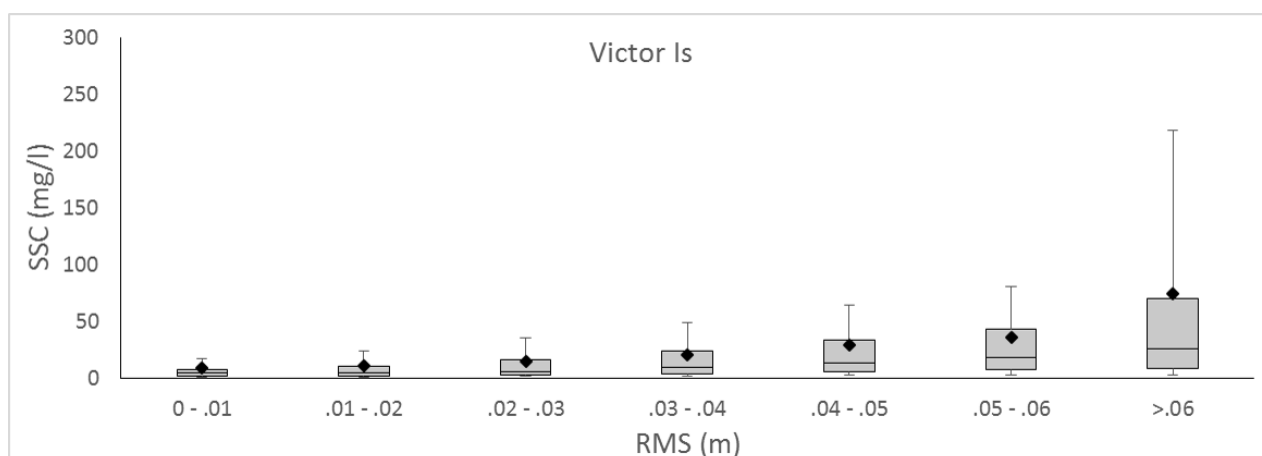


Figure 3.21 2016-2017 Box plot distribution of SSC at RMS water depth intervals using the data from the following sites: a) Relocation (Spoil) Ground (AMB 8) b) Freshwater Point (AMB 1), c) Hay Reef (AMB 2), d) Round Top Island (AMB 3B), e) Keswick Island (AMB 12), f) Slade Island (AMB 5), and g) Victor Island (AMB 10)

3.3.3 Deposition

Deposition of sediment is a natural process occurring in all coastal marine waters. Suspended sediment naturally deposits in environments where the systems energy is not sufficient to remain suspended in the water column. Deposition of sediment in a marine environment is of interest to environmental monitoring studies when it changes from its natural state. The Water Quality Guidelines for the Great Barrier Reef Marine Park (2010) references De'ath and Fabricius 2008 in noting that 10mg/cm²/day sedimentation is valid in areas of coarse sediment, but that where sediments are smaller and of high organic content the trigger limits need to be lower. The guidelines set the sedimentation trigger value at a mean annual value of 3 mg/cm²/day and a daily maximum of 15 mg/cm²/day.

The statistical summary of the daily average deposition rates for each site are presented in Figure 3.22 as box plots and summarised in Table 3.5. The data indicates that Keswick Island (AMB 12) and Freshwater Point (AMB1), had the greatest deposition with means of 7.01 and 7.06 mg/cm²/day, respectively, and median daily average deposition rates of 2.71 and 3.36 mg/cm²/day respectively. Again it is suggested that the median rather than the mean values be used to provide an unskewed impression of the data. The median daily average deposition rate ranged from 1.34 – 1.68 mg/cm²/day at the remaining 5 sites. These values may be more easily visualised by calculating them into the thickness of the sediment deposited. For example, using the relationship between density, mass and volume, a deposition value of 5 mg/cm² is equivalent to a layer of sediment of thickness less than 35 µm, assuming a sediment density of 1.5 g/cm³.

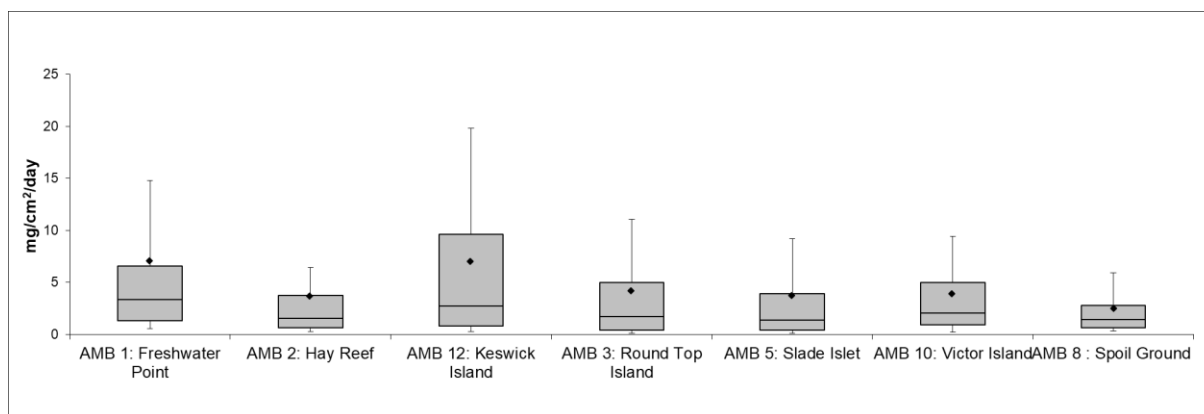


Figure 3.22 Box plot of daily deposition rate at sites for the year deployment commencing in July 2016 to July 2017

Table 2.5 2 hourly deposition rate statistics at 7 sites for the year deployment commencing in July 2016 to July 2017

Daily Deposition Rate (mg/cm ² /d) Statistics							
Site	AMB 1: Freshwater Point	AMB 2: Hay Reef	AMB 12: Keswick Island	AMB 3: Round Top Island	AMB 5: Slade Islet	AMB 10: Victor Island	AMB 8: Spoil Ground
Mean	7.06	3.69	7.01	4.17	3.71	3.88	2.50
median	3.36	1.56	2.71	1.68	1.38	2.04	1.40
min	0.03	0.02	0.00	0.00	0.00	0.03	0.05
lower quartile	1.29	0.66	0.78	0.41	0.40	0.91	0.63
upper quartile	6.53	3.72	9.63	4.99	3.93	5.00	2.76
max	118.48	75.62	96.93	47.27	44.17	25.98	23.14
90 th percentile	14.79	6.41	19.82	11.07	9.22	9.40	5.94
10 th percentile	0.56	0.29	0.27	0.07	0.12	0.18	0.34
n	340	249	313	259	302	214	244
St. Dev	12.87	8.11	10.10	6.48	6.58	4.74	3.43
St. Error	0.70	0.51	0.57	0.40	0.38	0.32	0.22

The time series deposition data suggests that a peak occurs following high RMS water height events, but with a lag so that peak deposition occurs at a time when RMS water height has decreased to near background levels. An explanation for this lag is that as waves resuspend sediment, little deposition is expected because the energy in the system will keep the sediment in suspension. It is only when waves decrease and there is no longer enough energy in the system to keep the same quantity of sediment in suspension that deposition begins to occur.

3.3.4 Water temperature

As has been the case in previous reports (Waltham et al., 2015, 2016), water temperature data matched closely among all sites. Seasonal changes in water temperature were apparent, with the mean monthly temperature peaking between December and March at approximately 29.0 -29.3 °C (Figure 3.23); a factor that was also observed in the field *in-situ* water temperature surveys. The lowest mean monthly temperatures were observed between May to July, where values dropped to 20.7 – 21.7 °C. Decreases in temperature over short time periods match with increases in RMS water depth. Water temperature is generally not considered to be a compliance condition for approval operations, however the temperature data presented here holds importance in future interpretation of ecological processes in the region, and across the GBR (e.g. Johanson et al., 2015).

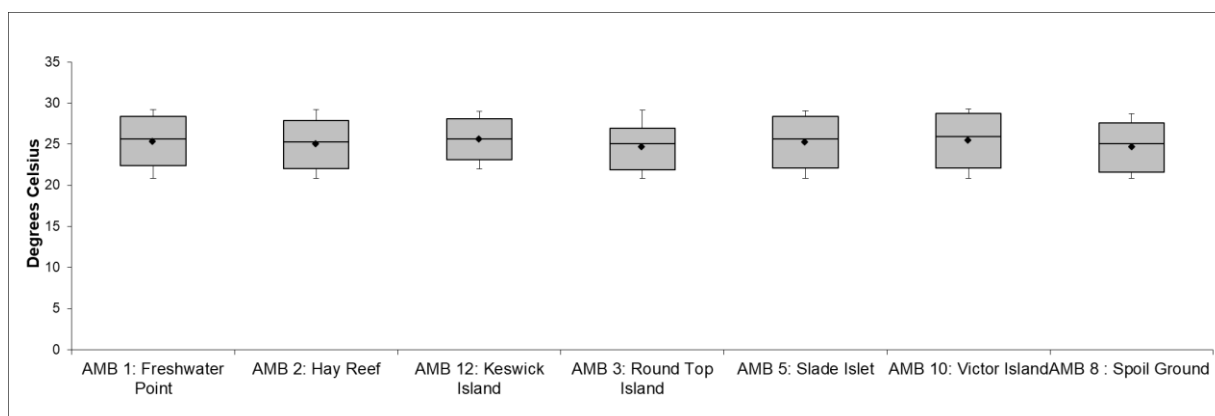


Figure 3.23 Box plot of temperature at sites for the deployment between July 2016 and July 2017

Table 3.6 Temperature statistics at sites for the deployment between July 2016 and July 2017

Temperature Statistics							
Site	AMB 1: Freshwater Point	AMB 2: Hay Reef	AMB 12: Keswick Island	AMB 3: Round Top Island	AMB 5: Slade Islet	AMB 10: Victor Island	AMB 8 : Spoil Ground
Mean	25.37	25.05	25.62	24.73	25.28	25.48	24.69
median	25.67	25.31	25.67	25.06	25.62	25.96	25.07
min	19.55	19.83	21.11	20.27	20.23	19.98	20.33
lower quartile	22.37	22.05	23.15	21.91	22.10	22.09	21.62
upper quartile	28.36	27.92	28.07	26.98	28.39	28.72	27.57
max	31.71	30.73	29.95	30.03	30.09	30.68	29.25
90 th percentile	29.20	29.24	28.99	29.16	29.07	29.30	28.68
10 th percentile	20.83	20.88	21.98	20.83	20.86	20.83	20.88
n	49831	43694	49955	37841	47669	45725	38697
St. Dev	3.11	3.07	2.63	2.86	3.07	3.25	2.95
St. Error	0.01	0.01	0.01	0.01	0.01	0.02	0.01

3.3.5 Multiparameter predictive NTUe/SSC model

Natural turbidity (NTUe/SSC) is primarily driven by the re-suspension of sediment due to wave and current stress on the sea floor. The natural environment frequently has periods where high turbidity is observed. During dredging, turbidity can be caused by both natural re-suspension processes and also from the dredging activity. Here, we provide a turbidity model that predicts the natural NTUe/SSC using the primary driving forces as inputs (Equation 2). The power of this model is that when it is used in conjunction with *in-situ* loggers, it enables management to differentiate between turbidity events that is the result of the natural conditions and that resulting from dredging activities. Excess turbidity or overburden (the difference between natural and dredge related turbidity) is likely to result in deposition as the re-suspension processes (i.e. the model inputs) are insufficient to keep the dredge related sediment in suspension.

$$\hat{T}(t) = \alpha^1 X_{rms}(t)^{\beta^1} + \alpha^2 X_{rms}(t-1)^{\beta^2} + \alpha^3 X_{wh}(t)^{\beta^3} - \alpha^4 X_{tc}(t)^{\beta^4} + \alpha^5 X_{tr}(t)^{\beta^5} - \alpha^6$$

2

Equation 2 - where $\hat{T}(t)$ is the predicted daily turbidity, α^1 -6 and β^1 -5 are the model parameters and the input parameters are: wave stress at the seafloor (X_{rms}), wave stress at the sea floor of the previous day ($X_{rms}(t-1)$), water height (X_{wh}), tidal current (X_{tc} – by calculating the difference between 20 minute water height measurements), and tidal range (X_{tr})

Model parameters were optimised at each site by fitting the model to the daily averaged turbidity measurements ($T(t)$) of the first half of the data set from each site (Figure 3.24 – 3.29). The model performance was then compared to the second half of the continuous dataset. For example, the model generated to predict turbidity at Hay Reef (AMB 2) used data from July 2015 through to June 2016 to fit the parameters and data from July 2016 through to July 2017 was used to test the ‘fit’ of the model as a predictive tool. R^2 values were calculated for the fit and test period at each site (Table 3.7). These R^2 values show that the models generally performed well when tested (with the exception of Round Top Island). With the continuation of *in-situ* data collection these predictive models will only increase in their predictive accuracy.

Table 3.7 Summary of statistical relationship between measured and modelled turbidity data. Results are R^2 values calculated for the fit and test period from each site

Period of Test	Freshwater Point (AMB 1)	Keswick Island (AMB 12)	Round Top Island (AMB 3B)	Slade Islet (AMB 5)	Victor Island (AMB 10)
Fit period	0.56	0.16	0.01	0.75	0.14
Test period	0.86	0.19	0.00	0.48	0.74

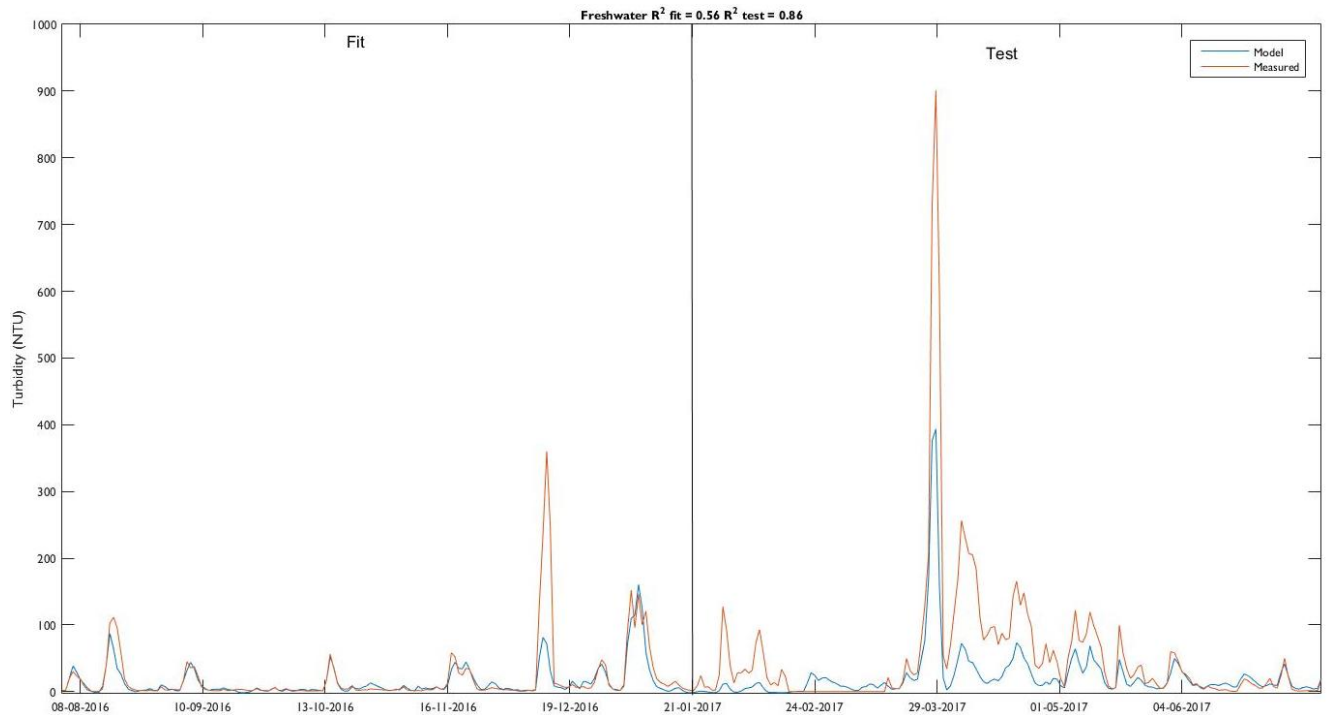


Figure 3.24 Freshwater Point (AMB 1) predictive NTUe/SSC model. The model was generated using the first twelve months of data (August 2015 to July 2016) and tested on the remaining data (August 2016 to July 2017)

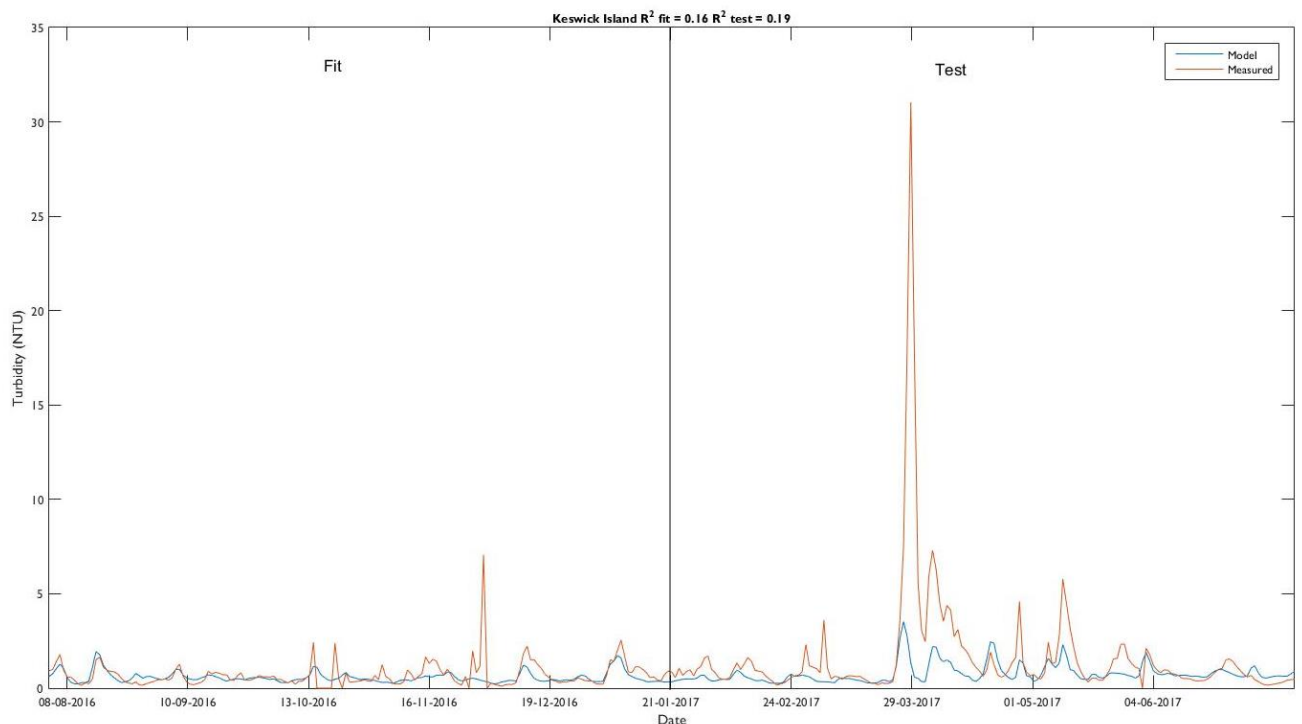


Figure 3.25 Keswick Island (AMB 12) predictive NTUe/SSC model. The model was generated using the first twelve months of data (August 2015 to July 2016) and tested on the remaining data (August 2016 to July 2017)

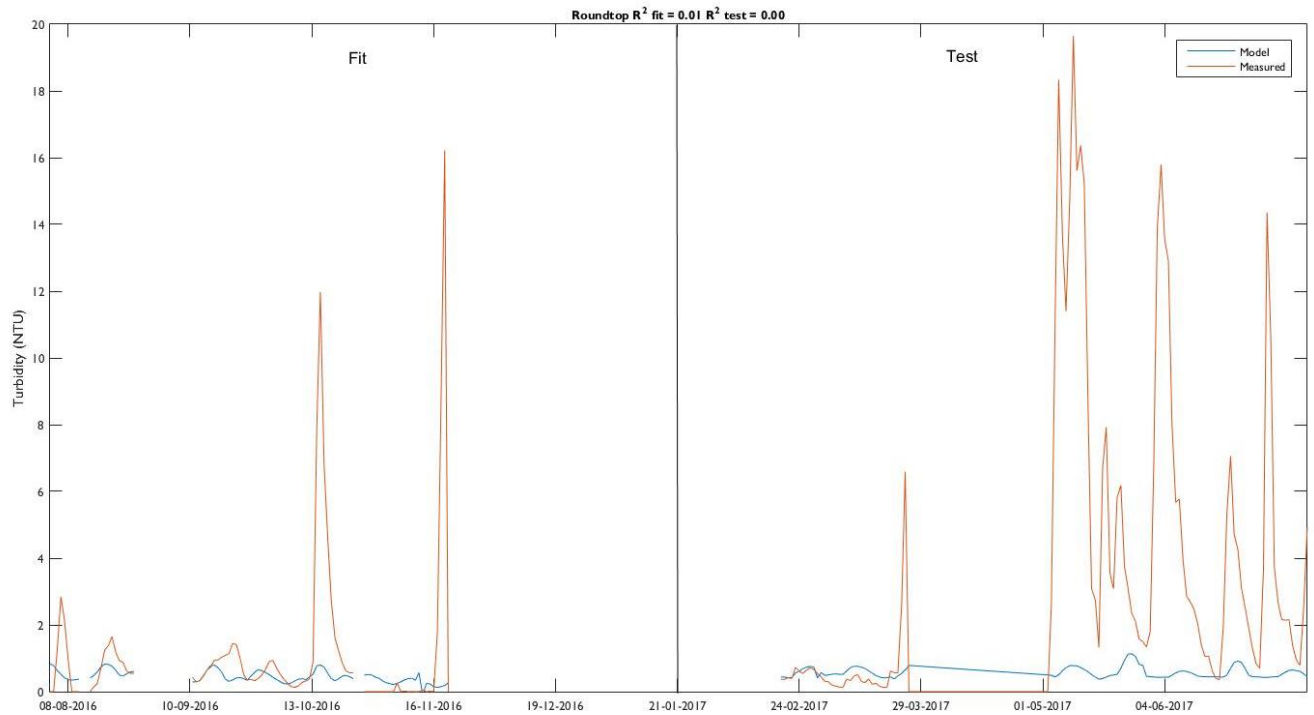


Figure 3.26 Round Top Island (AMB 3) predictive NTUe/SSC model. The model was generated using the first ten months of data (August 2015 to July 2016) and tested on the remaining data (August 2016 to July 2017)

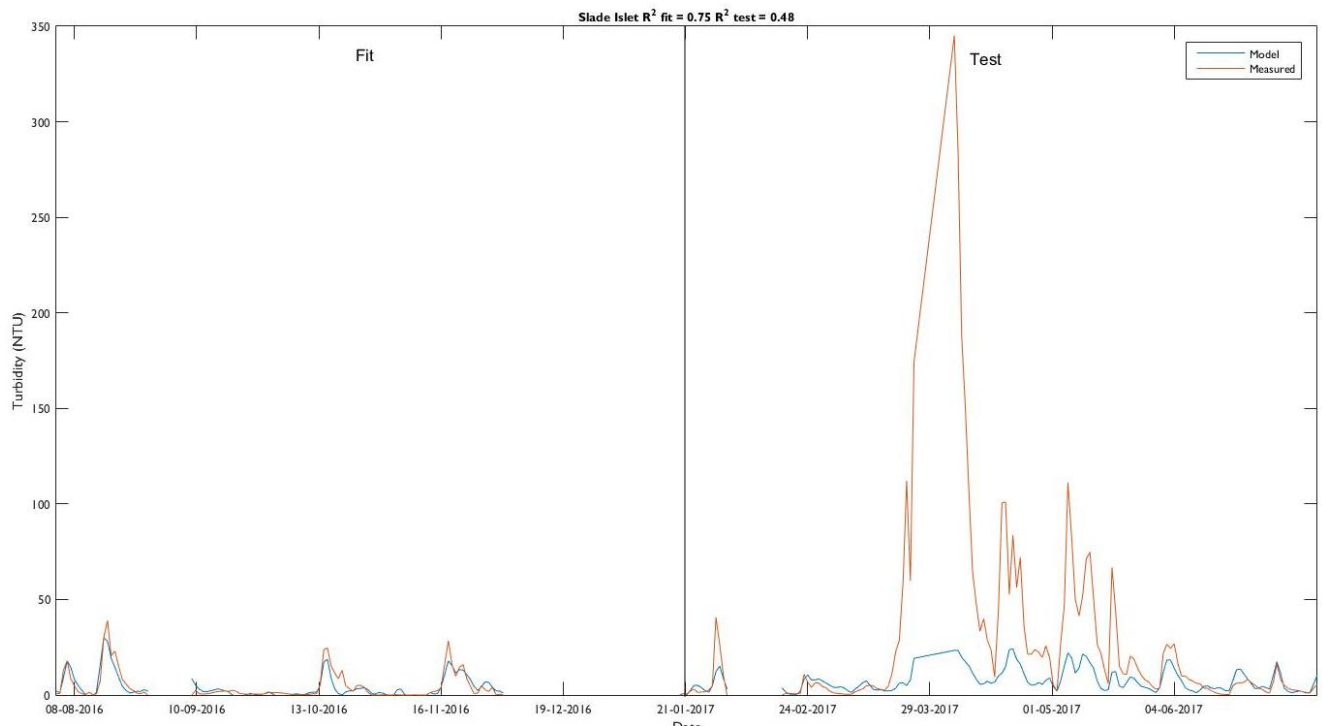


Figure 3.27 Slade Islet (AMB 5) predictive NTUe/SSC model. The model was generated using the first twelve months of data (August 2015 to July 2016) and tested on the remaining data (August 2016 to July 2017)

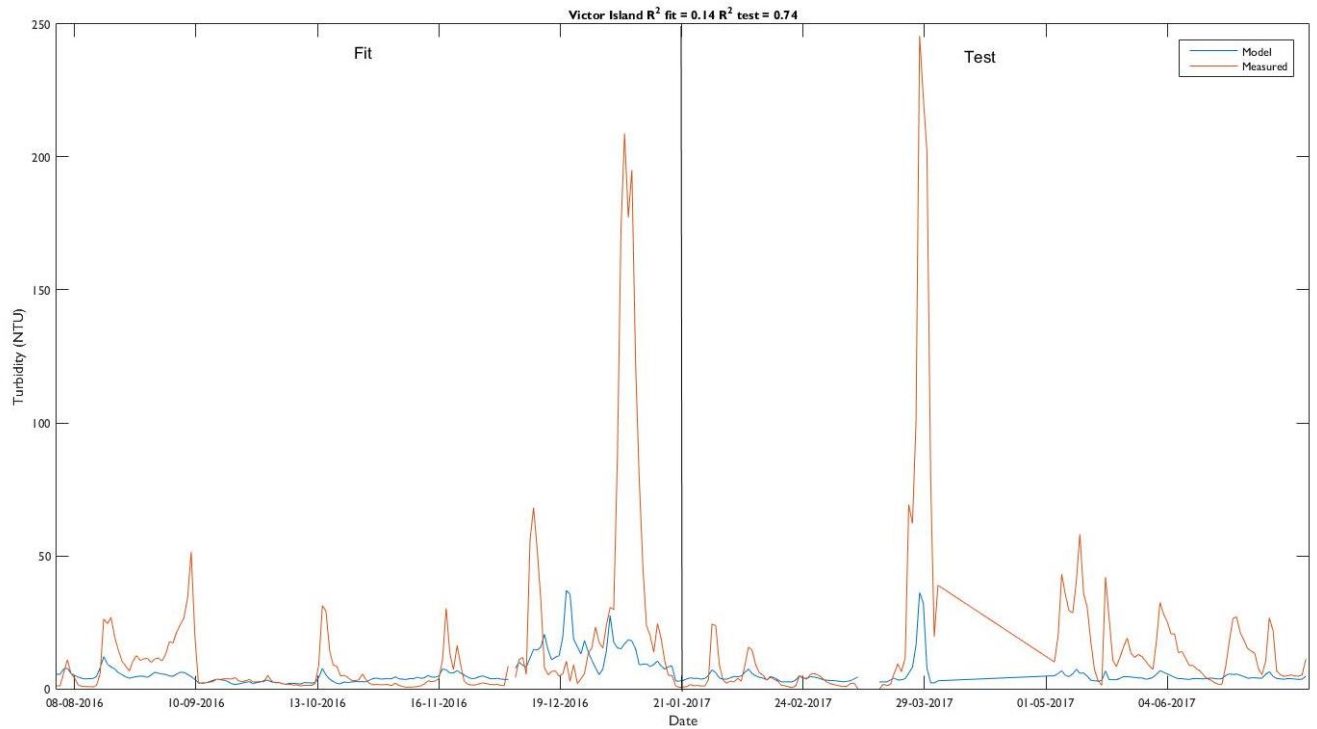


Figure 3.28 Victor Islet (AMB 10) predictive NTUe/SSC model. The model was generated using the first twelve months of data (August 2015 to July 2016) and tested on the remaining data (August 2016 to July 2017)

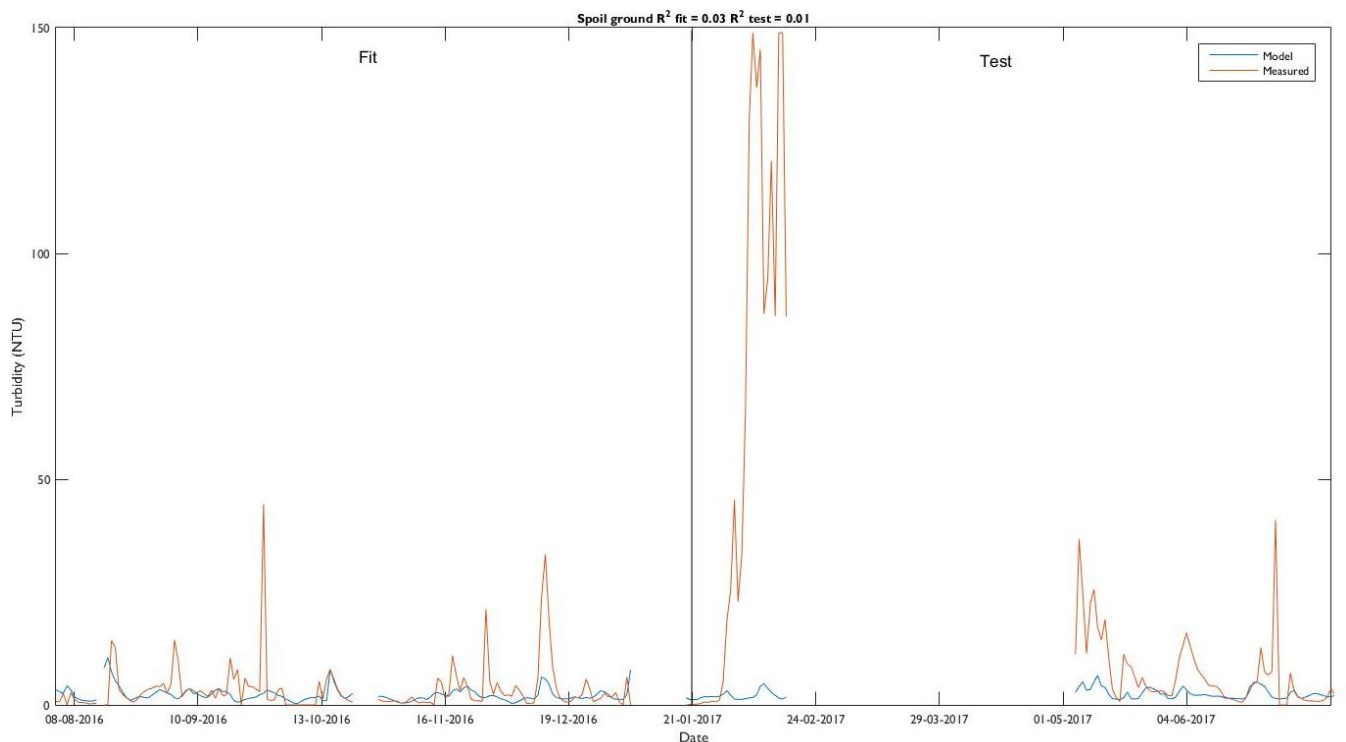


Figure 3.29 Relocation grounds (AMB 8) predictive NTUe/SSC model. The model was generated using the first six months of data (August 2015 to July 2016) and tested on the remaining data (August 2016 to July 2017)

3.4 Photosynthetically active radiation (PAR) logging

Benthic photosynthetically active radiation (PAR) was monitored at 7 sites from July 2016 and July 2017 (Figure 3.30). Using statistics (Table 3.8) and graphical representations of time series with highlighted examples of inshore (Victor Islet), mid shore (Round Top Island) and offshore (Keswick Island) sites, we describe trends and temporal differences among sites and investigate possible drivers of significant decreases in PAR. Levels of benthic PAR at sites were strongly influenced by water depth with a general trend of lower mean PAR values occurring at deeper sites (e.g. AMB 8), while higher levels were more regularly measured at shallower sites (e.g. AMB 12), with the exception of Hay Reef (AMB 2) which has the lowest mean and median PAR values probably due to its high suspended sediment levels.

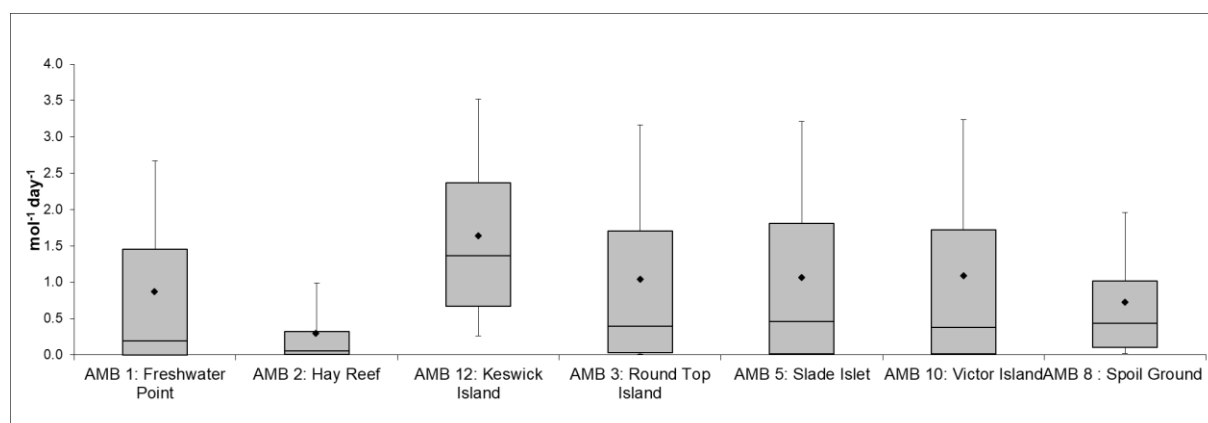


Figure 3.30 Box plot of daily PAR (mol photons /m²/day) at sites for the deployment between July 2016 and July 2017

Table 3.8 Summary statistics for daily PAR (mol photons /m²/day) recorded at sites during the program (July 2016– July 2017)

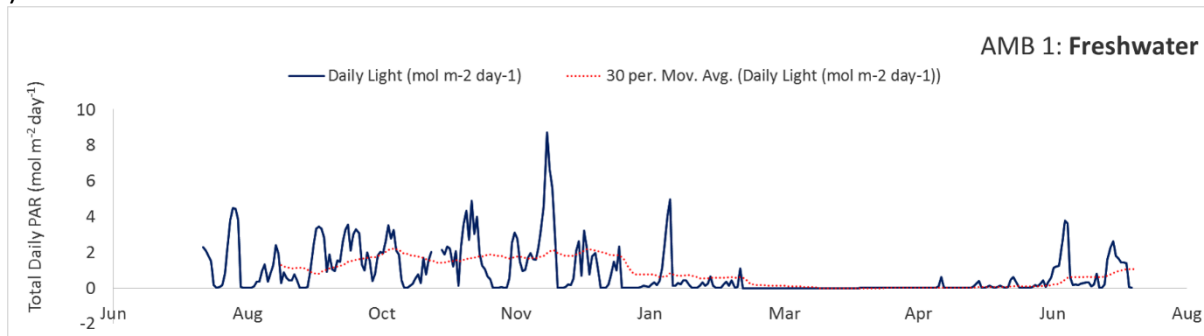
Daily PAR Statistics							
Site	AMB 1:	AMB 2: Hay Reef	AMB 12: Keswick	AMB 3: Round Top	AMB 5: Slade Islet	AMB 10: Victor	AMB 8 : Spoil
Mean	0.87	0.30	1.64	1.05	1.07	1.09	0.72
median	0.19	0.05	1.37	0.39	0.46	0.38	0.43
min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
lower quartile	0.00	0.00	0.67	0.03	0.02	0.02	0.10
upper quartile	1.45	0.32	2.37	1.71	1.81	1.72	1.02
max	8.70	4.05	5.65	5.43	7.25	9.88	4.18
90 th percentile	2.67	0.99	3.52	3.16	3.21	3.24	1.96
10 th percentile	0.00	0.00	0.27	0.01	0.00	0.00	0.02
n	344	303	346	259	329	317	267
St. Dev	1.29	0.55	1.26	1.31	1.34	1.55	0.84
St. Error	0.07	0.03	0.07	0.08	0.07	0.09	0.05

Benthic PAR was highly variable within sites throughout the year, with peaks and troughs occurring both regularly and intermittently over time (Figure 3.31). Semi-regular oscillations between low and high PAR levels were overridden by Cyclone Debbie (March 25-27th, 2017) at most sites (except Keswick Island, Figure 3.31c). Following this extreme weather event, PAR levels were generally much lower.

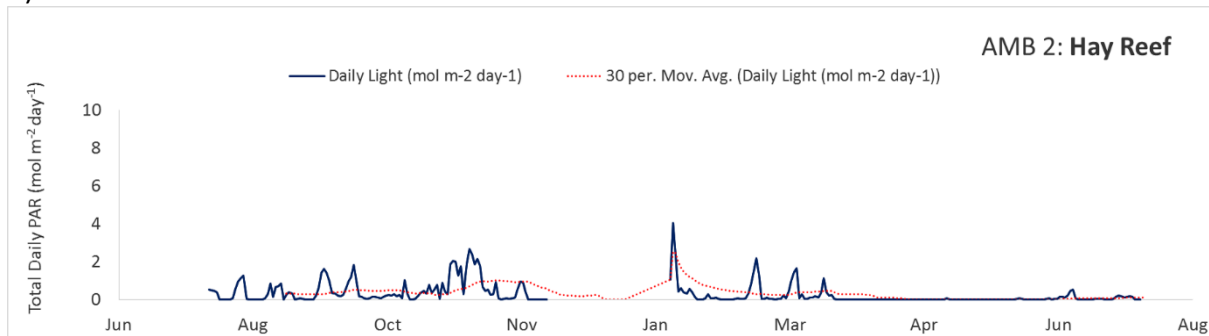
The offshore Keswick Island site (Figure 3.32c) showed light peaking between November 2016 and December 2016, and lower levels around March and April 2017. This is similar to the

previous year which showed light peaking between October 2016 and December 2016. PAR levels were similar in May, June and July 2016 to the previous annual period (2015) across all sites. Investigating examples of monthly variation among sites show an initial period of increasing daily PAR levels from August to December 2017, with levels dropping around April/May 2017 across all three representative sites. This is similar to the pattern of greater daily PAR levels seen in previous years (Waltham et al. 2015, 2016).

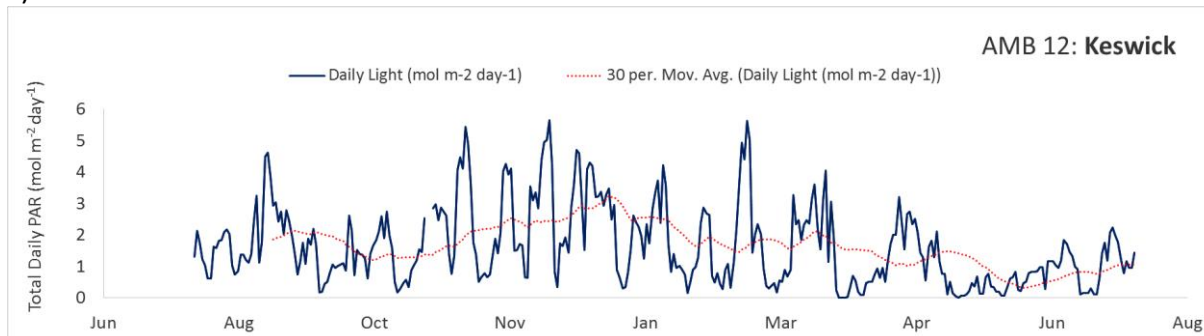
a)



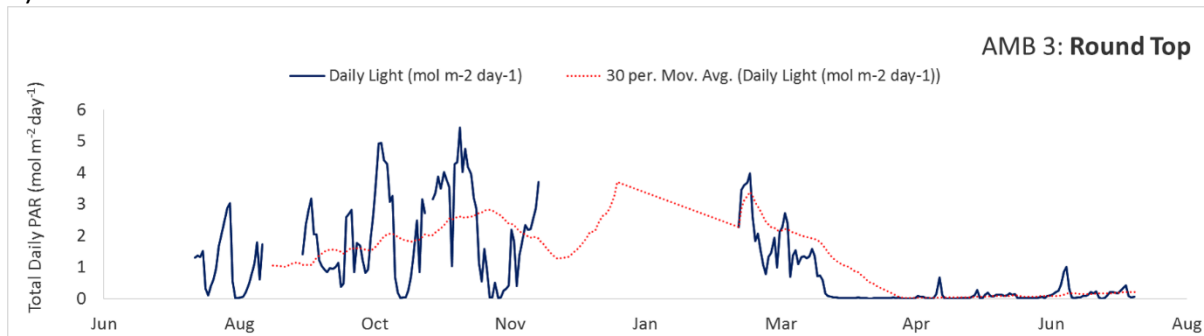
b)



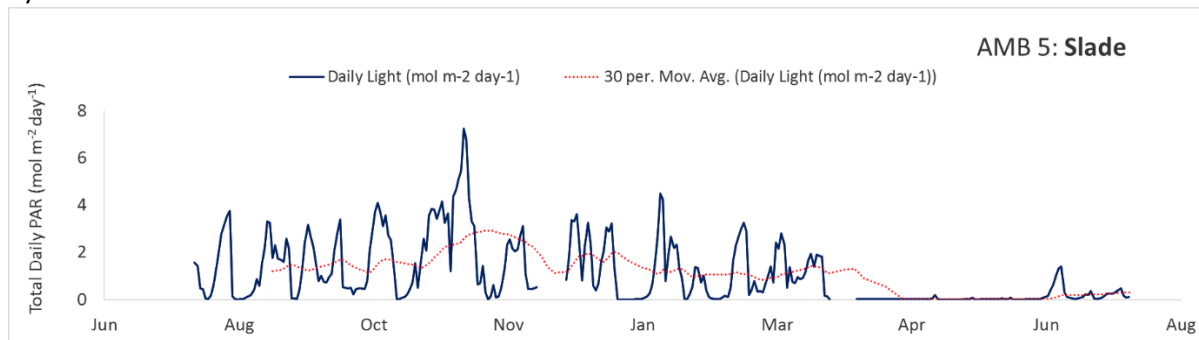
c)



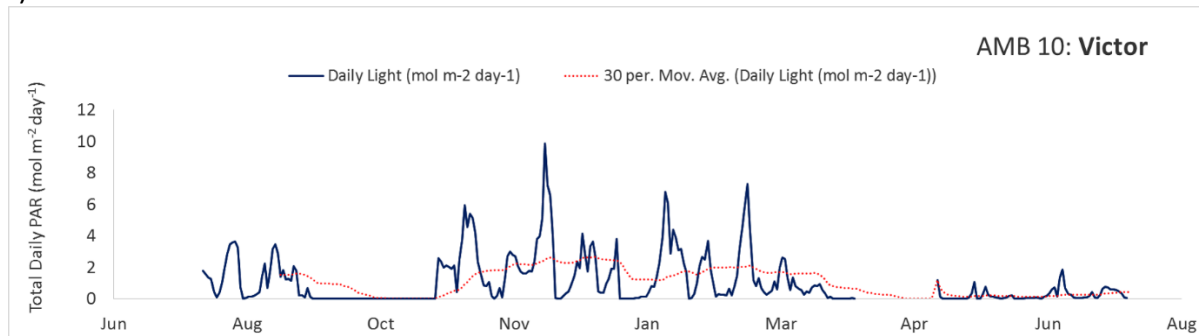
d)



e)



f)



g)

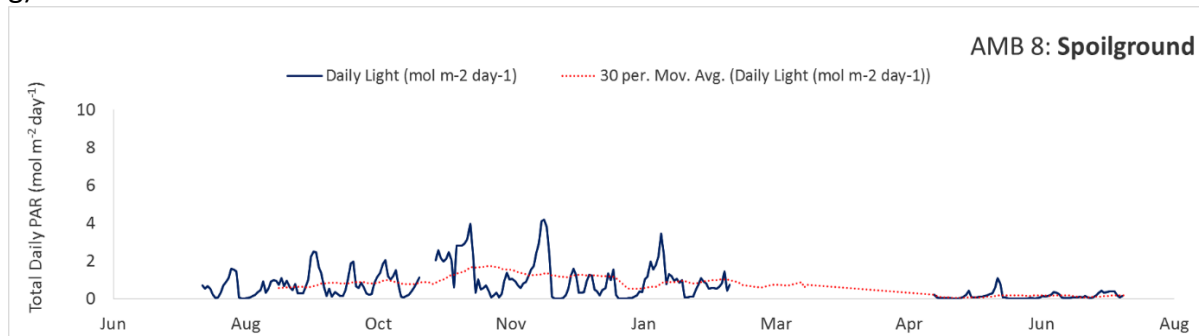
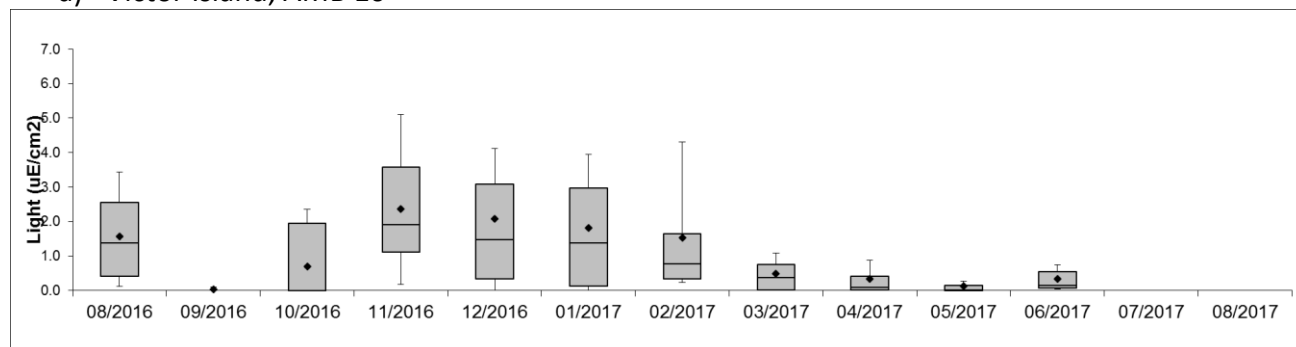


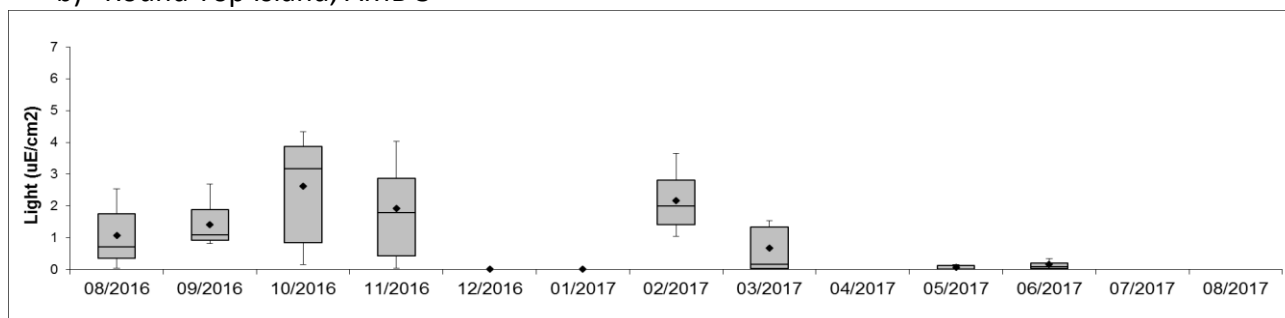
Figure 3.31

Time series of mean total daily photosynthetically active radiation (PAR) (mol photons /m²/day) recorded at all sites during the second year of the program (August 2016 - July 2017). 30 day moving average trend line depicted in red: a) Freshwater (AMB 1), b) HayReef (AMB 2), c) Keswick Island (AMB 12), d) Round Top Island (AMB 3B), e) Slade Island (AMB 5), and f) Victor Island (AMB 10) g) Relocation (Spoil) Ground (AMB 8)

a) Victor Island, AMB 10



b) Round Top Island, AMB 3



c) Keswick Island, AMB 12

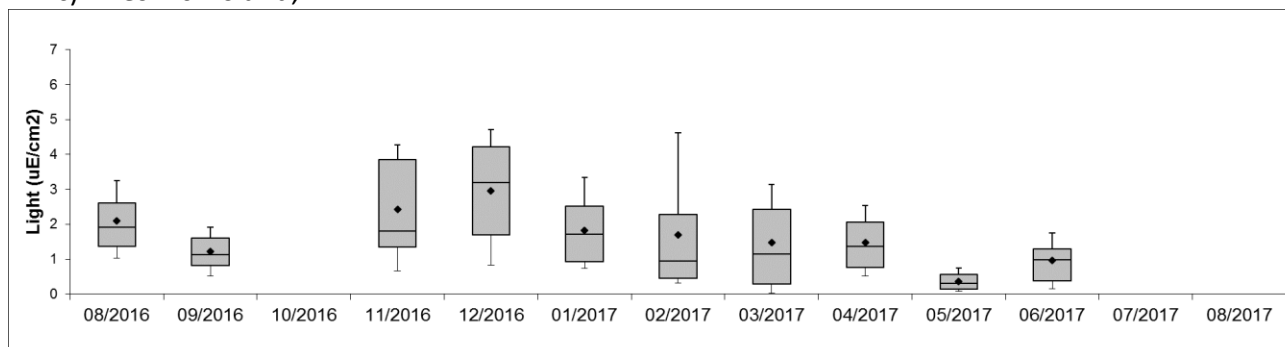


Figure 3.32 Monthly means and variation in total daily photosynthetically active radiation (PAR) (mol photons m^2/day) at a representative inshore site: a) Victor Islet, AMB 10; b) representative deeper coastal site (Round Top Island, AMB 3); and c) offshore site (Keswick Island, AMB 12) during 2016/2017

3.4.1 Similarities in patterns of PAR among sites

As sites were located at various depths below the lowest astronomical tide datum (LAT), direct comparisons of PAR among sites are not statistically valid. Therefore, the similarity in patterns of PAR over time among different sites was compared by plotting total daily PAR to examine the strength of the relationship using pairwise comparisons (Figure 3.33). The strength of the linear relationship between sites was measured using an R^2 value shown on each pairwise scatterplot.

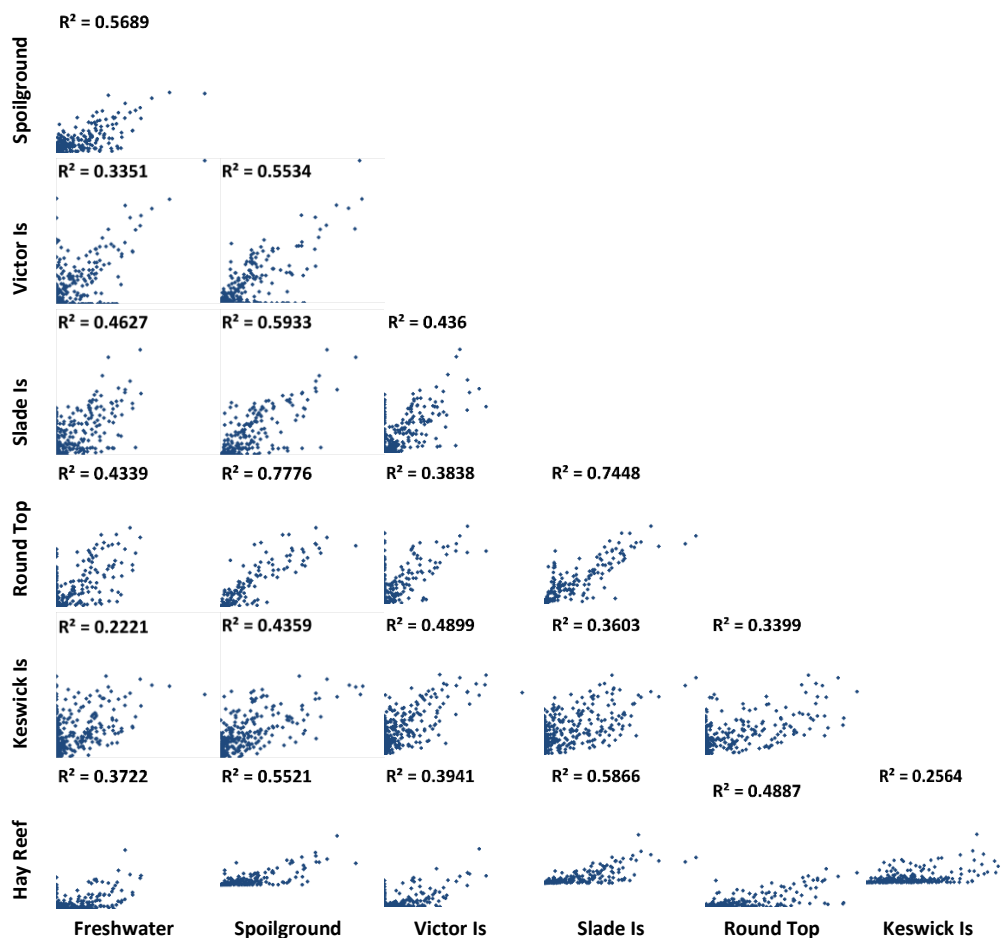


Figure 3.33 Scatterplots of pairwise comparisons among sites indicating the strength of the relationship between patterns of daily PAR (R^2 values are presented for each comparison)

Relationships in patterns of benthic PAR are found among shallow coastal sites with similarities generally strengthening between sites that were situated in closer geographic proximity to each other (e.g. Round Top Island, Slade Island, and Relocation ground sites $R^2 = 0.59$ - 0.78). There were also strong similarities between distant coastal sites that were located in similar environments (e.g. Victor Islet and Slade Islet, $R^2 = 0.44$, which are both located on the northern sides of islands). As was found in the previous reports, Keswick Island exhibited the least similarities among other coastal sites with very weak relationships in pairwise comparisons. This analysis assists in understanding site redundancy opportunities, without missing important detail in characterising water quality in the region.

3.4.2 Relationship between light attenuation and suspended solid concentrations

In sediment-rich coastal waters, the dominant physical process that reduces PAR light intensity is scattering, which if turbidity levels are high enough, can cause underwater light to become isotropic. Investigations into the light attenuation coefficient provides an insight into the dynamic relationship between suspended solid concentrations and PAR light intensities.

Absorption and scattering describe the attenuation of light through water by interacting in a nonlinear and complex fashion within the radiative transport equations (Mobley 1994). These equations cannot be solved analytically; however the diffuse attenuation coefficient (k_d) (averaged across the PAR waveband 400-700 nm) may be approximated in ocean waters by using Beer-Lambert's law (Gordon 1989; Dennison et al. 1993; Kirk 1994),

$$I_z = I_{z0}e^{-k_d(z-z_0)}$$

where I_{z0} and I_z are the downward directed irradiances at an upper depth (z_0) and a lower depth (z) respectively, and k_d is the diffuse attenuation coefficient (averaged across the PAR waveband 400-700 nm) (Jerlov 1976; Kirk 1977). k_d is comprised of a component due to clear water and a component due to SSC.

Light attenuation and suspended sediment concentration (SSC) are examined for all seven sites. A general relationship is found, whereby as SSC increases, light levels decrease exponentially, as is well described by Beer-lambert's Law. An example of this relationship can be seen in Figure 3.34 where during periods of high SSC, light is attenuated and when SSC exceeds approximately 10 mg/L, light extinction occurs.

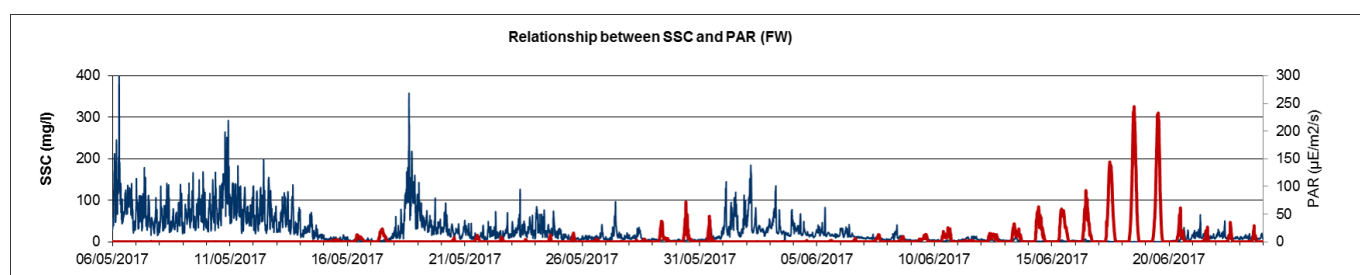


Figure 3.34 A typical example of the relationship between SSC (blue) and PAR light (red), showing light levels decreasing as SSC increases during May-June 2017 at Freshwater Point

3.4.3 Data comparison: 2014/2015, 2015/2016 to 2016/2017

Comparison of the 2014/2015, 2015/2016 and 2016/2017 statistics provides a greater perspective of data trends in the monitored environment. Noting any differences or similarities in the statistics between the two years and discussing whether these observations are natural, a result of the monitoring method or indications of human influence on the environment leads to a more thorough understanding of the ecosystem. Results are expected to have small variations year to year due to natural variation in weather.

RMS water height

RMS water height values are expected to change year to year if there are either changes to the locations where data was located or change in weather events for the year. The figures below are box plots of RMS water height from 2014/15, 2015/16 and 2016/17 (Figure 3.35). Inspection of trends in the figures features very similar results between the years. As expected, sites with low RMS values in 2014/2015 and 2015/2016 have remained low in 2016/2017 and the same for sites with high RMS water height values. Slight differences in the data are most likely the result of weather variances from year to year.

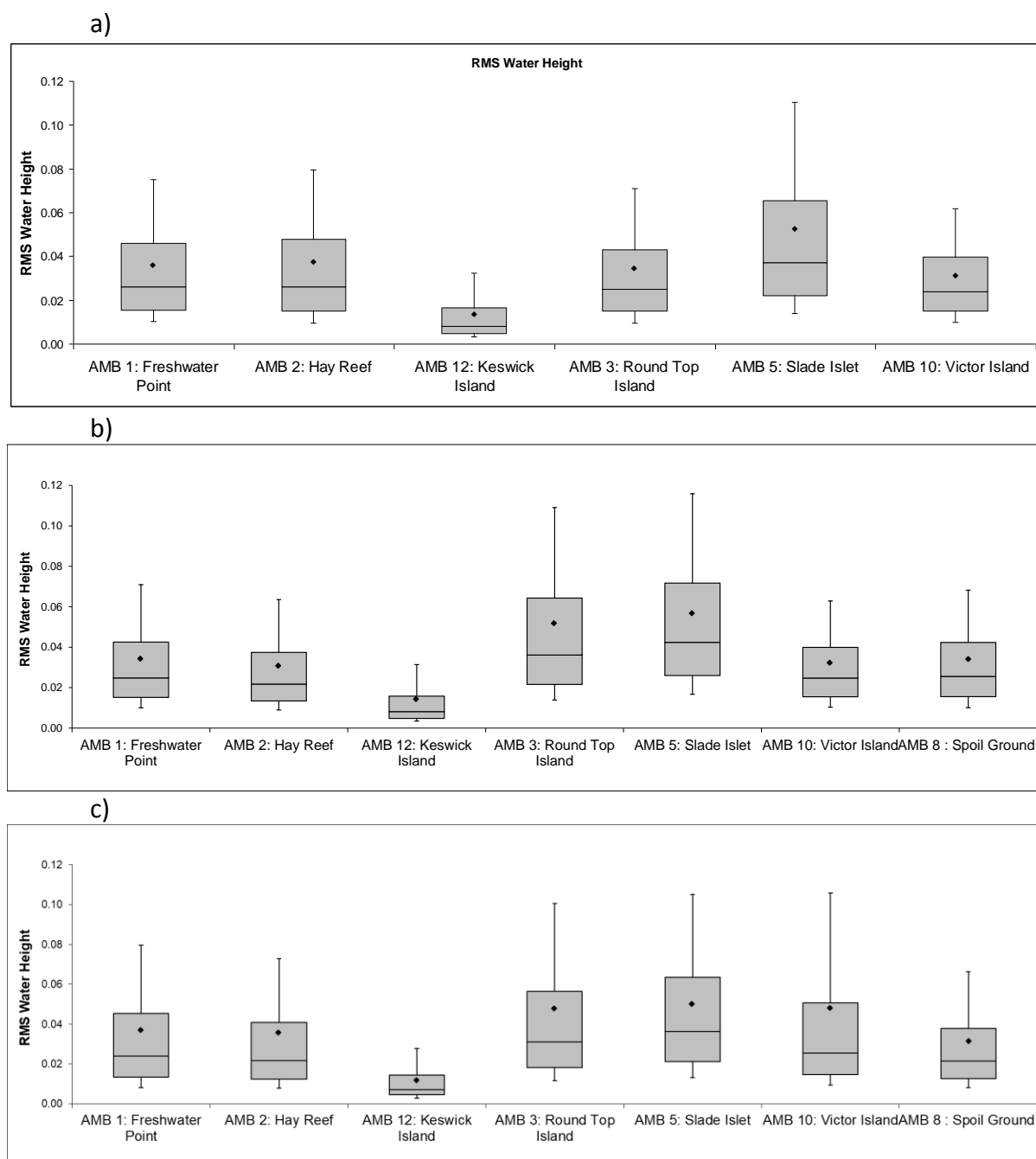


Figure 3.35 RMS water height box plots for: a) 2014/15, b) 2015/16 and c) 2016/17

SSC

SSC data show similar values across yearly statistical results (Figure 3.36). Keswick Island (AMB 12) and Round Top Island (AMB 3) SSC data depict very low values. Freshwater Point (AMB 1) data displayed much more variance in the second and third year. Large SSC events present in the 2015/2016 and 2016/2017 datasets, such as Tropical Cyclone Debbie, are likely causes for the increased variance compared to the 2014/2015 year.

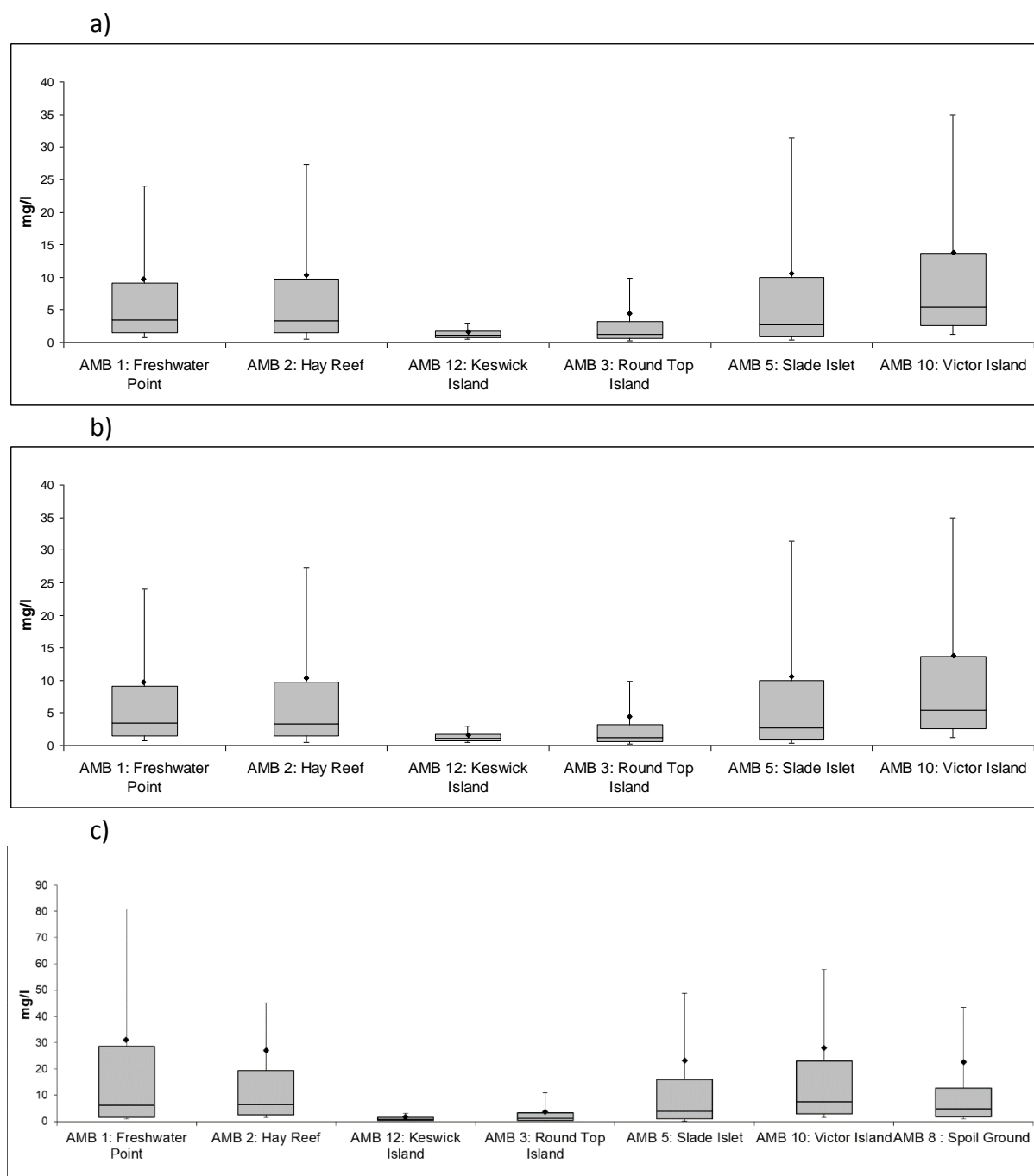


Figure 3.36 Suspended sediment concentration box plots for: a) 2014/15, b) 2015/16 and c) 2016/17

2hr Deposition Rate

Small variation in deposition rate is expected year to year and observed differences are likely the result of small changes in the environment (Figure 3.37). Slade Island (AMB 5) and Victor Island (AMB 10) showed higher deposition rates in the 2014/2015 year. The other sites show similar deposition values year to year. There was no overall trend of increasing or decreasing deposition rates across all sites and further analysis is required before any relations between changes between the years at individual sites can be attributed to any influencing factors.

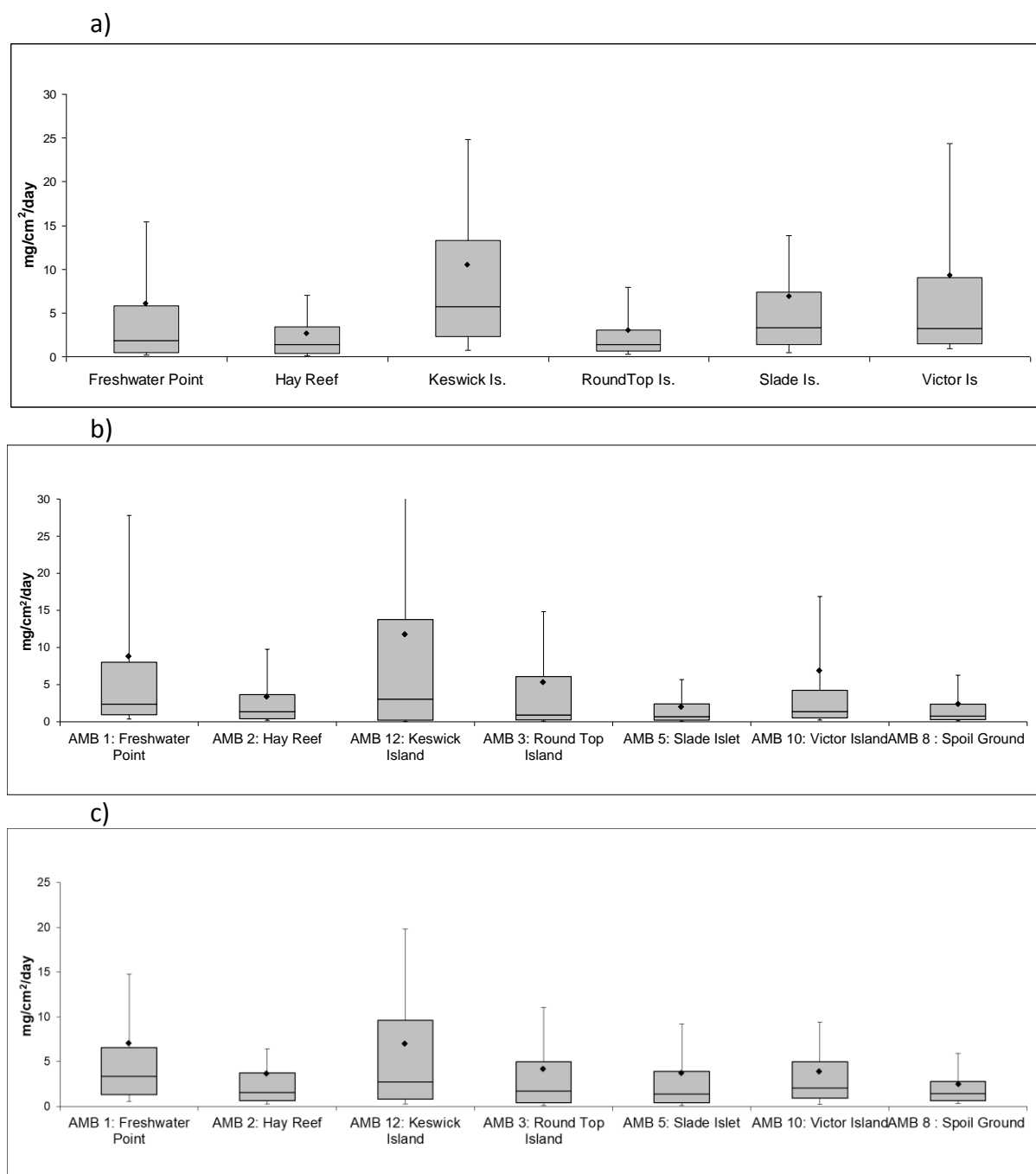


Figure 3.37 2hr deposition rate box plots for: a) 2014/15, b) 2015/16 and c) 2016/17

3.4.3 Seasonal variation: wet vs dry

Seasonal variation of all marine water properties is often assumed. The following comparison of wet and dry season statistics at all monitored sights shows there to be much less variation than many would expect.

RMS water height

Wet seasons are associated with large storms, wind and rain. It is often assumed that there is a large difference in wave energy between the wet and dry seasons in the Mackay region. As in previous years, the results from the 2016/2017 data set show that this is not the case. There

is an indiscernible difference in RMS water height data between the wet and dry season periods and this is clearly observed (Figure 3.38).

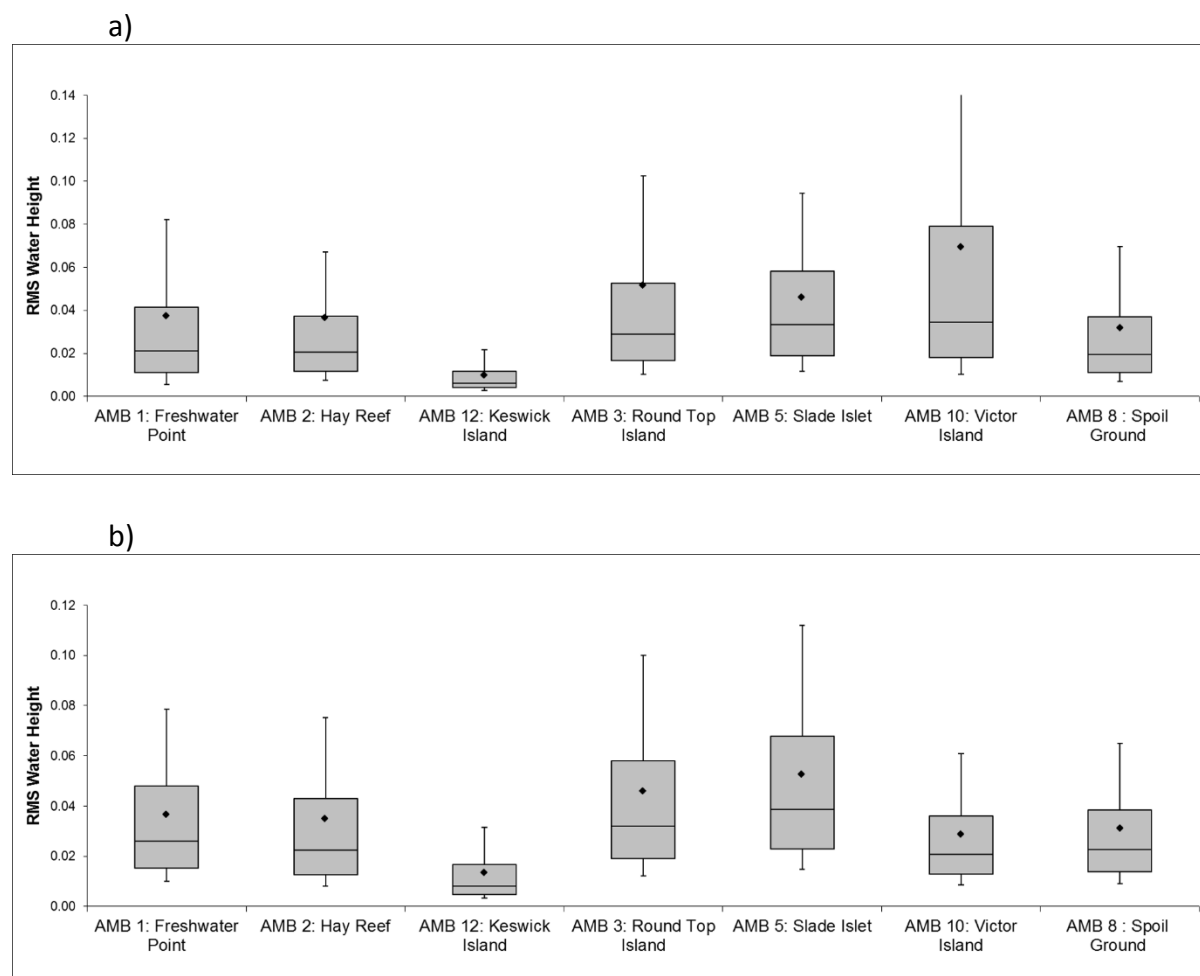


Figure 3.38 2016/17 RMS water height box plots for: a) wet season; and b) dry season

SSC

For some sites small differences in the statistical SSC results, between the wet and dry seasons, have been found (Figure 3.39). However, there was no consistent increase or decrease in SSC between seasons. Instead, sites had either slightly higher or lower values when comparing median values between wet and dry season. Overall the SSC values do not change considerably between the wet and dry season statistics.

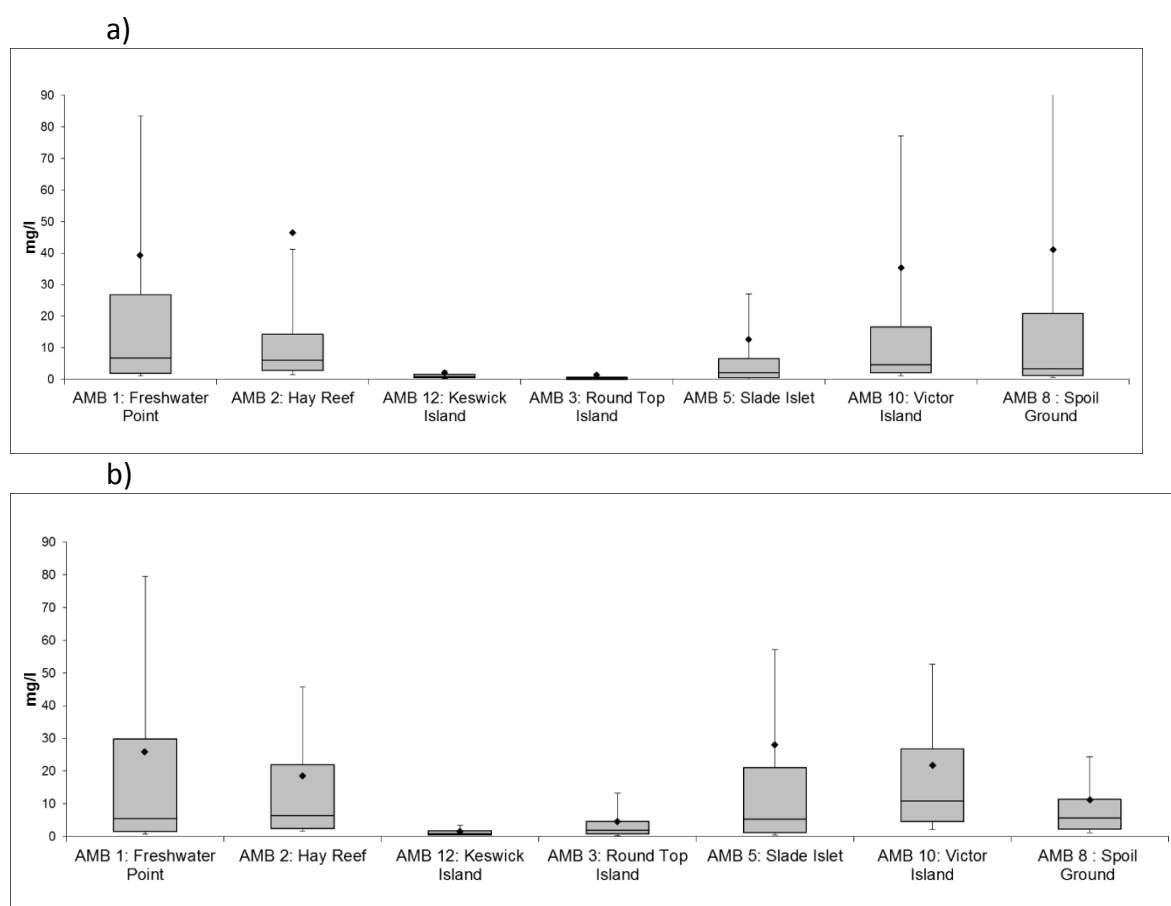


Figure 3.39 2016/17 SSC box plots for: a) wet season; and b) dry season

2hr deposition rate

The deposition rate statistics observed during the wet and dry seasons are notably different at Freshwater Point (AMB 1), Keswick Island (AMB 12), Round Top Island (AMB 3), and Victor Islet (AMB 10) (Figure 3.40). Freshwater point and Victor Island show decreases in median deposition rate during the wet season, while the other two sites show increases in median deposition rates during the wet season. Investigating the season to season variance in deposition rate values in future studies will allow for these results to be either verified to be seasonal trends or to show they are non-seasonal events that drove the statistical values observed in the 2016/2017 results.

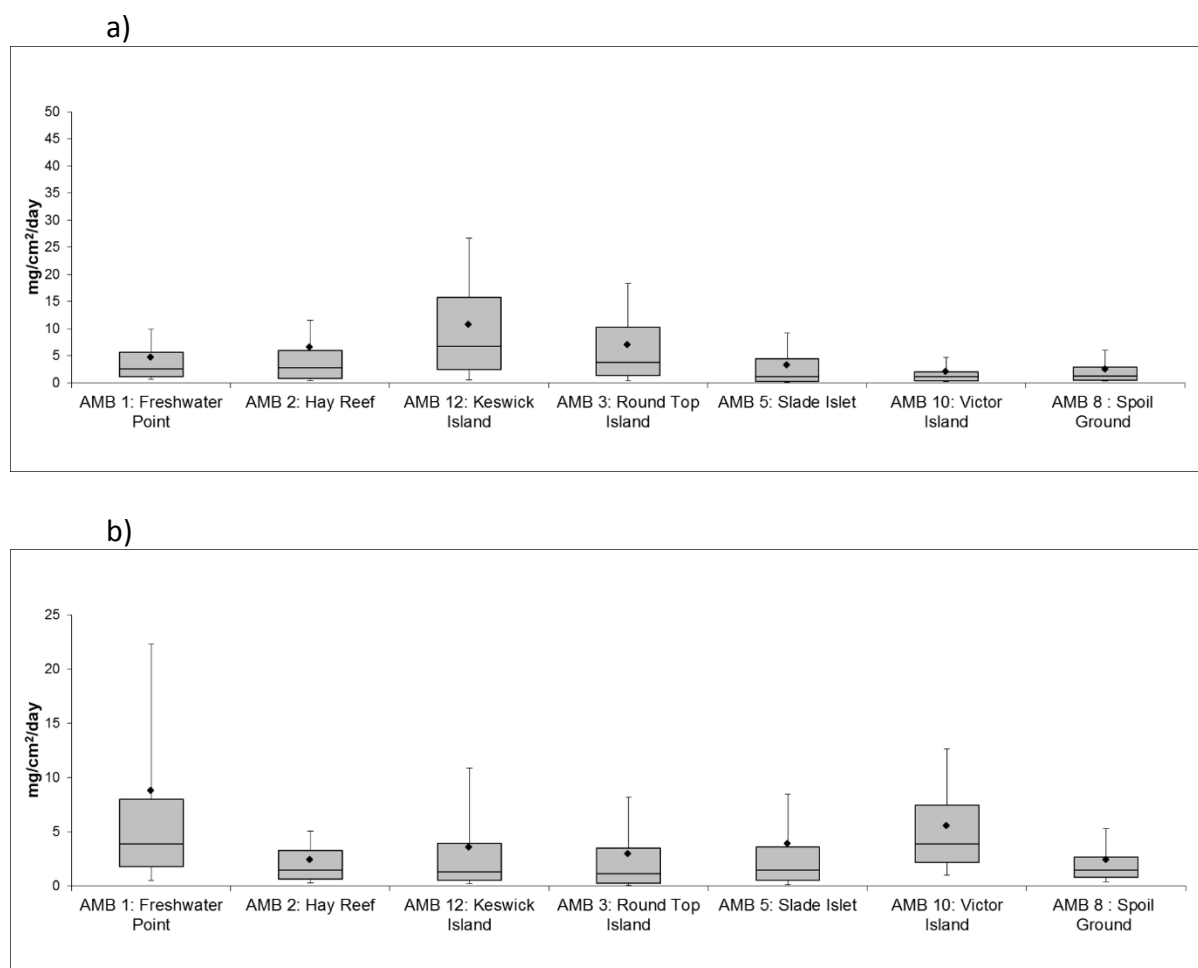
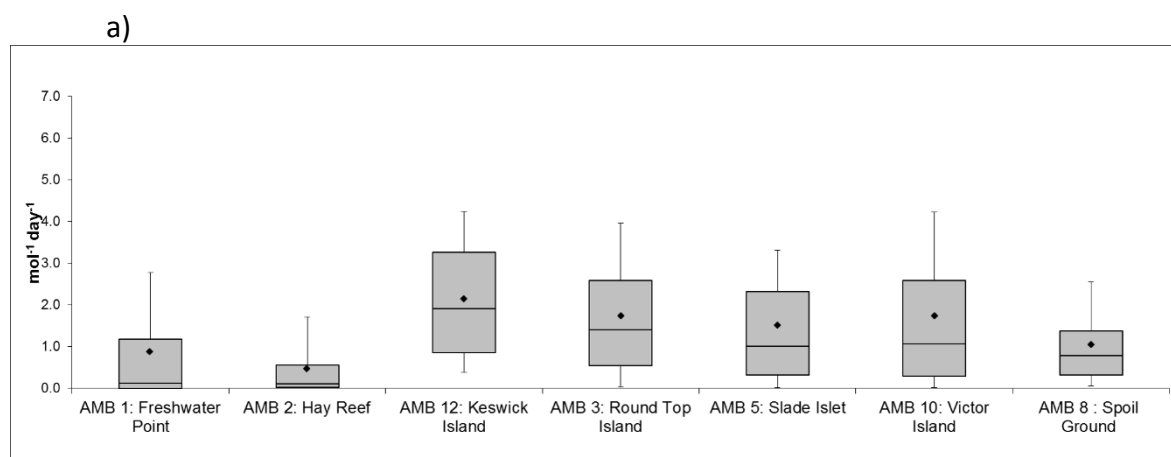


Figure 3.40 2016/17 2hr deposition rate box plots for: a) wet season; and b) dry season

Total daily PAR

Daily total PAR values are generally higher during the wet season in comparison to the dry season, except at Freshwater Point (Figure 3.41). This pattern may be linked to longer daylight hours during the wet season.



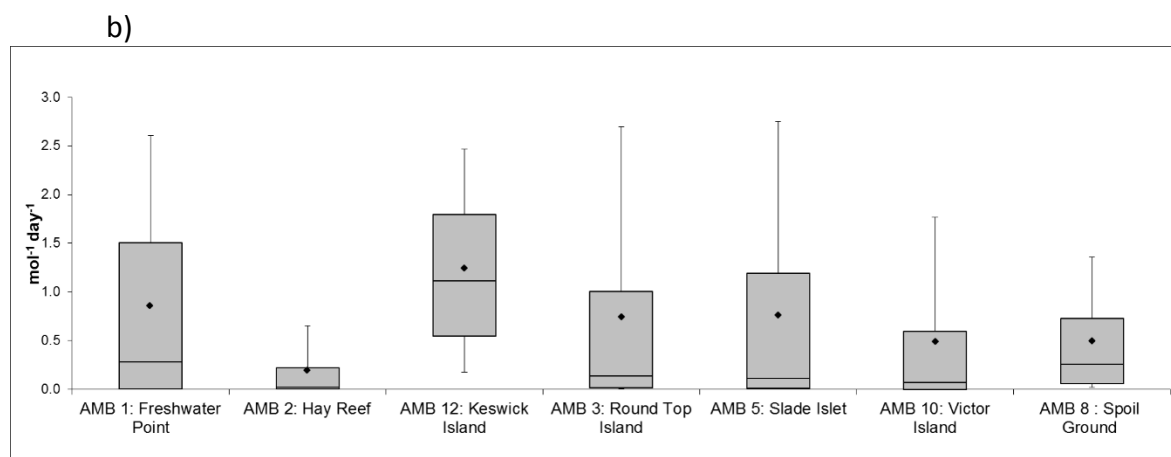


Figure 3.41 2016/17 PAR box plots for a) wet season; and b) dry season

Water temperature

There is a clear pattern of differences in water temperature between the wet and dry season (Figure 3.42). Temperatures during the wet season are notably higher, median temperatures between 28 and 29°C at all sites, and have much less variation. Dry season temperature statistics show all sites to have median temperature values between 23 and 24°C and variation to be larger than during the wet season.

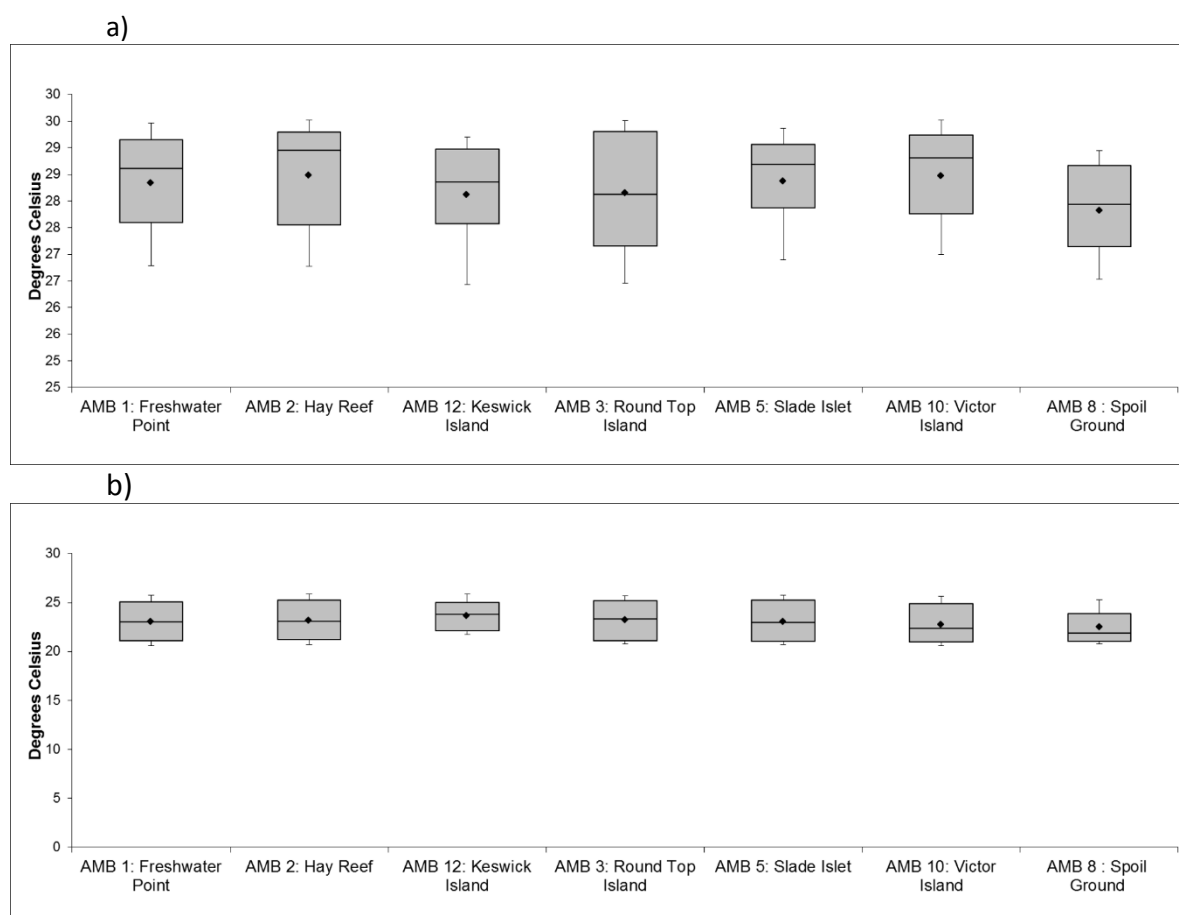


Figure 3.42 2016/17 water temperature box plots for a) wet season; and b) dry season

3.4.4 Current meter

Current meter data was collected at Slade Islet (AMB 5), Hay Reef (AMB 2) and Relocation grounds (AMB 8). Marotte HS current meter instruments were deployed for periods of between 1 and 2 months. The current meter data indicates the prominent current direction and velocity at each site. Data shows that coastal current, tidal current or a combination of both influence current direction and magnitude. The figures below display the current meter data in current rose and average current speed rose diagrams. The current rose diagrams provide a visual representation of relative prominence of current velocity and direction. The average current speed rose diagrams displays the average current speed in every direction. Presented together these diagrams highlight the prominent direction of current and the average velocity of the current in this direction. The appendix includes a video with the various sites on a map showing how the current speed and direction changes over time.

Slade Islet (AMB 5) current meter data

The current at Slade Islet ranges from SSE to WNW with peaks at SSE and SW, average velocities are between of 0.1 m/s and 0.3 m/s (Figure 3.43 and Figure 3.44). This indicates that a coastal current dominates this site. Changes in current velocity are likely the result of tidal current influence.

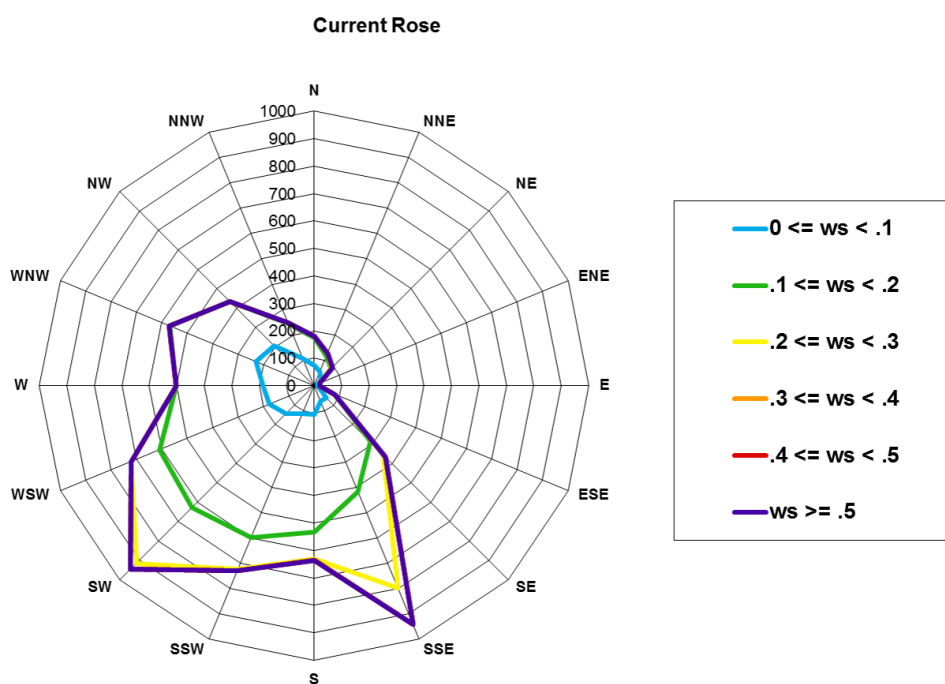


Figure 3.43 Current rose at Slade Island (AMB 5). The legend shows the ws, current speed, ranges and the number of recorded values are labelled on the radar axis (August 2016 - July 2017)

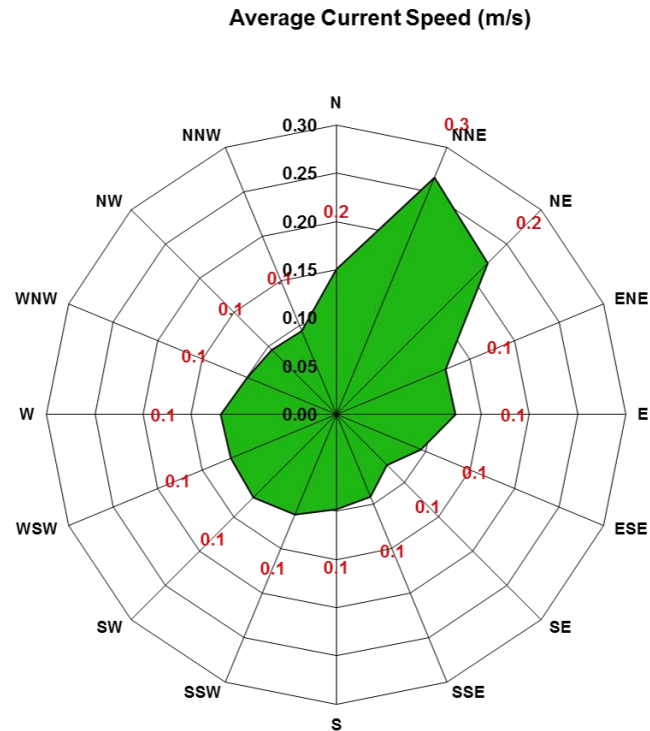


Figure 3.44 Average current speed rose at Slade Island (AMB 5). Red numbers indicate average current speed at specified direction. Average current speed is labelled on the radar axis. Green area shows the recorded average current speed data (August 2016 - July 2017)

Hay Point current meter data

Currents at Hay Reef (AMB 2) flowed predominately to the North and the South indicating tidal currents with a change of direction between the ebb flood tides. Average current speeds ranged between 0.1 m/s and 0.2 m/s.

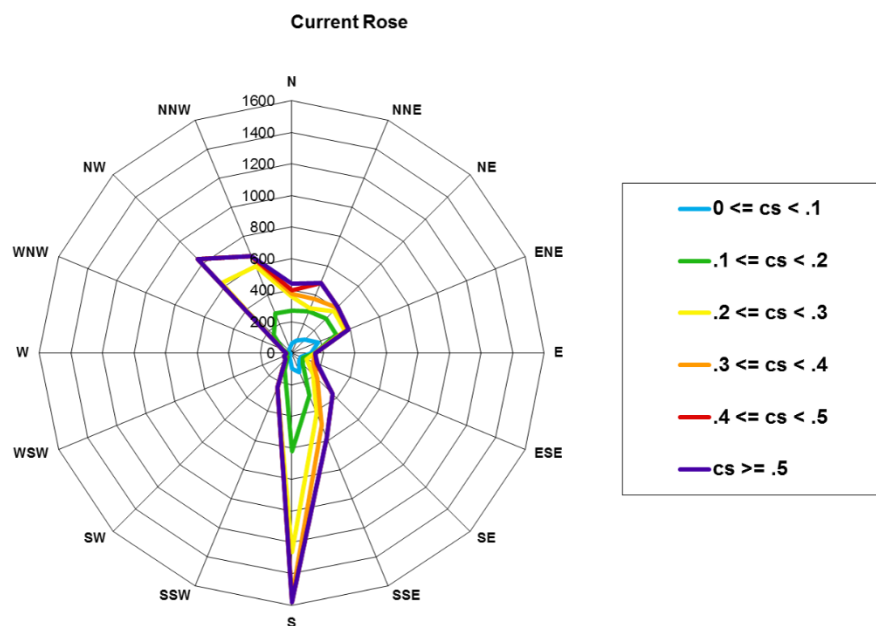


Figure 3.45 Current rose at Hay Point. The legend shows the cs, current speed, ranges and the number of recorded values are labelled on the radar axis (August 2016 - July 2017)

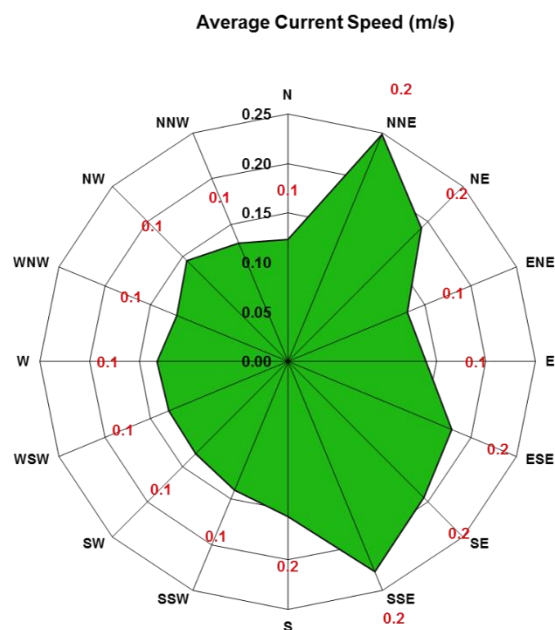


Figure 3.46 Average current speed rose at Hay Point. Red numbers indicate average current speed at specified direction. Average current speed is labelled on the radar axis. Green area shows the recorded average current speed data (August 2016 - July 2017)

Relocation grounds (AMB 8) current meter data

The two current directions that dominate at Relocation grounds (AMB 8) are in the NNW and S directions (Figure 3.47). An average current velocity of 0.2 m/s was recorded in both the NNW and S directions. Interestingly an average current velocity of 0.3 m/s was recorded in the SSW direction, although relatively very little data was recorded at this bearing (Figure 3.48). Again the change in direction is likely explained by changes in tidal current direction.

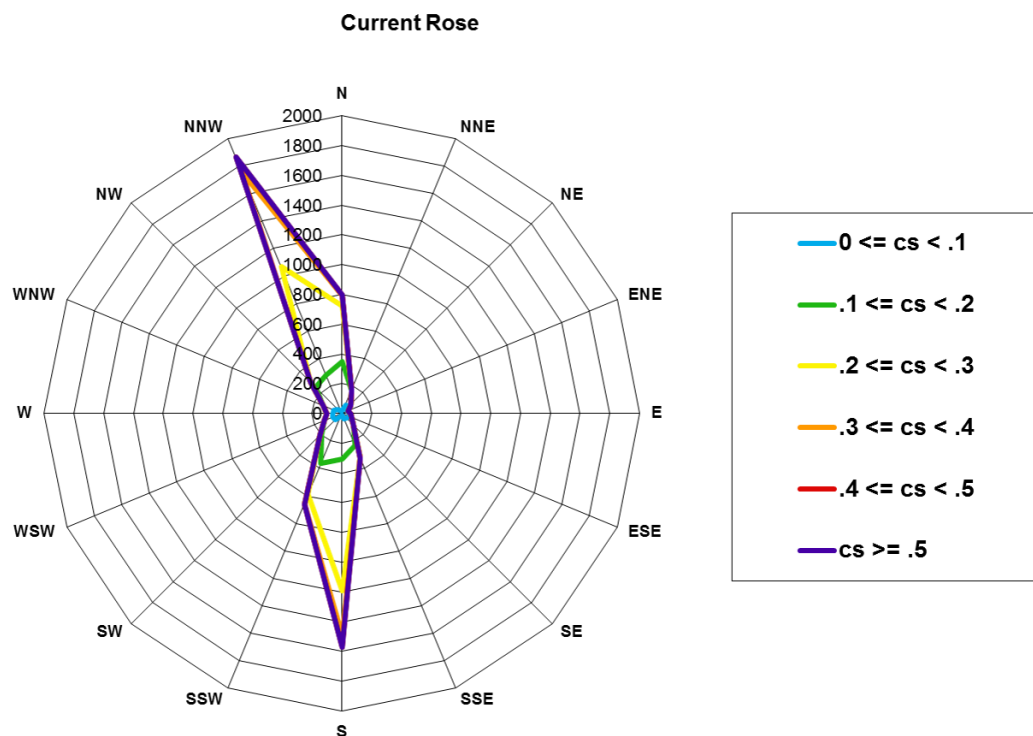


Figure 3.47 Current rose at Relocation grounds (AMB 8). The legend shows the cs, current speed, ranges and the number of recorded values are labelled on the radar axis (August 2016 - July2017)

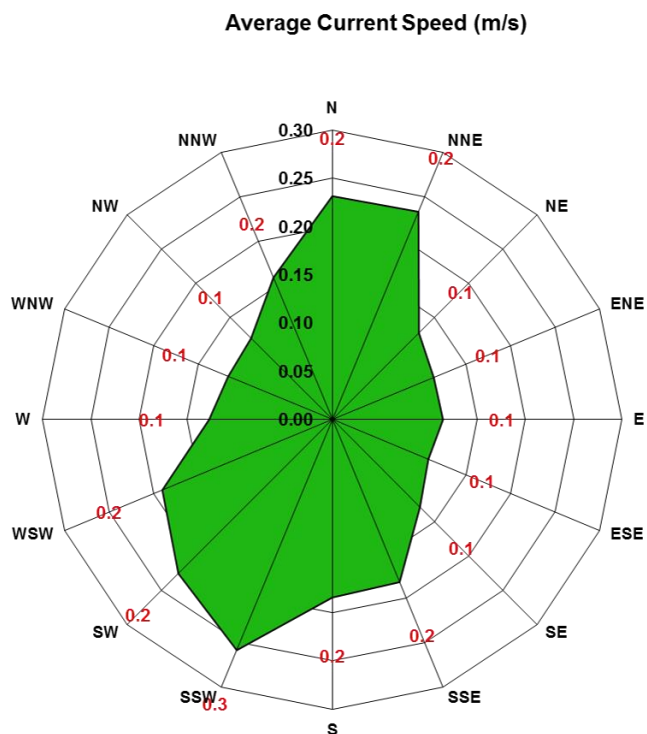


Figure 3.48 Average current speed rose at Relocation grounds (AMB 8). Red numbers indicate average current speed at specified direction. Average current speed is labelled on the radar axis. Green area shows the recorded average current speed data (August 2016 - July2017)

3.5 River plumes

3.5.1 Site specific outputs

Freshwater Point (AMB 1)

A stepwise regression analysis was run against the Freshwater Point data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth, both wind components, tide amplitude and the Pioneer River discharge explained 69% of the SSC variability (Box 1). The relative importance analysis suggested that RMS of water depth is the most influential parameter on SSC, followed by Pioneer River discharge. Together these two variables explained about 49% of the SSC variability at Freshwater Point (Figure 3.49). The NWSE and NESW wind components and tide amplitude combined explained around 21% of SSC variability. Results of the partial effects plots (Figure 3.50) followed expected trends for SSC in relation to each environmental parameter selected in the model. Clear patterns in SSC were observed against all the environmental parameters, with the wind_NESW component exhibiting the widest confidence intervals. Overall, an increase in SSC was observed with increases in the environmental predictors. The stronger the winds coming from the east (i.e. positive values for wind_NESW and negative values for wind_NWSE) the higher the SSC readings were. These results are extremely similar to the Freshwater Point site-specific outputs for the 2015-2016 monitoring of Freshwater Point.

Box 1: Statistical summary of the stepwise regression analysis to Freshwater Point data

Coefficients

	Estimate	Std. Error	t value	Pr (> t)
(Intercept)	1.779433	0.41126	4.327	1.95e-05 ***
Log (RMS)	0.944805	0.073069	12.93	< 2e-16 ***
Log (Pioneer + 1)	0.393715	0.393715	13.932	< 2e-16 ***
Wind_NESW	0.019862	0.007346	2.704	0.00718 **
Wind_NWSE	-0.039028	0.007149	-5.459	8.79e-08 ***
Amplitude	0.20878	0.042017	4.969	1.03e-06 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8905 on 369 degrees of freedom

Multiple R-squared: 0.6978, Adjusted R-squared: 0.6937

F-statistic: 170.4 on 5 and 369 DF, p-value: < 2.2e-16

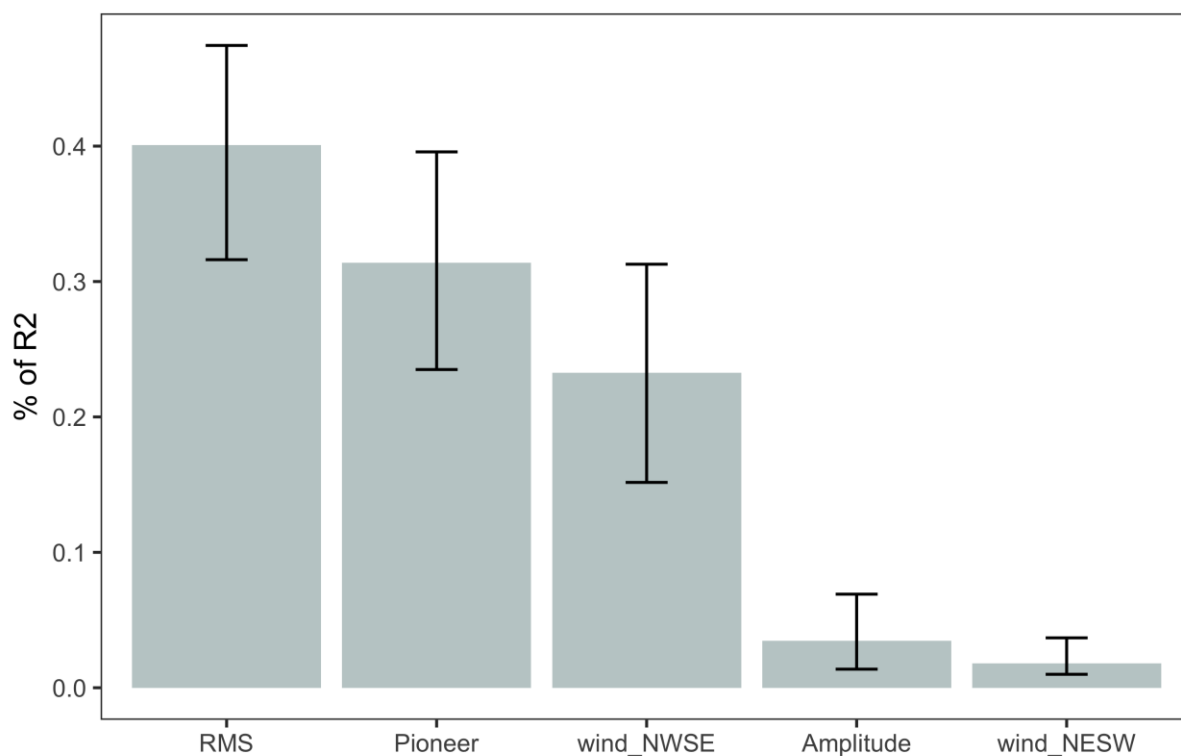


Figure 3.49 Freshwater Point bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall $R^2 = 0.69$

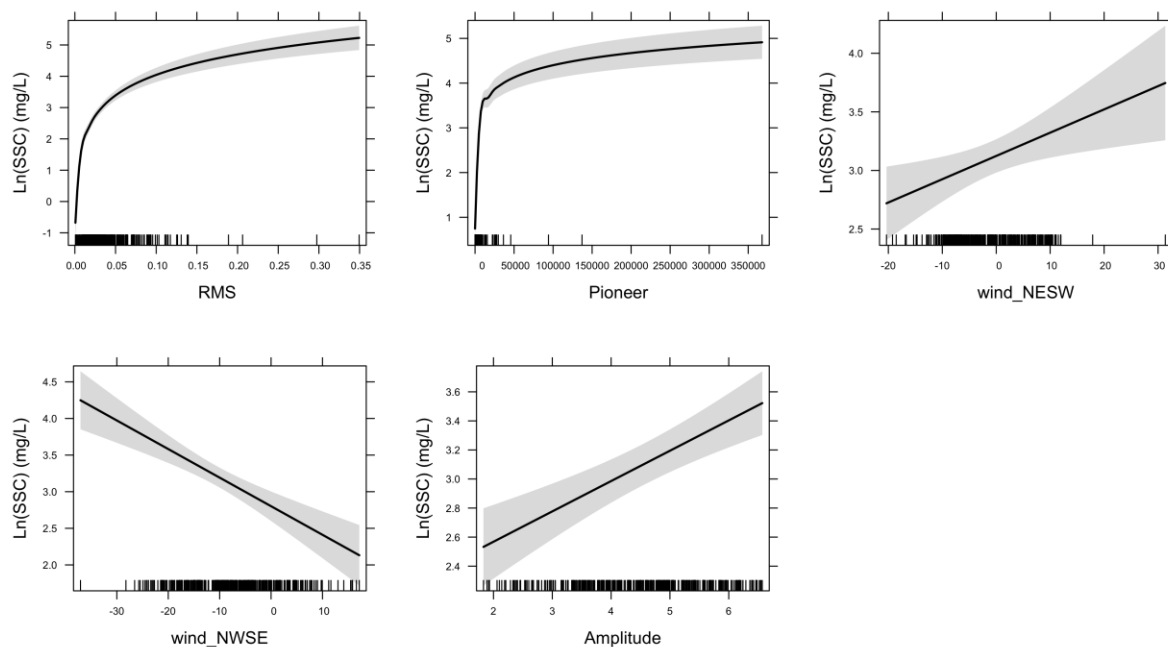


Figure 3.50 Partial effect plots for Freshwater Point parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and run on x-axis stand for data density

Hay Point Reef (AMB 2)

A stepwise regression analysis was run against the Hay Point Reef data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth, tide amplitude, and Pioneer River discharge explained 81% of the SSC variability (Box 2). The relative importance analysis suggested that RMS of water depth is by far the most influential parameter on SSC, explaining about 56% of the SSC variability at Hay Point reef (Box 2). RMS, Pioneer River discharge, and tide amplitude combined explained around 24% of SSC variability (Figure 3.51). Results of the partial effects plots (Figure 3.52) followed expected trends for SSC in relation to each environmental parameter selected in the model. Clear patterns in SSC were observed against all the environmental parameters. Overall, an increase in SSC was observed with increases in the environmental predictors. These results are similar to the Hay Point Reef site specific outputs for the 2015-2016 monitoring, although the NESW wind component was no longer found to be an influential variable in this years' model.

Box 2: Statistical summary of the stepwise regression analysis to Hay Point Reef data

Coefficients

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	4.09361	0.35959	11.384	< 2e-16 ***
Log (RMS)	1.30179	0.05278	24.666	< 2e-16 ***
Log (Pioneer + 1)	0.26101	0.02513	10.387	< 2e-16 ***
Amplitude	0.20411	0.03264	6.254	1.50e-09 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.5865 on 278 degrees of freedom

Multiple R-squared: 0.8053, Adjusted R-squared: 0.8032

F-statistic: 383.4 on 3 and 278 DF, p-value: < 2.2e-16

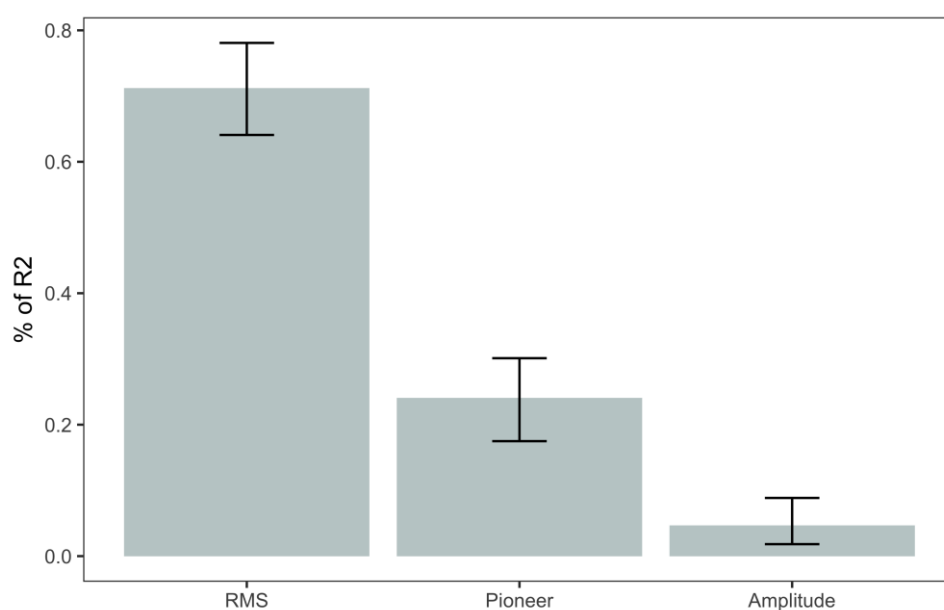


Figure 3.51 Hay Point Reef bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall $R^2 = 0.8053$

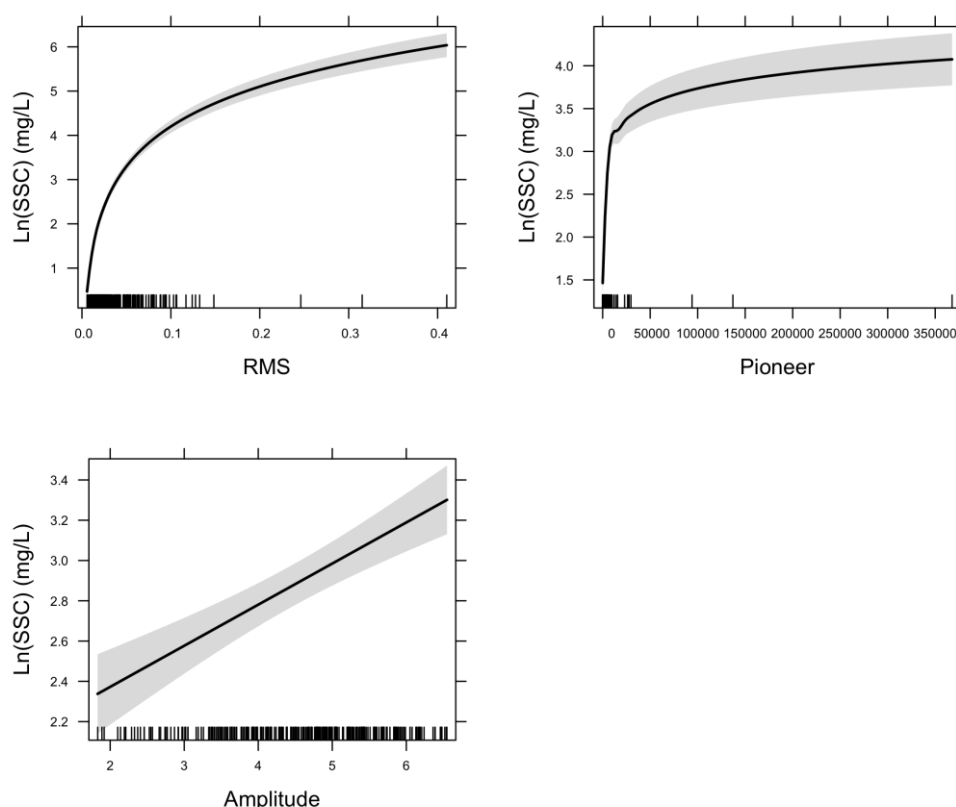


Figure 3.52 Partial effect plots for Hay Point Reef parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and run on x-axis stand for data density

Keswick Island (AMB 12)

A stepwise regression analysis was run against the Keswick Island data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth, the wind component NWSE, tide amplitude and the Pioneer River and Sandy River discharges explained about 42% of the SSC variability (Box 3). The relative importance analysis suggested that RMS of water depth was the most influential parameter on SSC, explaining approximately 29% of the SSC variability at Keswick Island (Figure 3.53). Tidal amplitude explained the remaining 13% of SSC variability at Keswick Island (Figure 3.53). Results of the partial effects plots (Figure 3.54) generally followed expected trends for SSC in relation to each environmental parameter selected in the model. Overall, an increase in SSC was observed with increases in the environmental predictors.

Box 3: Statistical summary of the stepwise regression analysis to Keswick Island data

Coefficients				
	Estimate	Std. Error	t value	Pr (> t)
(Intercept)	1.52217	0.24607	6.186	1.74e-09 ***
Log (RMS)	0.52647	0.041	12.841	< 2.00e-16 ***
Amplitude	0.22653	0.02876	7.876	4.41e-14 ***
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
Residual standard error: 0.593 on 346 degrees of freedom				
Multiple R-squared: 0.4163, Adjusted R-squared: 0.4129				
F-statistic: 123.4 on 2 and 346 DF, p-value: < 2.2e-16				

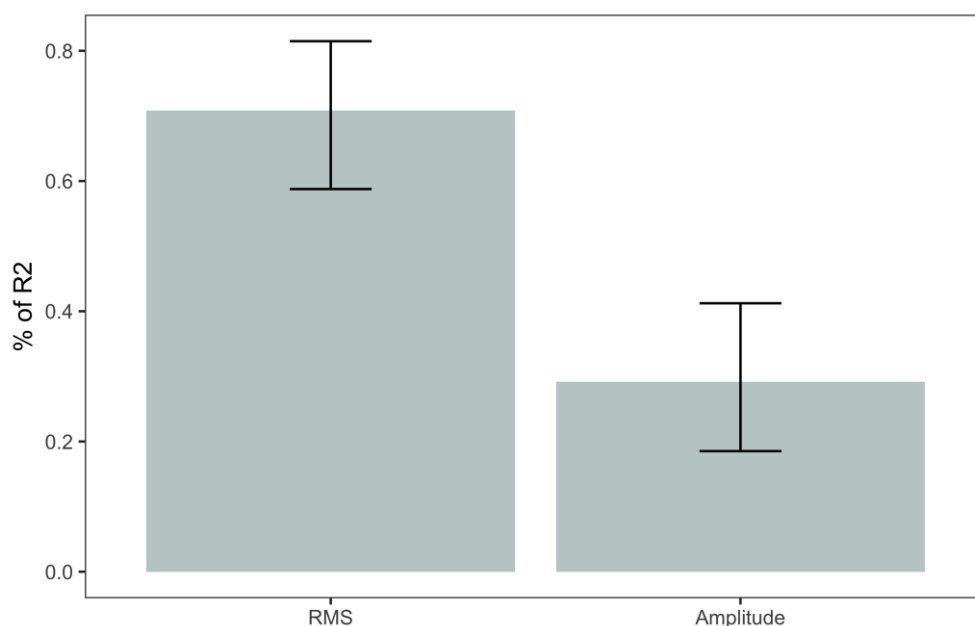


Figure 3.53 Keswick Island bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall $R^2 = 0.4163$

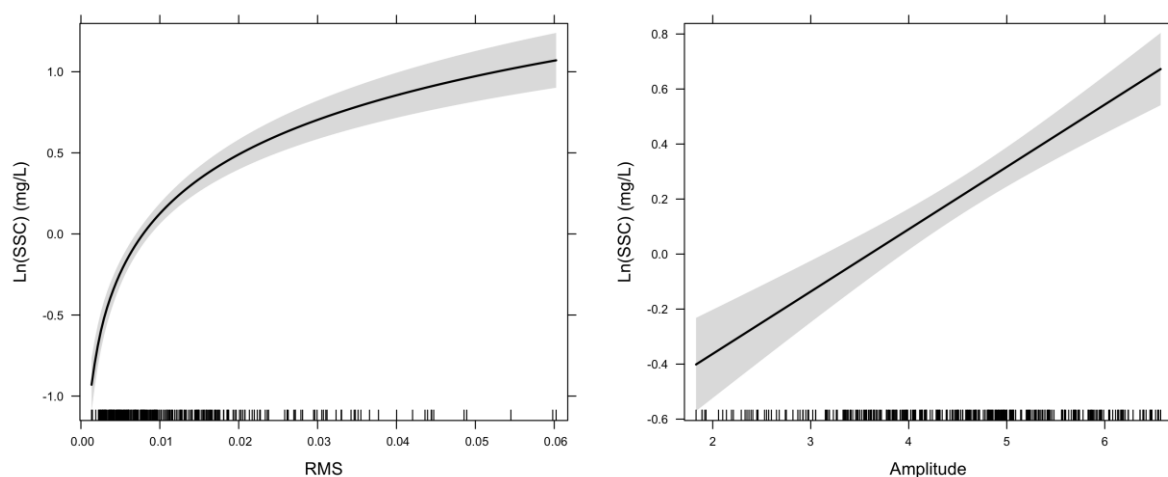


Figure 3.54 Partial effect plots for Keswick Island parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and run on x-axis stand for data density

Round Top Island (AMB 3)

A stepwise regression analysis was run against the Round Top Island data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth, the NESW wind component, and tide amplitude were the most influential factors of SSC variability, together explaining 30% of SSC variability (Box 4). The relative importance analysis suggested that the NESW wind component was the most influential parameter on SSC, explaining about 14% of the SSC variability at Round Top Island (Box 4). The remaining variables combined explained around 17% of the explained SSC variability (Figure 3.55). Overall, an increase in SSC was observed with increases in the environmental predictors, except for the NESW wind component. Results of the partial effects plots (Figure 3.56) show that strong winds coming from the west (i.e. negative values for wind_NESW) correspond with high SSC readings. These results differ with the models for

Round Top Island reported for the 2015-2016 monitoring. Notably, RMS is no longer the most influential parameter on SSC, and wind coming from the west has replaced wind coming from the east as an important parameter. Additionally, discharge from the Pioneer River is no longer explaining variability in SSC.

Box 4: Statistical summary of the stepwise regression analysis to Round Top Island data

Coefficients	Estimate	Std. Error	t value	Pr (> t)
(Intercept)	0.63169	0.60492	1.044	0.29768**
Log (RMS)	0.47344	0.14041	3.372	0.000904***
wind_NESW	-0.0697	0.01388	-5.02	0.00000118***
Amplitude	0.28876	0.07159	4.034	0.0000793*

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.105 on 191 degrees of freedom

Multiple R-squared: 0.3084, Adjusted R-squared: 0.2975

F-statistic: 23.38 on 3 and 191 DF, p-value: 3.179e-15

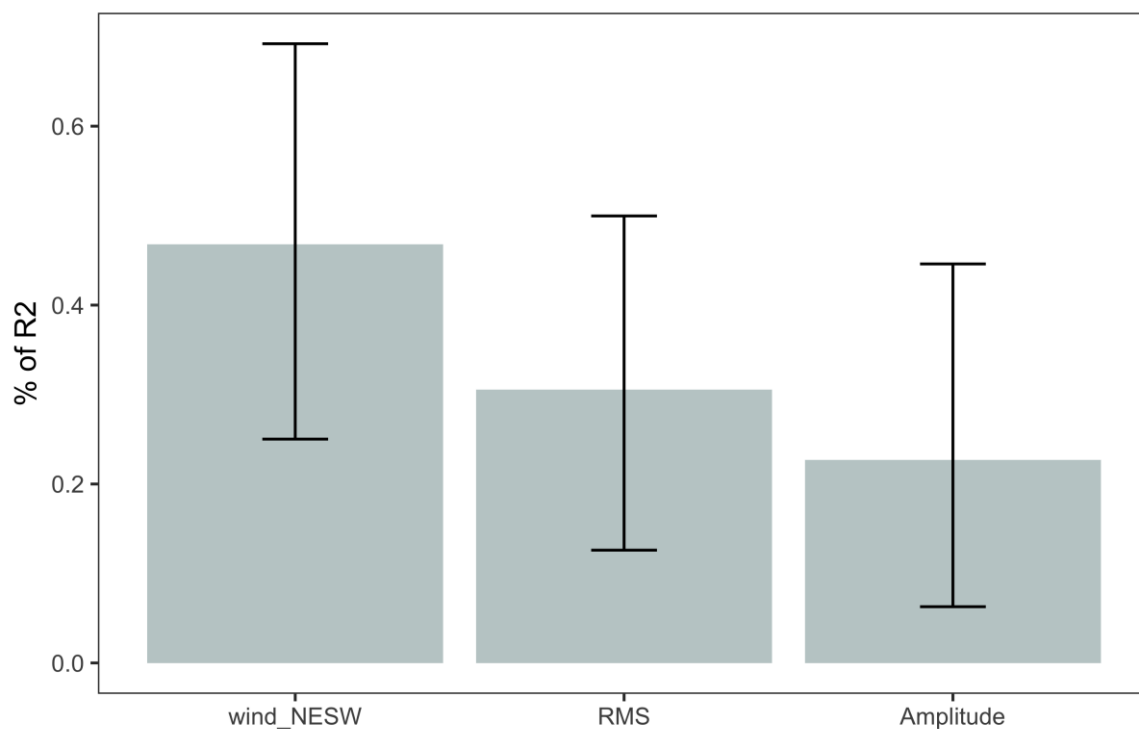


Figure 3.55 Round Top Island bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall $R^2 = 0.30$

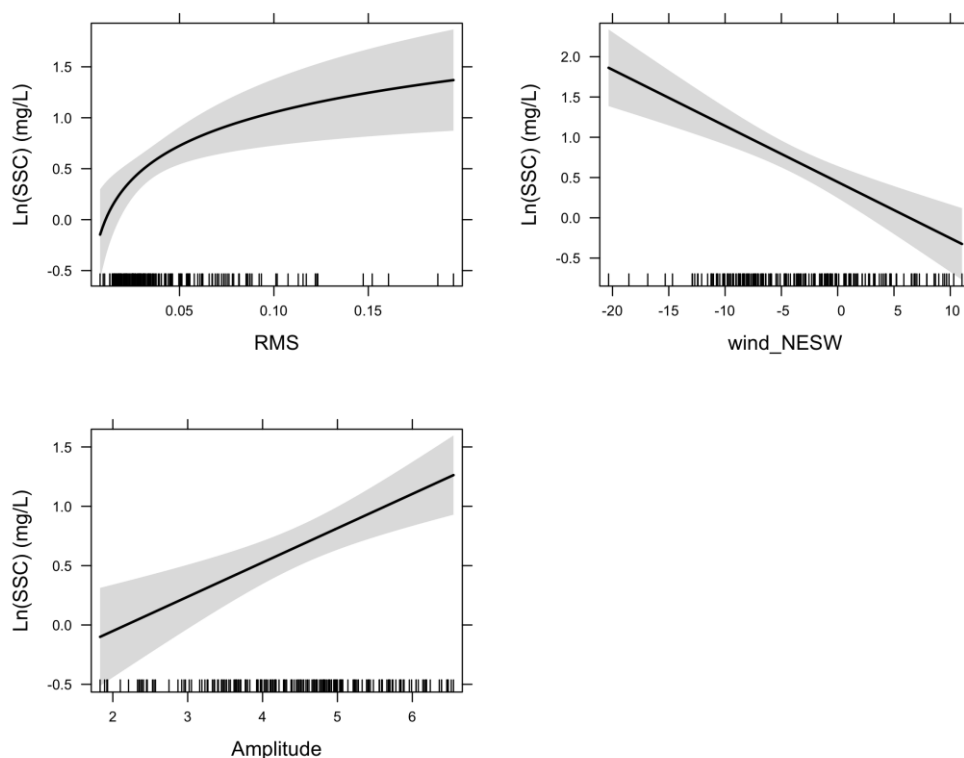


Figure 3.56 Partial effect plots for Round Top Island parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and run on x-axis stand for data density

Slade Islet (AMB 5)

A stepwise regression analysis was run against the Slade Islet data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth and, Pioneer River discharge, the NESW wind component, and tide amplitude together explained about 67% of the SSC variability (Box 5). The relative importance analysis suggested that RMS of water depth was the single most influential parameter on SSC, explaining almost 39% of the SSC variability at Slade Islet (Box 5). The remaining variables combined also explained around 26% of SSC variability (Figure 3.57). Overall, an increase in SSC was observed with increases in the environmental predictors, except for the NESW wind component (Figure 3.58). This suggests that strong winds from the west (i.e. negative values for wind_NESW) are associated with high SSC. The results differ from the 2015-16 site specific monitoring with wind and tide amplitude variables being influential in this years' model, while Sandy river discharge was not.

Box 5: Statistical summary of the stepwise regression analysis to Slade Islet data

Coefficients	Estimate	Std. Error	t value	Pr (> t)
(Intercept)	3.88063	0.66899	5.801	1.75e-08 ***
Log (RMS)	1.88756	0.12831	14.711	< 2e-16 ***
Log (Pioneer + 1)	0.42596	0.04738	8.99	< 2e-16 ***
wind_NESW	-0.03497	0.01235	-2.831	0.004976 ***
Amplitude	0.21873	0.0628	3.483	0.000574 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.157 on 285 degrees of freedom

Multiple R-squared: 0.6665, Adjusted R-squared: 0.6618

F-statistic: 142.4 on 4 and 285 DF, p-value: < 2.2e-16

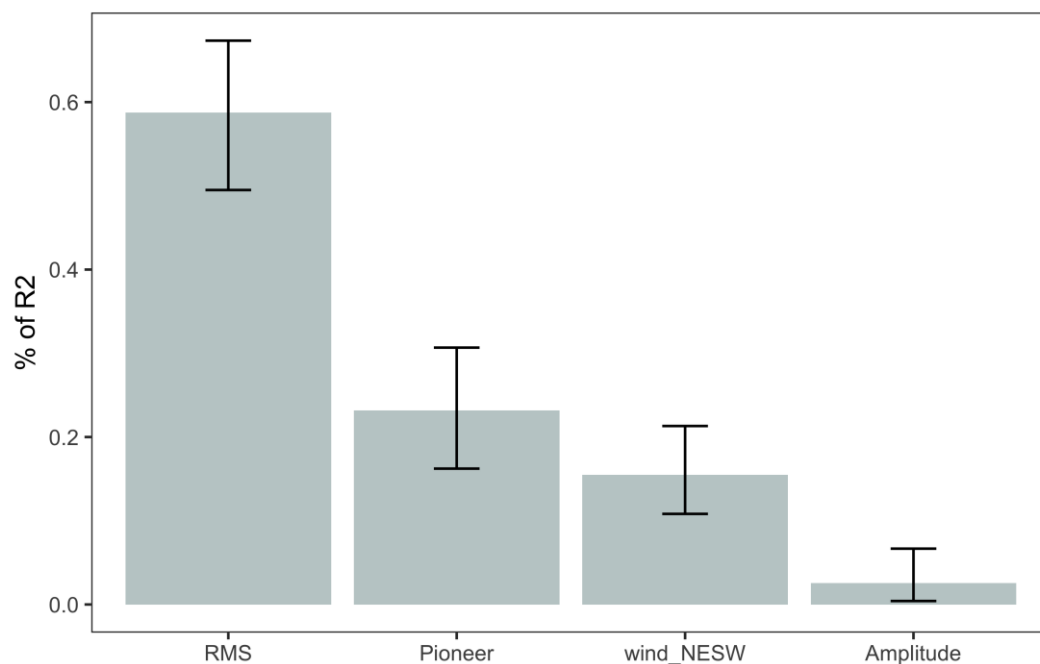


Figure 3.57 Slade Islet bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall $R^2 = 0.66$

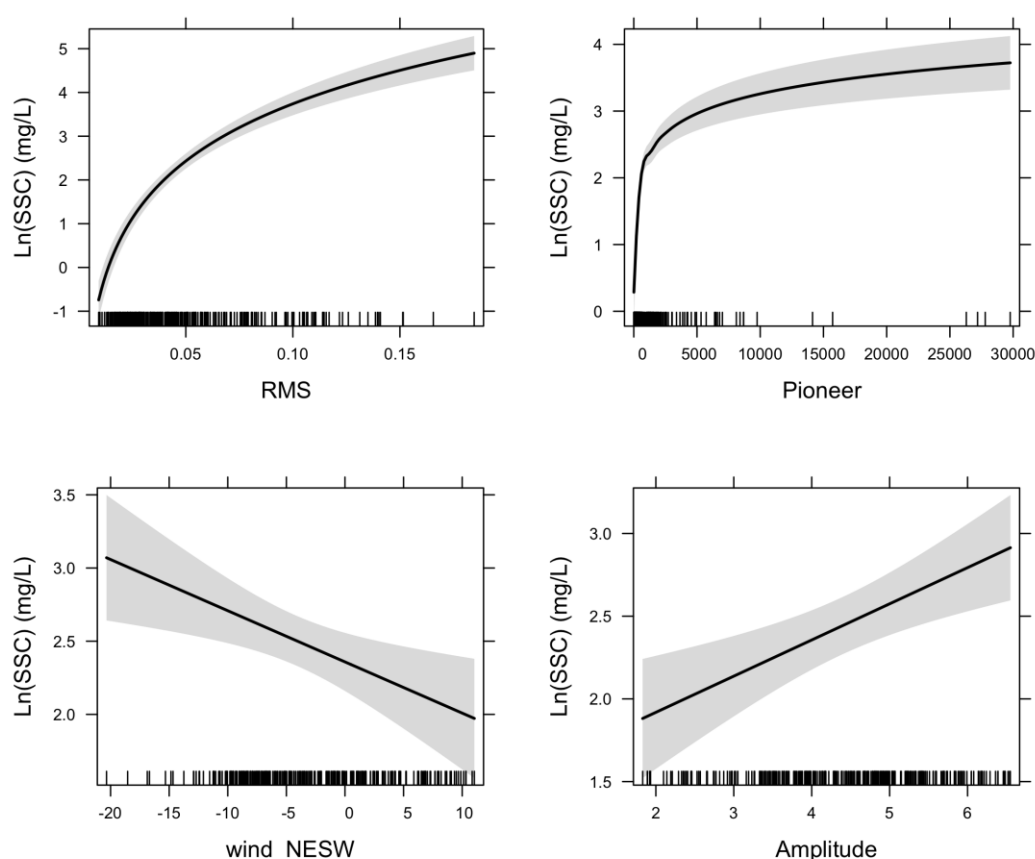


Figure 3.58 Partial effect plots for Slade Islet parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and run on x-axis stand for data density

Victor Islet (AMB 10)

A stepwise regression analysis was run against the Victor Islet data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth, Sandy River discharge, the NESW wind component, and tide amplitude together explained about 54% of the SSC variability (Box 6). The relative importance analysis suggested that RMS of water depth was the most influential parameter on SSC, explaining about 27% of the SSC variability at Victor Islet (Box 6). The remaining variables combined also explained around 27% of SSC variability (Figure 3.59). Results of the partial effects plots (Figure 3.60) followed expected trends for SSC in relation to each environmental parameter selected in the model. Clear patterns in SSC were observed against all the environmental parameters. Overall, an increase in SSC was observed with increases in the environmental predictors, except for the NESW wind component. Strong winds from the west (i.e. negative values for wind_NESW) were associated with high SSC. This contrasts results from previous monitoring periods, where stronger the winds coming from the east were related to higher SSC readings.

Box 6: Statistical summary of the stepwise regression analysis to Victor Islet data

Coefficients	Estimate	Std. Error	t value	Pr (> t)
(Intercept)	3.109535	0.383018	8.119	1.00e-14 ***
Log (RMS)	0.776482	0.065156	11.917	< 2e-16 ***
Log (Sandy + 1)	0.208371	0.029466	7.072	9.53e-12 ***
wind_NESW	-0.053405	0.007208	-7.409	1.12e-12 ***
Amplitude	0.240611	0.046461	5.179	3.94e-07 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.9055 on 323 degrees of freedom

Multiple R-squared: 0.5394, Adjusted R-squared: 0.5337

F-statistic: 94.58 on 4 and 323 DF, p-value: < 2.2e-16

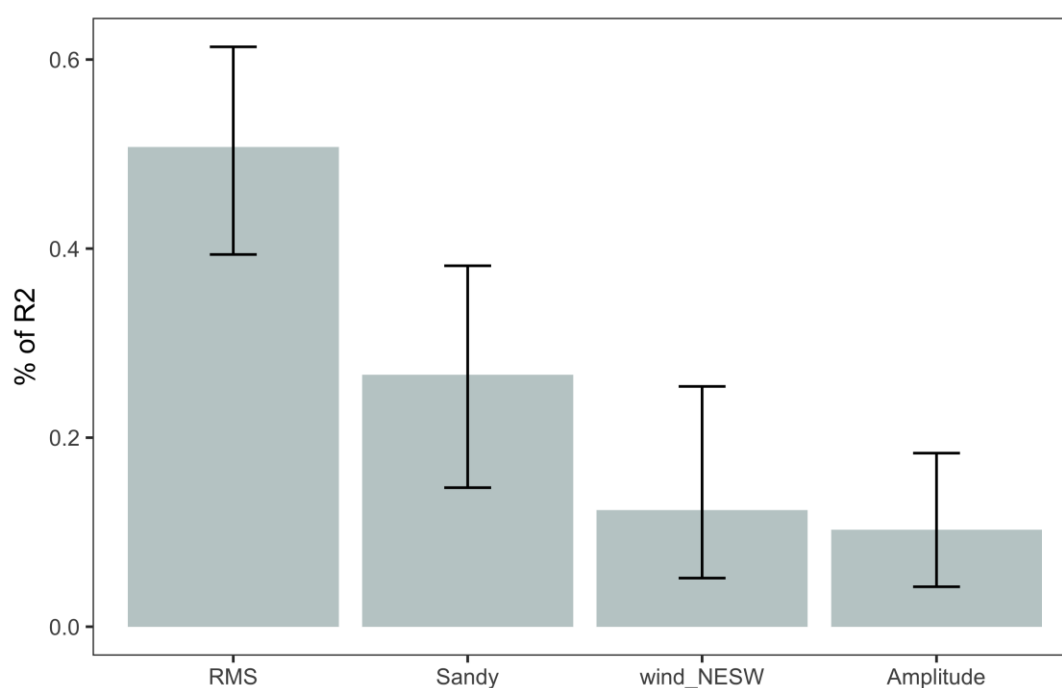


Figure 3.59 Victor Islet (AMB 10) bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r^2 values are normalized to sum 100%. Overall $R^2 = 0.54$

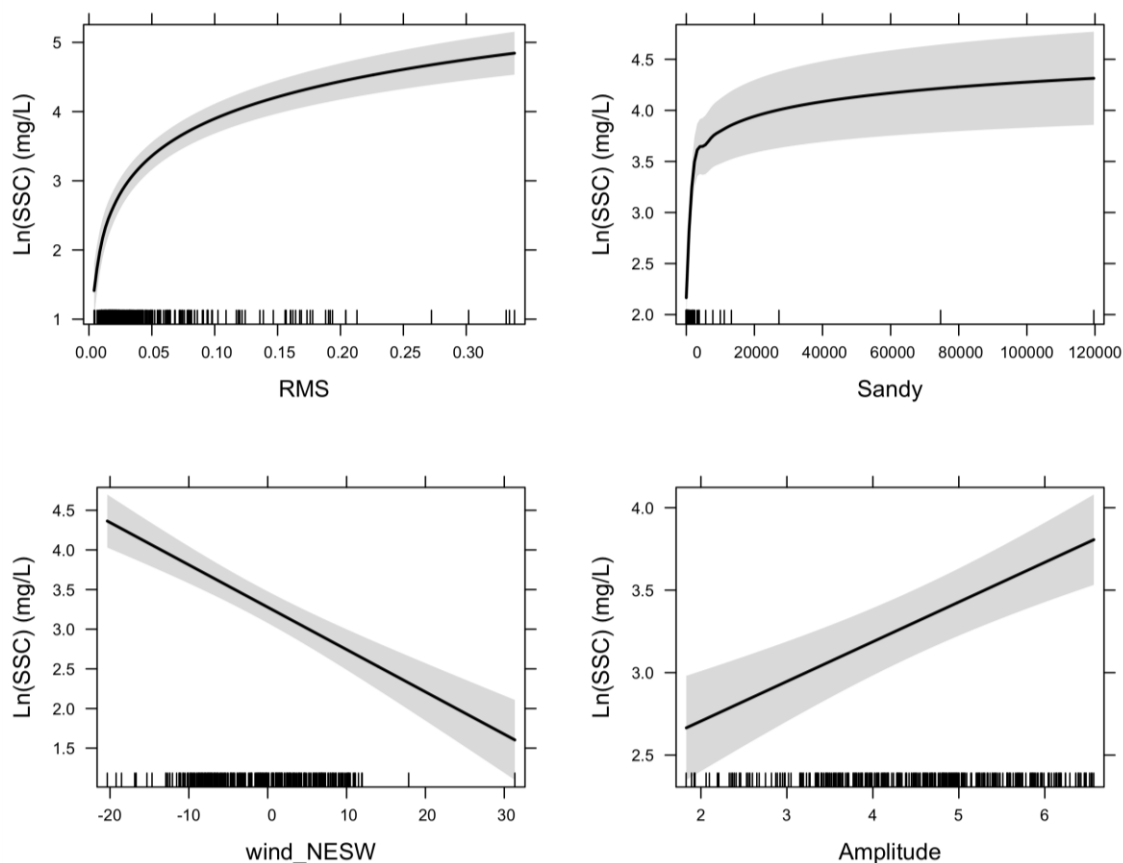


Figure 3.60 Partial effect plots for Victor Islet parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and run on x-axis stand for data density

Relocation ground (AMB 8)

A stepwise regression analysis was run against the Relocation ground data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth, Pioneer River discharge, and tide amplitude together explained about 27% of the SSC variability (Box 7). The relative importance analysis suggested that Pioneer River discharge and RMS of water depth were the most influential parameter on SSC, each explaining about 11% of the SSC variability at Relocation ground (Box 7). Tide amplitude explained around 3% of SSC variability (Figure 3.61). Results of the partial effects plots (Figure 3.62) followed expected trends for SSC in relation to each environmental parameter selected in the model. Clear patterns in SSC were observed against all the environmental parameters, with an overall increase in SSC with increases in the environmental predictors (Figure 3.62).

Box 7: Statistical summary of the stepwise regression analysis to Relocation ground data

Coefficients	Estimate	Std. Error	t value	Pr (> t)
(Intercept)	1.50667	0.69173	2.178	0.0302 *
Log (RMS)	0.67213	0.12005	5.599	5.18e-08 ***
Log (Pioneer + 1)	0.29681	0.05026	5.906	1.02e-08 ***
Amplitude	0.23785	0.06753	3.522	0.0005 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.211 on 278 degrees of freedom

Multiple R-squared: 0.2741, Adjusted R-squared: 0.2662

F-statistic: 34.99 on 3 and 278 DF, p-value: < 2.2e-16

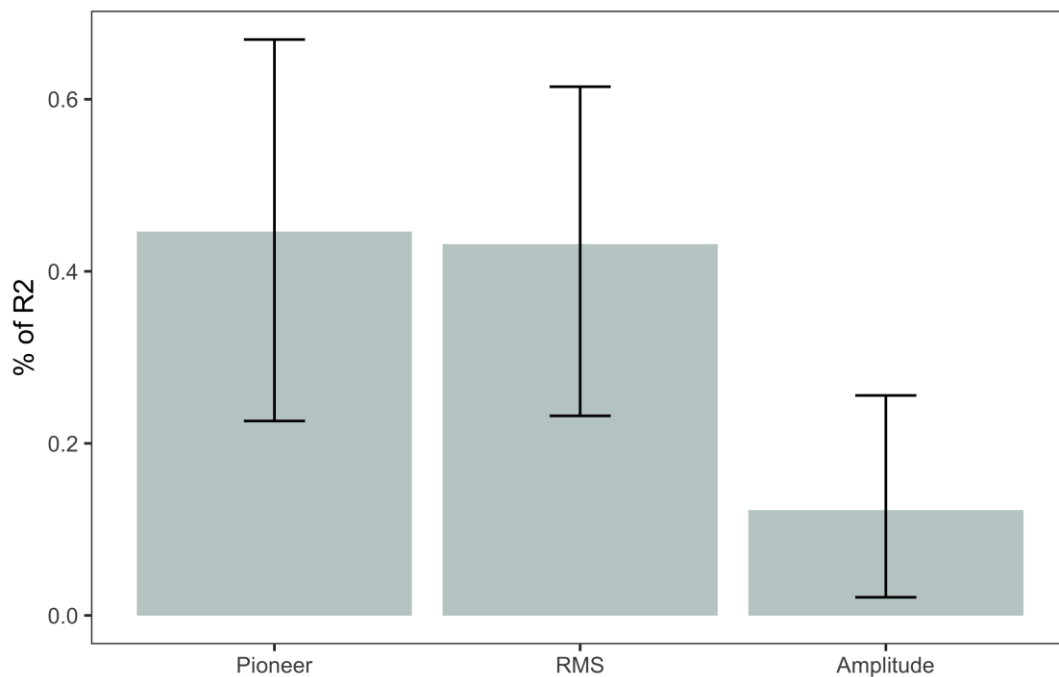


Figure 3.61 Relocation ground (AMB 8) bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall $R^2 = 0.27$

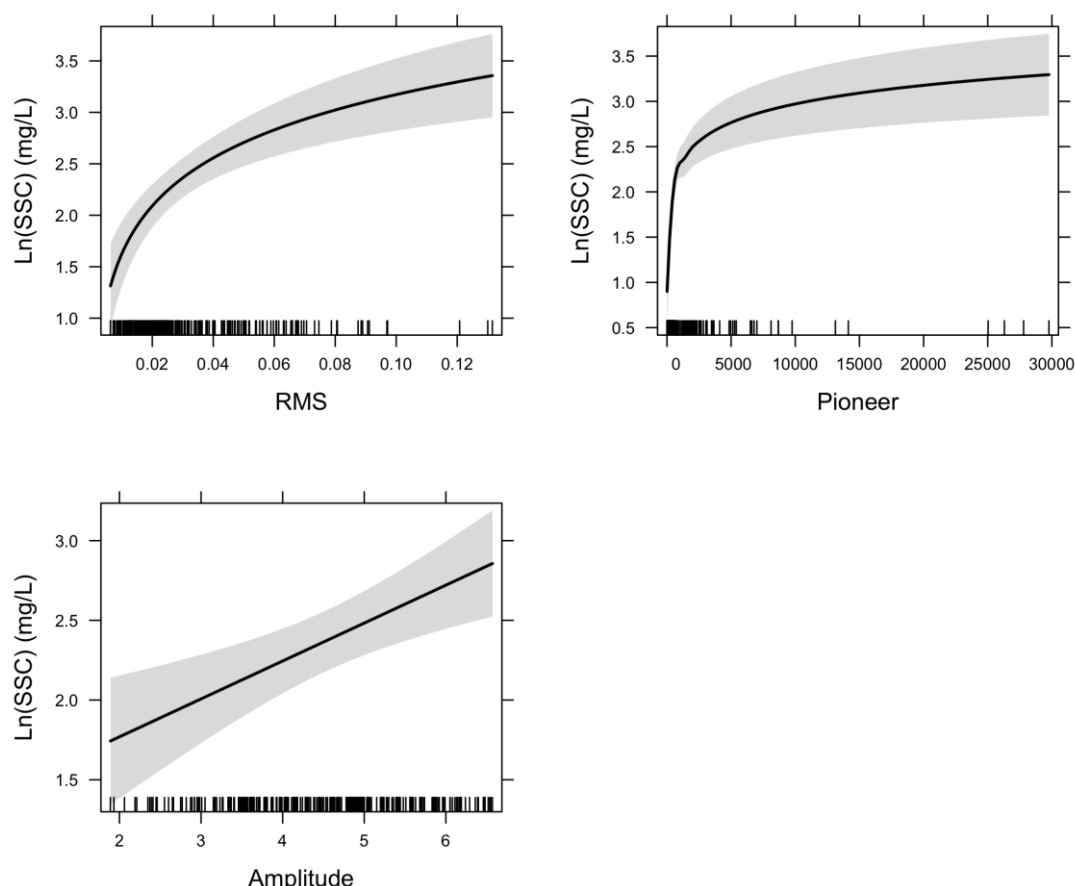


Figure 3.62 Partial effect plots for the Relocation grounds parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

4.1.1 Climatic conditions

- An important factor to consider in interpreting data during this year of monitoring is that the 2016/17 wet season was in the order of the 90 %ile for the Mackay and Hay Point region. The contribution of river plume discharge that occurs each wet season to nutrient, sediment and contaminant loads in the coastal zone in the GBR, and the recovery back to pre-flooding conditions, has not been appropriately experienced here.
- In the years prior to commencement of the ambient marine monitoring program, rainfall in the Mackay region was lower. In fact, the 2014/15 wet season was in the lower 5 percentile of the distribution of rainfall over the past 115 years. This high inter-annual variability shows in order to adequately characterise conditions a number of years of continuous data is required before any statistical rigor can be given to the information presented.
- Comparison of these data with future years will be important to characterise ambient water quality conditions, particularly should the program experience above average rainfall in the future.

- The wind speed and direction recorded at Mackay airport during the study period has been a useful inclusion in this assessment. The daily average wind speed and direction recorded at Mackay airport for the reporting period (2016/17) was predominantly from the south east and south west, with more than 45% of the days reaching more than 24km/hr, which is higher than previous years.

4.1.2 Ambient water quality

- There continues to be a strong seasonal pattern for water temperature, with highest temperatures experienced during summer months, while winter months experience much cooler conditions. The amplitude in water temperature across the region between winter and summer is almost 10°C, with typically less than 2°C difference through the water column.
- The water column profile for dissolved oxygen, temperature, electrical conductivity and pH continue to be well mixed. The exception continues to be turbidity which is generally higher at bottom horizon, contributing to a distinct separation of water horizons in the multivariate statistics. This pattern for turbidity is probably related to the bottom horizon proximal to the sea floor and the remobilisation of sediments.
- Particulate nitrogen and phosphorus continue to be elevated above local relevant guidelines. In fact this year recorded some of the highest concentrations (following local rainfall events). The contributing factors to these data results might include some localised signal associated with runoff from land use activities such as farming and urban runoff from centres along the Mackay coastline region. The elevation is a concern for the region and requires ongoing investigation and management in order to identify broader catchment landscape processes. The Mackay/Whitsunday region has been previously identified as a high risk area for nutrient, sediment and herbicides, in light of extensive agricultural activity (Waterhouse et al., 2012).
- Chlorophyll-*a* concentrations continue to exceed local relevant guidelines, particularly when associated with high nutrient concentrations. In fact concentrations were highest in coastal sites, including Dudgeon Reef (AMB 6), and in the Mackay Marina (AMB 11), presumably influenced by local land uses.
- Phytoplankton and zooplankton communities were most similar in their species composition during the dry season (May, July, and September 2017), and there is a weak, but significant, relationship with plankton communities and available nutrients.
- Trace heavy metals continue to be non-detectable across the monitoring period this year. Atrazine, Diuron, and Hexazinone were detected at several coastal sites, particularly during the wet season survey (March 2017).
- Diuron, atrazine and hexazinone were the only herbicides detected across the site network this year. These herbicides are used in agricultural cultivation activities (Lewis et al., 2009). However, the input and influence of wet season flow has been limited, and thus would be reflected in the low to no detection of PS II herbicides in the marine environment. In a higher rainfall year it might be expected to detect herbicides at coastal marine monitoring sites, given the extensive agricultural activities that occur in the region. PSII herbicides have been a continuing concern in the Mackay region (Mitchell et al., 2005), and have been linked to the dieback of mangroves in the region in the 1990's (see Bell and Duke 2005).

- The database for the region continues to expand, with more data generated under various environmental conditions particularly given the increased monitoring frequency for particulate nutrients and chlorophyll-a, there is a possibility to begin to investigate the implications of the measured water quality conditions as part of this program on sensitive receptor habitats and species, such as coral reefs (De'ath and Fabricius, 2010), marine plants (see Coles et al., 2015; McKenna et al., 2015), and also economically important marine fauna (Jones et al., 2000).
- Discussions continue to integrate these data into the Mackay/Whitsunday regional water quality report card, and could assist in developing locally specific water quality objectives (WQOs) to be scheduled in the Environmental Protection Act (Queensland).

4.1.3 Sediment deposition and turbidity

- Continuous sediment deposition and turbidity logging data supports the pattern found more broadly in North Queensland coastal marine environments, that during dry periods with minimal rainfall, elevated turbidity along the coastline is driven by the re-suspension of sediment (Orpin and Ridd 2012), and this has been most notable here given the links drawn between RMS water depth and NTUe/SSC. Large peaks in NTUe/SSC and RMS water depth were recorded over periods longer than a week.
- SSC statistics show that the natural annual mean values at six of the seven monitored sites are frequency above the trigger limit of 2 mg/L.
- Evaluation of the results suggest that trigger limits should be median rather than mean values to provide a more accurate representation of the environment for the monitoring period. (The same could apply to particulate nitrogen and particulate phosphorus).
- It is suggested that the trigger limits need to be revised to reflect the natural variance observed in the inshore coastal environment where higher SSC values are consistently observed at some sites.
- Sediment deposition median site specific trigger limits are also suggested for the monitored coastal sites to provide a more accurate guidelines in the future.
- Cyclone Debbie, a category 4 system, caused widespread wind damage and flooding in Mackay and surrounding areas in March 2017. Increased wave heights and suspended sediment levels were observed in response to this extreme weather event.
- The multivariate predictive NTUe/SSC model has been developed at sites AMB 1, AMB 2, AMB 3, AMB 5, AMB 8, AMB 10 and AMB 12 to forecast natural turbidity levels. The model utilises wave, water depth and tidal components from pressure sensor data as inputs. The continuation of monitoring at these locations will increase the accuracy of these models.
- The model developed here provides a powerful tool for use during port operations, for example, as the differentiation between natural turbidity and port activity related turbidity may be monitored. This means that during a port activity the difference in the measured turbidity compared to that predicted using this model, represents the contribution associated with the activity.
- Current monitoring conducted during this monitoring year has provided further information on the hydrodynamics of the coastal system. These data highlight the natural variability in current speed and direction among sites. Future monitoring of

current in this region will build a more thorough data index that may be used in active dredge monitoring in the future.

4.1.4 Photosynthetically active radiation (PAR)

- As was observed in previous years (2014/2015/2016), PAR patterns were strongly driven by tidal cycles with fortnightly increases in PAR coinciding with neap tides and lower tidal flows. Longer periods of low light conditions are driven by a well-established cascade of physical processes. Strong wind events facilitate increased wave height, the induced orbital wave motion moves downward, toward the sea floor. This is demonstrated most clearly by the decreased PAR values at coastal sites in response to Cyclone Debbie. Shear stresses then cause resuspension of sediment particles from the bed (Orpin and Ridd 2012). The Root Mean Squared (RMS) of water depth, which is a proxy for wave energy was again the major driver of changes in PAR.
- As SSC increases, photons are absorbed and scattered by particulate matter and thus light levels are exponentially attenuated, as is well described by Beer-Lambert's Law (Kirk 1985; Davis-Colley and Smith 2001). Similarities in PAR were stronger between sites situated in closer geographic proximity to each other and also between distant coastal sites that were located in similar environments. It is important to note that due to depth variation at each site, benthic PAR is not directly comparable among sites as a measure of water quality.
- The Keswick Island site appears to have the most stable light environment. These features may be attributed to the site location, which is 26km from the coast and sheltered on the leeward side of Keswick and St Bees Island.
- While turbidity is the main indicator of water quality used in monitoring of dredge activity and benthic light is significantly correlated with suspended solid concentrations (Erftemeijer and Lewis 2006; Erftemeijer et al. 2012), the relationship between these two parameters is not always strong (Sofonia and Unsworth 2010). At most sites where both turbidity and benthic light are measured, the concentration of suspended solids in the water column explained less than half of the variation in PAR. PAR is commonly becoming a useful management tool to examine condition of photosynthetic benthic habitats such as seagrass, algae and corals (e.g. Chartrand et al. 2012). For this reason, it is important to include photosynthetically active radiation (PAR) in the suite of water quality variables when characterising local baseline ambient water quality.
- The PAR monitoring component of the program continues to utilise optimum sampling locations, providing a strong spatial representation contributing to the effective characterisation of local and regional patterns in benthic light around the ports of Hay Point and Mackay.

4.2 Recommendations

4.2.1 Plankton and nutrient concentrations

Inclusion of plankton assemblage and increasing frequency of nutrient monitoring is building an interesting data series for the region. The results this year are preliminary, although provide some data that the region continually experiences elevated nutrient concentrations.

The frequency of this monitoring should remain in place, in order to continue examining the spatial and temporal patterns that are emerging already.

4.2.2 Consolidation of the water quality loggers

During a review of the data performed in the March 2016 progress report, it was recommended that the ambient monitoring program remain into the 2016/17 period. This recommendation should remain in place, until the database covers a greater range of seasonal rainfall conditions.

4.2.3 Data base repository

An electronic version of the ambient marine water quality database is available upon request. It currently comprises MS-Excel Workbooks containing raw data files including results for water chemistry (*in-situ* field measurements, nutrients, filterable metals, pesticides/herbicides) collected as during the quarterly sampling, and all the continuous high frequency logger data files for sediment deposition, PAR, turbidity, water temperature, and RMS recorded during the period July 2014 and July 2017. This data base continues to be maintained by TropWATER personal, with back up copy archived on the James Cook University network with restricted access.

5 LITERATURE SOURCED

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