Port of Mackay and Hay Point Ambient Marine Water Quality Monitoring Program

(July 2015 to July 2016)

Nathan Waltham, James Whinney, Caroline Petus, 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 2015 to July 2016 (building on the July 2014 to July 2015 ambient period). 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, along with satellite imagery to model the effect of river plumes on regional water quality.
3. The initial thirteen site network that made up the 2014/15 monitoring period was reduced to seven sites for the 2015/16 period. 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 2015/16 wet season rainfall across the study was within the 50th percentile of the distribution of total annual wet season rainfall recorded in the region (1910 to 2016). 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 January 2016. 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 95th percentile of historical records.
2. The low rainfall total across the 2015/16 wet season continues to prevent us 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. Conversely, the approximately average rainfall wet season continues to provide us with the opportunity to collect continuous water quality data for the region under a period of minimal catchment flow.
4. During the reporting period, the majority of wind in the Mackay region was from the south east, with more than 35% of days reaching more than 24km/hr.

Water chemistry

1. Field water quality conditions was 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 was highest during the summer months.
3. Water column was well mixed during each survey, with little differences among the three horizons examined. The exception was turbidity which was higher at the bottom horizon, probably due to remobilisation of the sea floor sediments. Secchi

disk to depth ratio (Zeu:Z) ranged between 20 and 100% of the water column at sites, suggesting that optical water clarity on survey days were generally good.

4. Particulate nutrient concentrations exceed relevant guidelines for the region, particularly so during the October and November 2015 surveys. Chlorophyll-*a* concentrations were also regularly elevated above the relevant guideline, particularly so in October and November 2015 – 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 were non-detectable across the monitoring period, a factor probably reflecting the low rainfall. Previously, ultra-trace concentrations of copper detected in Mackay marina where not detect in this reporting period.
6. Atrazine, Diuron, and Hexaninone were detected during the November 2015 (dry season) survey period, but not during the wet season survey (March 2016). Under an average rainfall year, it might be expected to detect other herbicides.
7. An assessment of the plankton community (both phytoplankton and zooplankton) was completed during this reporting period, with samples collected during November 2015 (dry season) and April 2016 (wet season). There were a clear separation in the plankton community between surveys, suggesting seasonal variation. Interestingly, sites supported generally similar species richness during winter survey, compared to wet season survey where sites were more spatially separated in the multivariate ordination.

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. 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, and will increase in accuracy following the 2015/16 logging period.

5. 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.
6. 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.
7. There was a small difference in RMS water height, SSC, deposition, PAR and water temperature between the dry and wet season. A similar distribution in results between these seasons is probably related to the failed wet season for the region.

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 was not as intimately linked with many of the episodic weather events that seemed to influence the sits adjacent to the Mackay coastline.
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.

River Plumes

1. The analysis here builds on results for the previous monitoring period and aimed to further test the potential of MODIS satellite data: (i) as a proxy for suspended solids concentration (SSC) in turbid coastal waters of Hay Point and the Port of Mackay; (ii) to provide historical time series of the natural variation in water turbidity; and (iii) to map the turbid waters associated with high flow conditions or resuspension events.
2. Time series MODIS remote sensing reflectance Rrs(B1)(hereafter MODIS turbidity proxy) were constructed at each in-situ sites locations. The MODIS turbidity proxy and *in-situ* SCC data were matched up to test agreements between the satellite data and *in-situ* water turbidity measurements on seafloor.
3. The time series of MODIS turbidity proxy followed a similar pattern to that of the *in-situ* SSC, with low background values and recurring peak events; except at Dudgeon reef site where the proxy values were noisy and generated a week trend.
4. Correlations between the daily MODIS turbidity proxy and the mean in-situ SSC (between 11 am and 3 pm) were, on average, weak (average R^2 of 0.15) at the monitored sites. These results were similar to last year (average R^2 of 0.11).
5. Correlations with the mean weekly satellite and in-situ values were stronger (average R^2 of 0.29), with the exception of the Slade Islet monitoring sites (R^2 = 0.08). The stronger correlations were observed at the Freshwater Point (R^2 = 0.44) and Round Top Island monitoring sites (R^2 = 0.43); similarly to last year results.
6. The use of remote sensing can be problematic in the nearshore coastal environment due to the influences of shallow, optically complex waters and the reduction in the number of images retrieved due to cloud cover to allow an adequate representation of conditions in this shallow environment. Another important factor to consider in interpreting the satellite data is that the relatively dry wet season limited the turbidity of the water and, thus, the ability of the satellite data to characterise turbidity levels due to increased atmospheric and bottom perturbations. Furthermore, loggers record bottom turbidity while MODIS record surface turbidity and disparities between the satellite and in-situ data are thus expected. These were likely to be important contributing factors to the low average predictability during the 2014/15 and 2015/16 periods.
7. The MODIS data time series were, however, able to reproduce the increase in in-situ SSC observed at Hay Point Reef, Round Top Island and Freshwater Point around November 2015, as well as the increase in in-situ SSC observed in response to higher river flow conditions in February and March 2016. The MODIS turbidity proxy was also effective in mapping increased level of turbidity associated with smaller river discharge rates; such as recorded in April 2016.
8. The use of MODIS true colour imagery and higher resolution satellite images (Landsat, 30 m resolution) of the coastal environment allowed distinguishing

the boundaries of coastal turbid waters (river plumes and resuspension), with finer details on the small-scale transport processes obtained using the higher resolutions images. Under a scenario of tracking the plume associated with a dredging campaign, analyses would be improved by using a combination of MODIS and high resolution satellite images.

9. Whilst there are limitations, the satellite images still provides a useful tool for monitoring increased turbidity conditions around the coastal sites and, thus important information that can be used in conjunction with high frequency in-situ data to monitor potential impacts associated with port development.

Recommendations

1. Refinements made to the ambient water quality program in the 2014/15 report were implemented in the program during this monitoring period. 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 2016/17 period, in order to (hopefully) capture a wet season period, where catchment runoff contributes to more typical water quality conditions in the region. This would effectively assist in characterising the upper water quality conditions for the region. Additional program refinements might be further possible with data collected during a higher rainfall year.
2. Plankton assemblage sampling should continue. The data at this stage are preliminary, but are beginning to illustrate some interesting data, 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.
3. Increasing the frequency of water logger maintenance to 6wks has been effectively in reducing redundant data. This maintenance schedule should remain in order to ensure high return on data.
4. River plume modelling using MODIS has produced a weak relationship this reporting period again. Given the nature of this methodology, it is suggested that the modelling be placed on hold until a typical wet season year is experienced, where the MODIS modelling could be completed retrospectively.

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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.

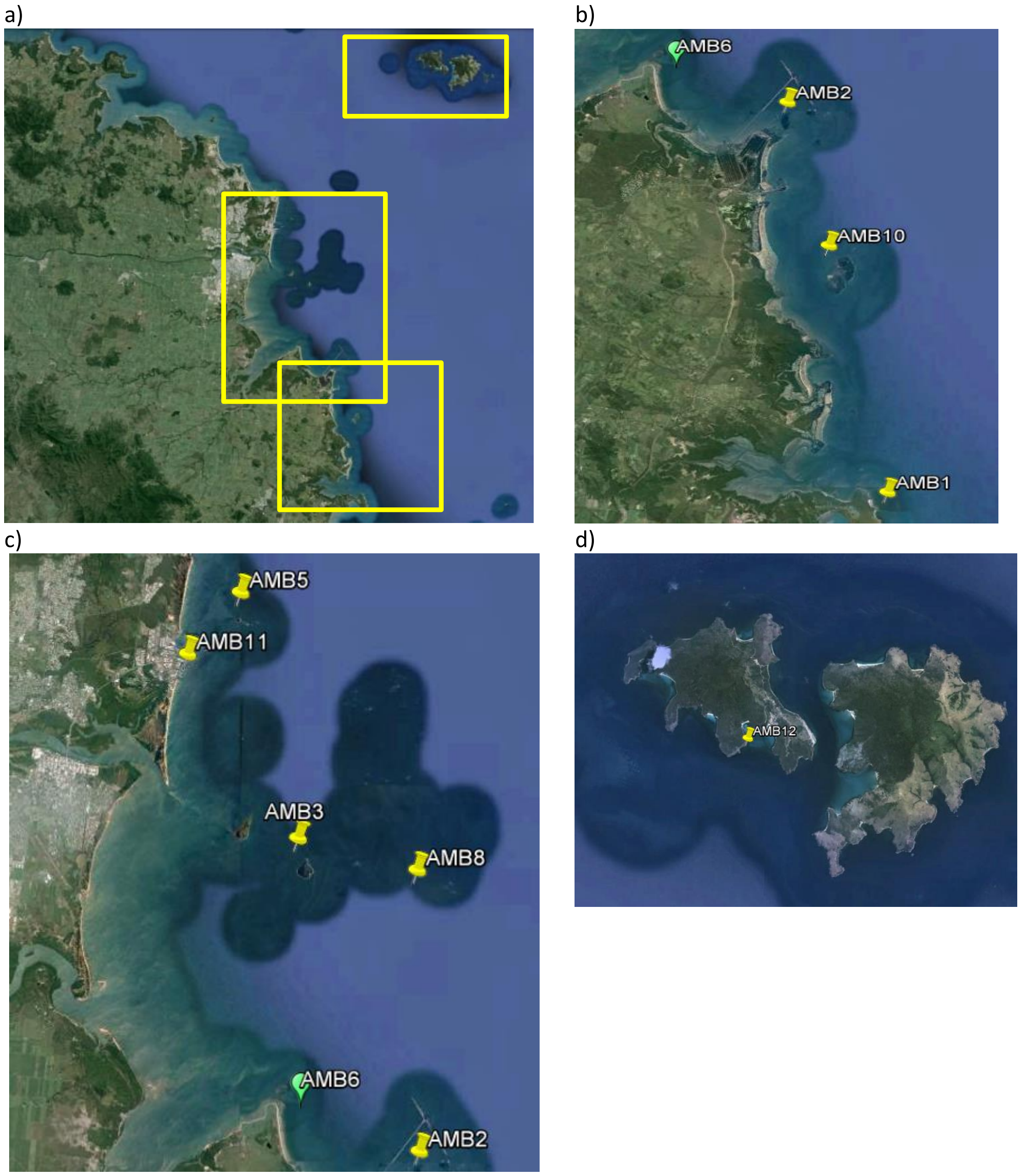


Figure 1.1 Locations of the marine water quality monitoring program sites during 2015/16 program. AMB6 is PAR logger only

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

The total wet season rainfall for the 2015/16 period (1536mm) was proximal to the long term average (1910 – 2016; 1512mm wet season rainfall total) for this rainfall station (Figure 1.2). While proximal to an average year rainfall, 73% of the total rainfall in fact was recorded during January and March 2016. These rainfall events generated some catchment flow (Figure 1.3), however, as short pulses. Overall, the 2015/16 wet seasons has continued to reduce our ability to characterise the upper range in marine water quality conditions. Data therefore in this report needs to be considered in this context.

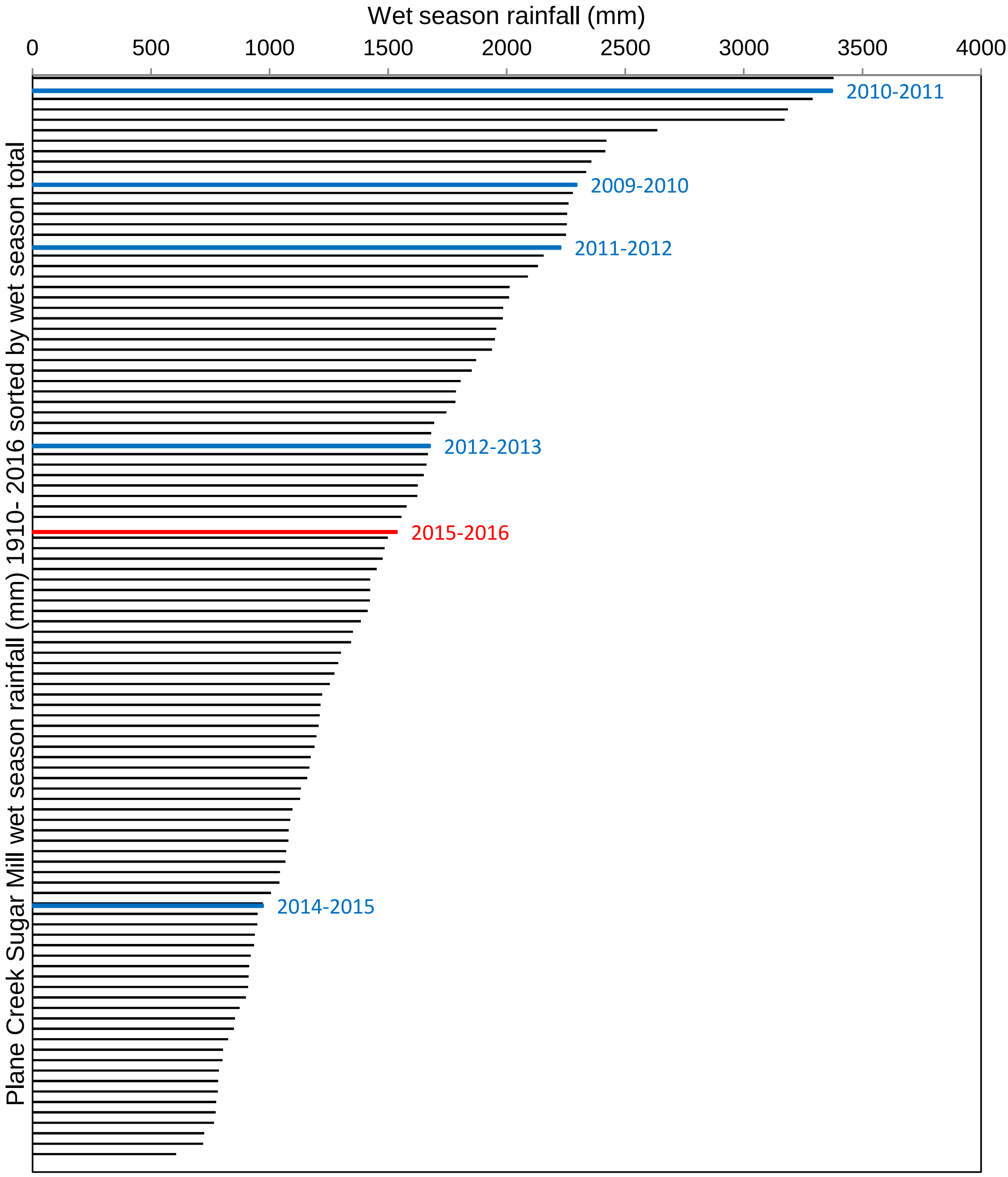


Figure 1.2 BOM wet season (November – February) rainfall data for Plane Creek Sugar Mill (station number: 33059) for years 1910 to 2015 ranked in order of decreasing total rainfall (mm). Blue bars show total rainfall over the past few years, red bar represents the 2015/16 ambient marine water quality monitoring period

Low rainfall during the monitoring period contributed to a relatively short hydrograph of flow in most river systems that drain to the Mackay coast. The example hydrograph for Pioneer River (Figure 1.3) shows a short peak in river flow in early 2016, with the tail of the hydrograph returning to pre-flow levels again with a week. 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.

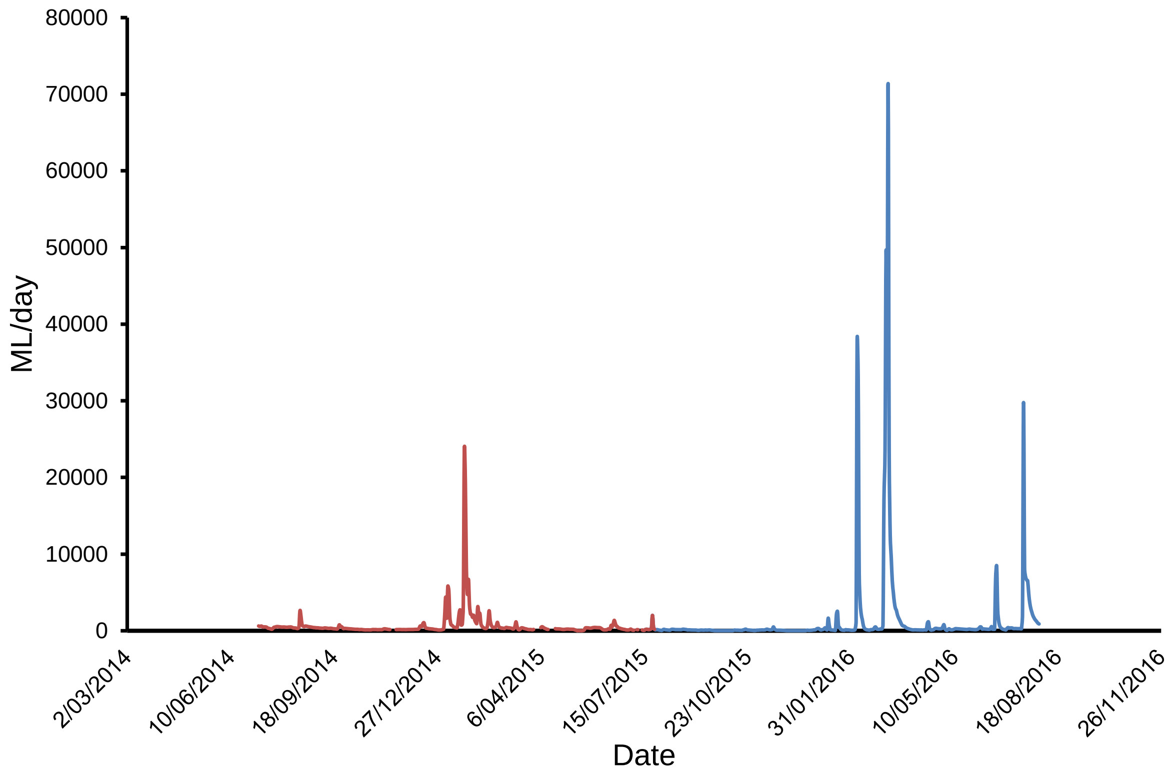


Figure 1.3 Flow recorded for Pioneer River. Red line is 2014/15 (July to July) period and blue 2015/16 (July to July) period

1.4 Wind for Mackay airport

The daily average wind speed and direction recorded at Mackay airport for the reporting period is predominantly from the south east, with more than 35% of the days reaching more than 24km/hr (Figure 1.4). There were occasions where wind came from north east and north-west direction, approaching speeds of 18km/hr, and also from a south direction, about 15% of the days during this reporting period. This wind pattern is similar to conditions experienced during the 2014/15 reporting period (Waltham et al. 2015).

In contrast to the 2014/15 monitoring period where tropical cyclone Marcia travelled close to the study area, crossing the coast to the south of Sarina in February 2015, there were no similar large weather systems crossing the Mackay coast during the 2015/16 monitoring period.

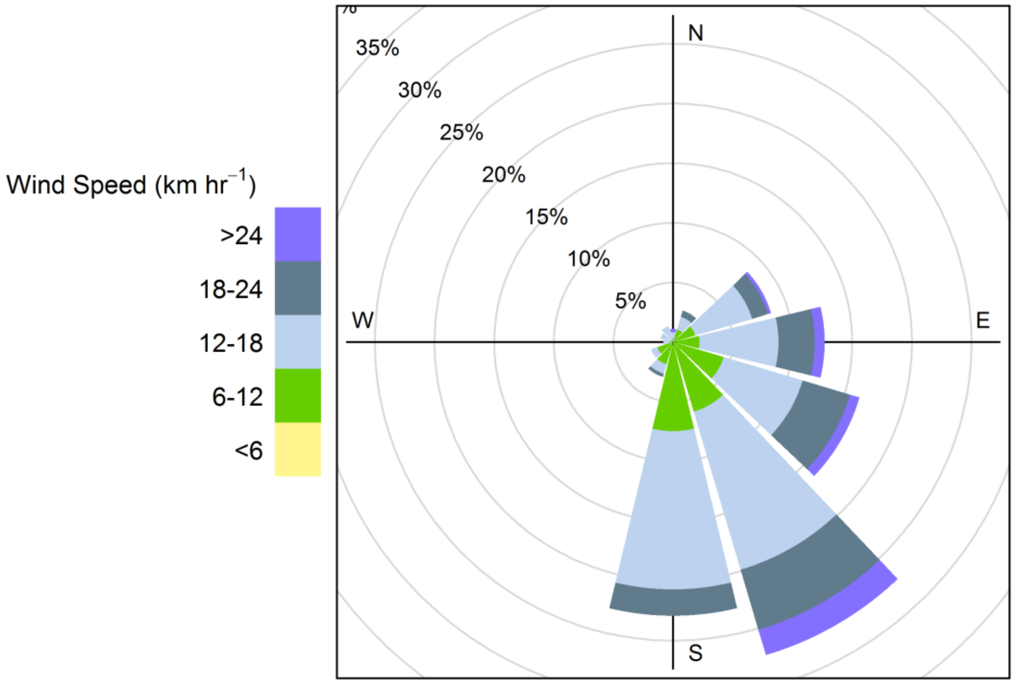


Figure 1.4 Daily average (July 2015 to July 2016) wind direction and strength recorded in Mackay airport for the survey period

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 second year of monitoring (July 2015 to July 2016). 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 to 2015 monitoring period.

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: chlorphyrifos, diazinon, malathion, pirimiphos-methyl, sulfotep, thiobencarb, diuron, ametryn, atrazine, cyanazine, prometryn propazine, simazine, terbuthylazine, 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 2015/16 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	Yes	
April 2016	Yes			Yes
May 2016	Yes			Yes
June 2016	Yes			Yes
July 2016	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		
Organophosphate pesticides	In house LC/MS method: EP234A	0.0002-0.001 µg/L
Thiocarbamates and Carbamates	In house LC/MS method: EP234B	0.0002 µg/L
Thiobencarb		
Dinitroanilines	In house LC/MS method: EP234C	0.001 µg/L
Pendimethalin		
Triazinone Herbicides	In house LC/MS method: EP234D	0.0002 µg/L
Hexazinone		
Conazole and Aminopyrimidine Fungicides Propiconazole, Hexaconazole, Difenoconazole, Flusilazole, Penconazole	In house LC/MS method: EP234E	0.0002 µg/L
Phenylurea Thizdiazolurea Uracil and Sulfonylurea Herbicides	In house LC/MS method: EP234F	0.0002 µg/L
Diuron, Ametryn, Atrazine, Cyanazine, Prometryn, Propazine, Simazine, Terbuthylazine, 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 the November 2015 (dry season) and March 2016 (wet season) surveys. 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.

a) b) c)

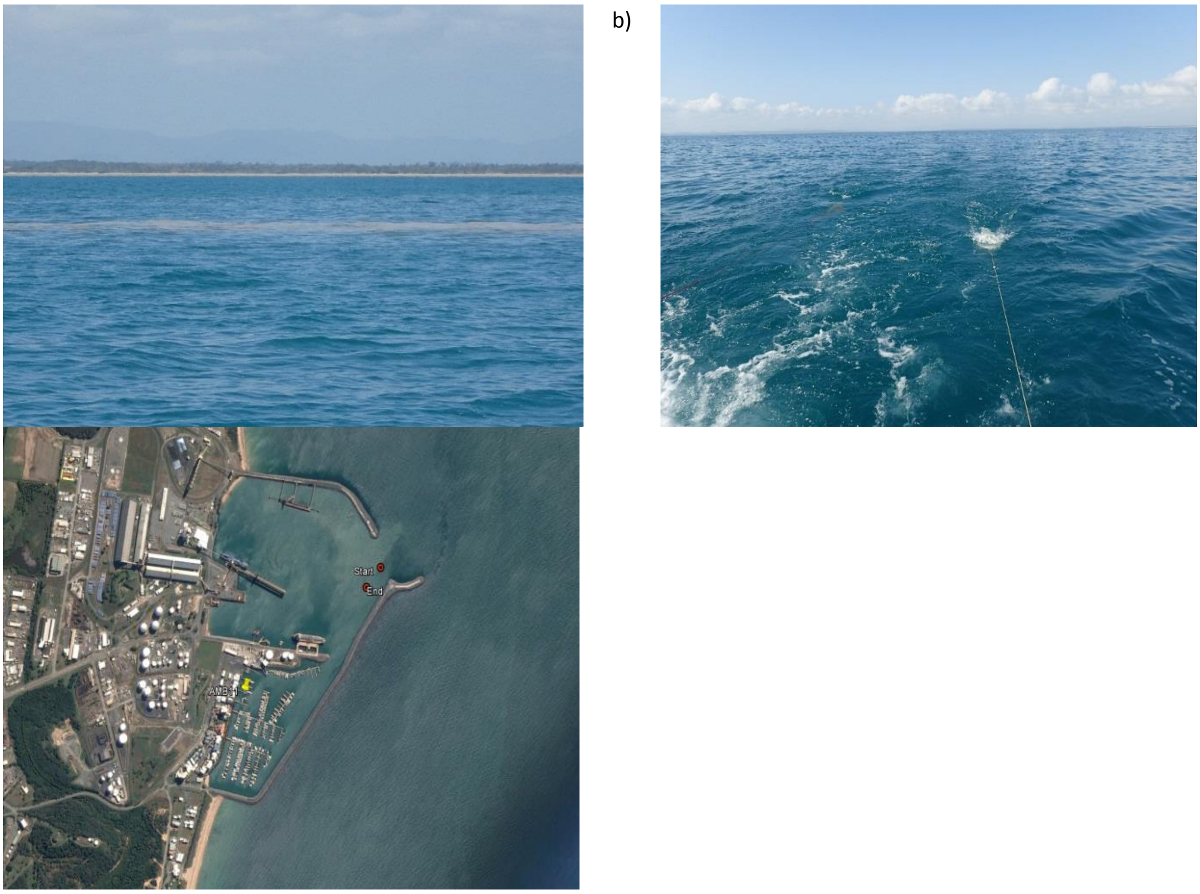


Figure 2.2 Plankton sample during November 2015 survey. a) Trichodesmium bloom on sea surface; b) phytoplankton (60µm) tow behind the survey vessel; and c) AMB 11 (Mackay Harbour) yellow dot ambient marine water quality site, black dots start and end of plankton tow

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/cm^2). 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/cm^2 and as a deposition rate in $mg/cm^2/day$. 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:

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

Equation 1 : where Dn is the *n*th of the 10 readings and $\overline{D}$ 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.

a)

b)

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.

a)

b)

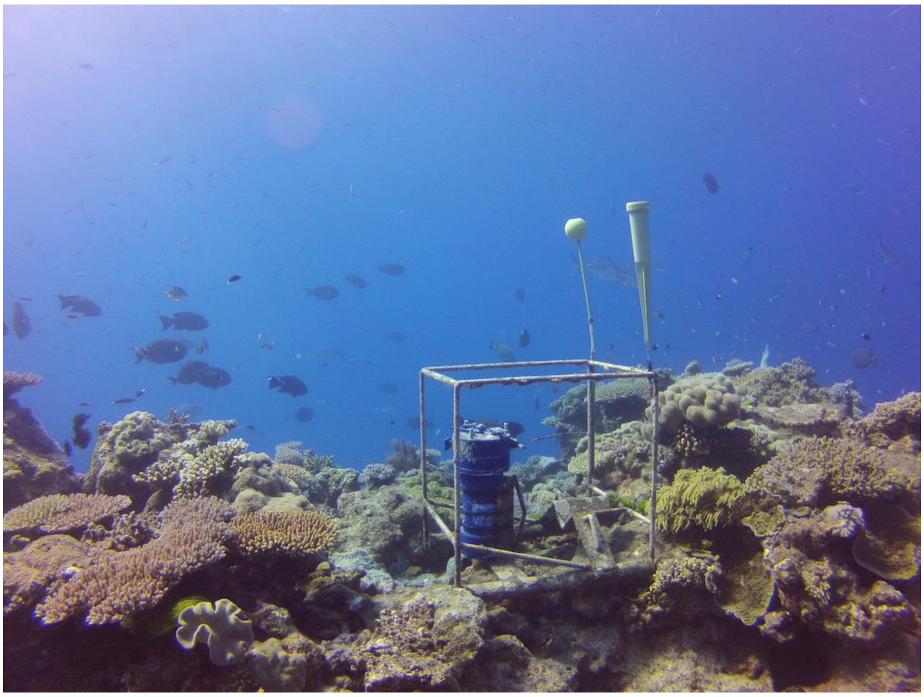


Figure 2.4 a) Basic schematic of Marotte HS current meter; and b) Marotte HS alongside Marotte at Moore Reef. Image courtesy of Eric Fisher

2.4 Measuring river plumes using satellite imagery

In measuring the influence of river plumes, the first task was to investigate the environmental controls on SSC at the ambient sites. This was undertaken by using stepwise regression analysis, 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).

Remote sensing analyses are conducted as part of the port of Mackay and Hay Point Ambient marine water quality monitoring program. The aim of these analyses is to provide historical baseline of the natural variation in water turbidity in the coastal water of the Port of Mackay and Hay Point. This baseline will be used in future to better define the potential impacts associated with port development, within the context of overall water quality conditions in the region. The remote sensing analyses use Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery to monitor surface turbidity. MODIS imagery is a free distributed satellite data with acceptable spatial resolution (250 m) and sufficient revisit times (at least once a day) available for monitoring coastal turbidity levels regularly over multi-annual time periods. Radiance or reflectance values measured at 250 m resolution in MODIS-Aqua Band-1 (645 nm) have been successfully used as qualitative proxy for SSC (e.g., Doxaran et al., 2009; Lahet and Stramski 2010; Petus et al., 2010; Ondrusek et al., 2012) or integrated in empirical regression algorithms to quantify the SSC (mg/L) or the turbidity levels (NTU) in marine waters (Miller and McKee 2004; Petus et al., 2010; 2014). For this study, it was decided to use the remote sensing reflectance values measured in MODIS-Aqua Band-1 at 645 nm (Rrs(645), in sr^{-1}, 250 m resolution) as a proxy for suspended solids concentration in Hay Point and Mackay coastal waters (hereafter, **"*MODIS turbidity proxy*").** MODIS true color imagery are also used to illustrate the sources and dispersion of turbid water in the study area.

The main objectives of the remote sensing part of the project were to:

- Test the potential of MODIS Rrs(645) data as a proxy for suspended solids concentration in turbid coastal waters;
- Test the potential of the MODIS turbidity proxy to provide historical time series of the natural variation in water turbidity in coastal waters of Mackay and Hay Point;
- Monitor temporal patterns of the MODIS turbidity proxy in relation to environmental (river discharges, tidal amplitude and wind) and anthropogenic (dredging) forcers.

2.4.1 Results for the previous monitoring periods

An historical satellite database (January 2009 to June 2014) has been created and Generalized Additive Mixed Models (GAMMs) were used to determine if the variations in the MODIS turbidity proxy could be predicted by the local river discharge, tide and wind measured in the study area (Table 2.3a and Table 2.4).

Table 2.3 Work objectives and results for the previous monitoring periods (see Waltham et al. 2015)

Dataset name	Dates	Analyses	Objective	Results
MONITORING PROGRAM: NOV 2014				
a) Historical	January 2009 to June 2014	Statistical analyses of MODIS Rrs(B1) and environmental data	Test if we can predict variations in daily Rrs(645) (for suspended solids concentration) data based on local river discharge, tide and wind and, thus provide an historical baseline again which eventually assess changes in turbidity associated with the dredging.	More than 70% the temporal variability observed in the remotely-sensed turbidity (determined as Rrs(645) readings) was not explained by the selected environmental vari*a*bles. **Conclusions: test with *in-situ* data and Match up analyses (see below)**
MONITORING PROGRAM: JULY 2014 TO JULY 2015				
b) Ambient (*in-situ*)	July 2014 to July 2015	Statistical analyses of *in-situ* SSC and environmental data	Test similar statistical analysis on *in-situ* SSC data (instead of the satellite Rrs(645)) to test the potential of the selected suite of environmental variables to drive turbidity in the study area	Proposed models to relate *in-situ* SSC with environmental variables were able to explain 49 % of the SSC variability at the six monitored sites (Freshwater Point, Hay Point Reef, Keswick Island, Round Top Island, Slade Islet and Victor Islet). **Conclusion: The low river influence on SSC is probably the result of the dry period experienced in the 2014/15 wet season**
c) Ambient (sat)	July 2014 to July 2015	Match-up analyses of MODIS Rrs(B1) and *in-situ* turbidity data from the ambient marine monitoring program	Undertake match-ups analyses of MODIS and *in-situ* SCC data from the ambient marine monitoring program to test if the extracted Rrs(645) can be used as proxy for suspended solids concentration in Hay Point and Mackay coastal waters	Correlations between the daily MODIS turbidity proxy and the mean SSC were weak (average R^2 of 0.11) at the six monitored sites. Correlations with the mean weekly values were stronger (average R^2 of 0.29), with the exception of the shallowest sites (Slade Islet, Victor Islet and Kenwick Island: R2 < 0.1). The stronger correlations were observed at the Freshwater Point (R2 = 0.69) and Hay Point reef monitoring sites (R2 = 0.59). **Conclusion: Failed wet season limited the turbidity of the water and, thus, the ability of the satellite data to characterise turbidity levels due to increased atmospheric and bottom perturbations.** **Conclusions: further test with *in-situ* data and match-ups during a high river discharge wet season**

Table 2.4 Description of the satellite and environmental databases

Database	Dates	Parameters	Source	Proxy for
Satellite	January 2009 to August 2015	Daily 250-m MODIS Band-1 (Rrs(645) nm) and Band-2 (Rrs(858) nm) satellite data	Derived from the 250-m surface reflectance land product (MYD09GQ)	turbidity level or SSC concentrations
Environmental	January 2009 to August 2015	Daily River discharges (ML day^{-1}) for the Pioneer and Sandy Rivers	Department of Natural Resources and Mines	suspended sediment loads, as freshwater volume of rivers is strongly correlated to its sediment loads
		Tide (m) measured at the Hay Point tide gauge station	Bureau of Meteorology of the Australian Government.	tidal current velocities
		Wind speed direction and zonal (u component: NESW) and meridional (v component: NWSE) components measured at the Mackay radar station	Bureau of Meteorology of the Australian Government.	wave-induced sediment resuspension.

Finally, the MODIS turbidity proxy and in-situ SCC data were matched up to test the validity of using MODIS Rrs(645) data as proxy for Suspended Solids Concentration in Hay Point and Mackay coastal waters (Table 2.4c). On average, the correlations between the daily MODIS turbidity proxy and the mean SSC were weak (R^2 of 0.11) at the six monitored sites. However, correlations with the mean weekly values were higher (average R^2 of 0.29), with stronger correlations observed at the Freshwater Point and Hay Point reef monitoring sites (R^2 = 0.69 and R^2 = 0.59) and the satellite data were able to reproduce an increase in in-situ SSC observed around late February 2015 at Hay Point Reef (AMB 2), Round Top Island (AMB 5) and Freshwater Point (AMB 1) (Waltham et al. 2015). These results suggested that the failed wet season in 2014-15 limited the turbidity of the water and the ability of the satellite data to characterise turbidity levels, but supported the ability of this monitoring tool during average or above average rainfall years. Further in-situ/satellite matchups were recommended.

2.4.2 Monitoring program: July 2015 to July 2016

Environmental and remote sensing databases

The environmental database was updated from July 2015 to present and contains historical environmental variables that may affect water turbidity in the study area, including the daily River discharge (ML/day) for the Pioneer and Sandy Rivers, tide (m), and wind intensity (windi in km/hr) and direction (windd in degree) data (Table 2.4).

The MODIS satellite database was updated to August 2016, and contains daily MODIS Rrs(645 nm), i.e. the MODIS turbidity proxy values, as well as MODIS Rrs data measured in the Band-2 (Rrs(858)) derived from the MODIS 250-m surface reflectance land product (MYD09GQ). The Rrs(858) data are used to mask the clouds in the study area. Rrs(645) and Rrs(858) were extracted from each daily 250-m MODIS Band-1 and Band-2 imagery at 10 ambient sites locations (Figure 2.5, excluding Keswick Island) from January 2009 to end of August 2016 using ArcMap Spatial Analyst (ESRI, 2010).

Comparison of Rrs(645) data with in-situ measurements

Comparisons were made between the MODIS turbidity proxy and in-situ SCC data. These analyses aimed to test the validity of using MODIS Rrs(645) data as a proxy for turbidity levels in the coastal waters of Mackay and Hay Point. Simple linear correlation analyses were calculated for the data collated over the July 2015 to July 2016 monitoring period using:

- In-situ SSC from the loggers (mean values calculated for daily period between 11am and 3pm) and the daily values of the MODIS turbidity proxy and,
- In-situ SSC and MODIS turbidity proxy values averaged per week.

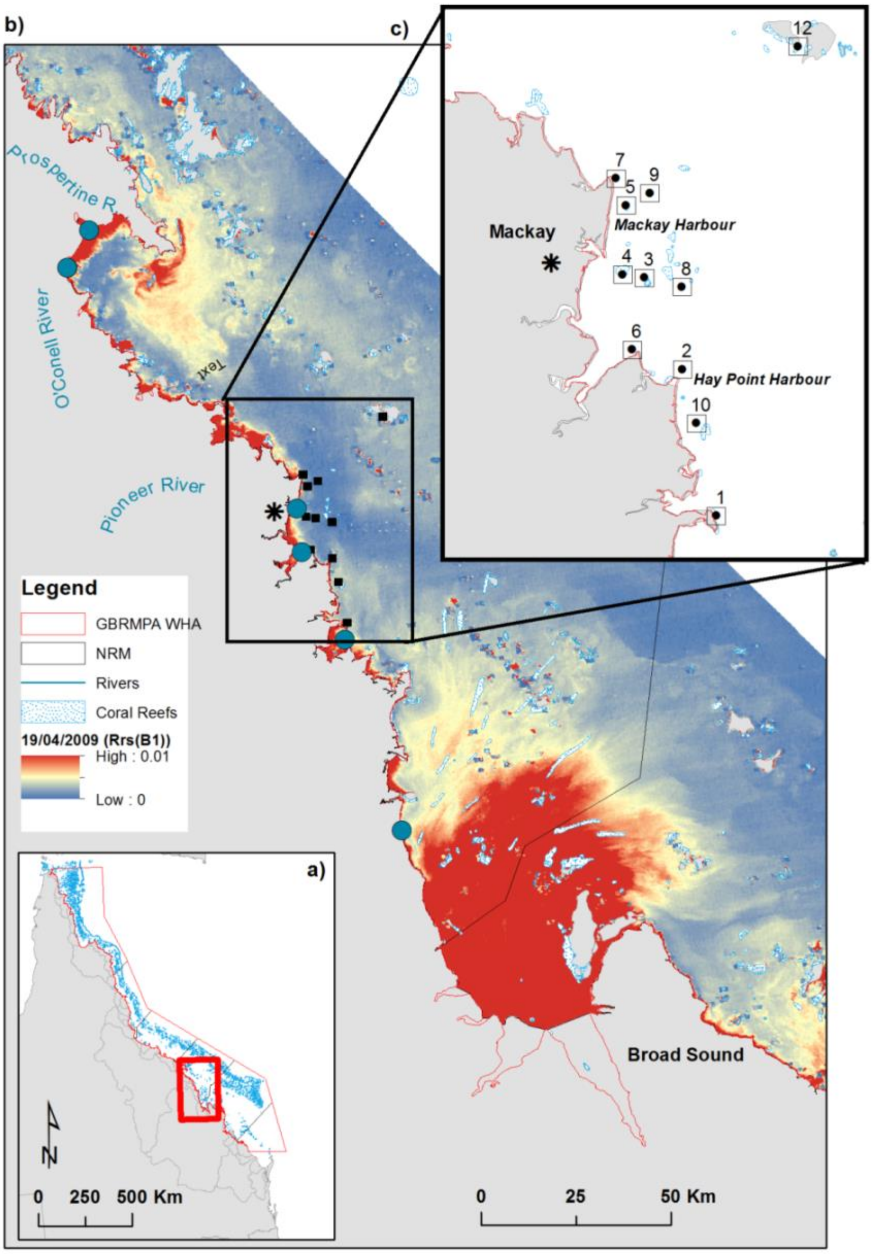


Figure 2.5 a) study area; b) example of MODIS data: Rrs(645) measured the 19 April 2009; and c) locations of ambient *in-situ* monitoring sites

Clouds were masked by assigning "No Data" to every pixel with a reflectance ratio (Rrs(858)max/Rrs(645)max) > 0.8 and < 1.2. Clouds are more reflective than turbid areas in the infrared wavelengths and this test makes use of the fact that the spectral reflectance at the 858 and 645 wavelengths must be similar over thick white clouds (ratio near 1), but different over water masses (Ackerman et al., 2006). Negative values and outliers (± 3 z-score) of the Rrs(645) time series corresponding to residual atmospheric or cloud perturbations at pixel level were removed. Final Rrs(645) time series were created by selecting all days that were not-affected by clouds.

2.4.3 Comparison of Rrs(645) data with in-situ measurements

Comparison of Rrs(645) data with *in-situ* SSC measurements collected from the ambient field survey were undertaken. These analyses aimed to test the capability of using MODIS Rrs(645) data as a proxy for turbidity levels in the coastal waters of Mackay and Hay Point (Table 2.3). Data collected between July 2015 and July 2016 were used to carry and match-up analyses between:

- *In-situ* SSC from loggers (mean values calculated for daily period between 11am and 3pm) and the daily Rrs(645) (satellite proxy for the turbidity levels); and
- *In-situ* SSC and Rrs(645) values averaged per week.

3 RESULTS AND DISCUSSION

3.1 Ambient water quality

3.1.1 Spot water quality physico-chemical

For the reporting period between July 2015 and July 2016, water temperature ranged between 20 and 30^{o}C (Figure 3.1). There continues to be a strong seasonal effect on water temperatures in the region, with the highest water temperatures (consistently through the water column indicating that the water column profile is not stratified and therefore well mixed) observed during surveys in the summer months (October, November, December), and cool water temperatures (consistently through the water column) observed during the winter months (July, August and September). 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). EC has remained between 51 mS/cm and 57 mS/cm, generally indicating oceanic conditions. The slight exception to this was during the July 2016 survey where all sites were slightly lower, ranging between 51 mS/cm and 55 mS/cm. These conditions are a reflection of the rainfall patterns that occurred again this 12mth period across the region.

Dissolved oxygen saturation levels ranged between 81 to 111% (Figure 3.3). There was some local variability among sites, with the lowest levels recorded at AMB 11 (Mackay Marina), particular 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 (Figure 3.4), with the exception of samples collected in April 2016 which were markedly lower, but still within expected range for marine waters (ANZECC, 2000). There seems to be a seasonal pattern in pH with summer a lower pH during summer months and slightly higher (more alkaline) in winter months (Figure 3.4a). This seasonal pattern seems to be consistent through the water column (Figure 3.4b).

Field turbidity measurements ranged between <1 to 53 NTU (Figure 3.5). There was an apparent pattern of increased turbidity with depth, with highest values occurring, a pattern observed during the July 2014 and July 2015 reporting period. Highest turbidity values were recorded at AMB 11 (Mackay Marina), particularly at the bottom horizon (Figure 3.5b). These higher values are probably a function of the increased boating activity in the marina.

Secchi disk depth (m) is a vertical measure of the optical clarity of water column and ranged between 1 and 13m (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 ration ranged between 10 and 100% of the water column, which means that water clarity ranged between 10% of the water through to the entire water column.

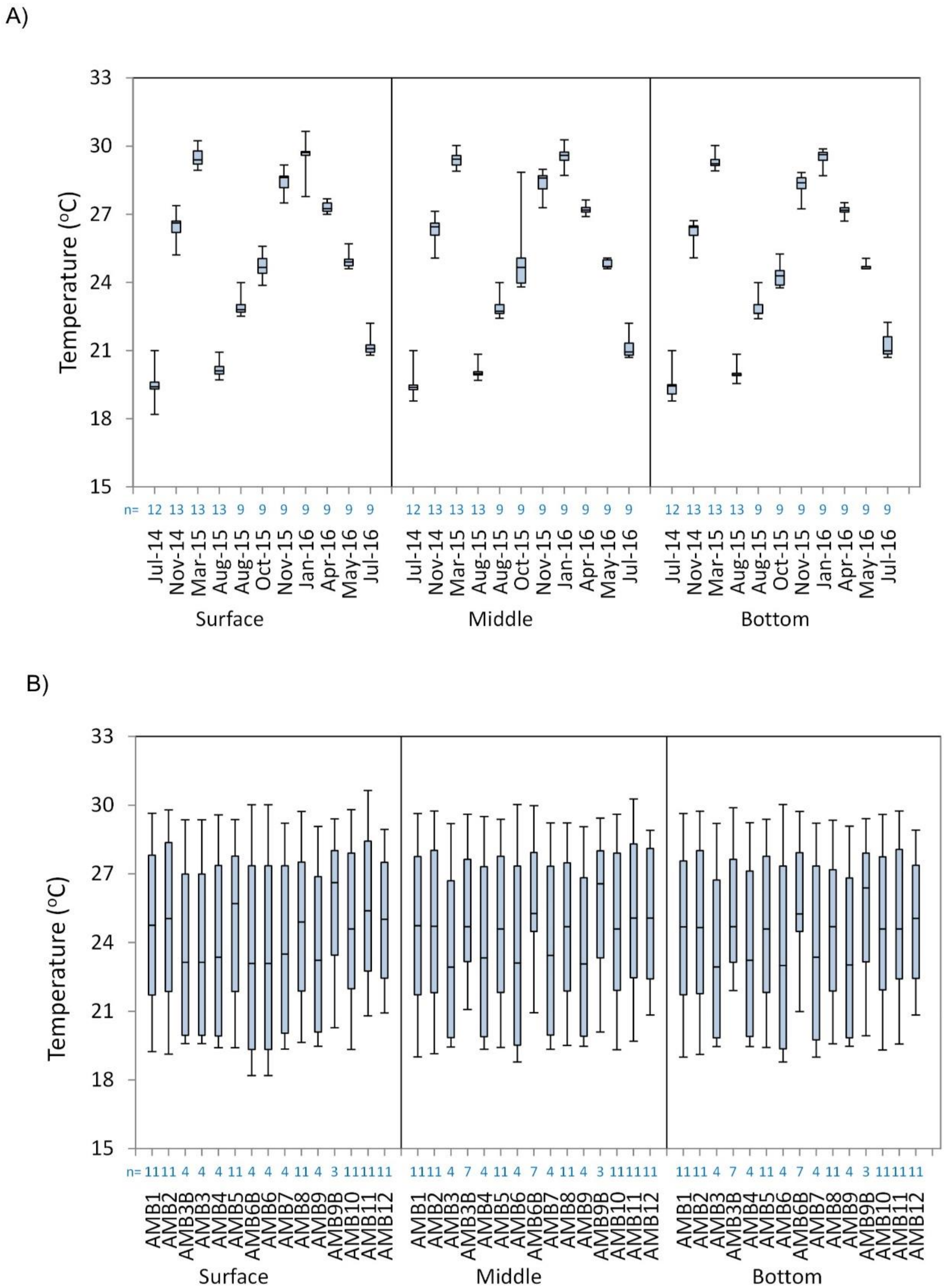
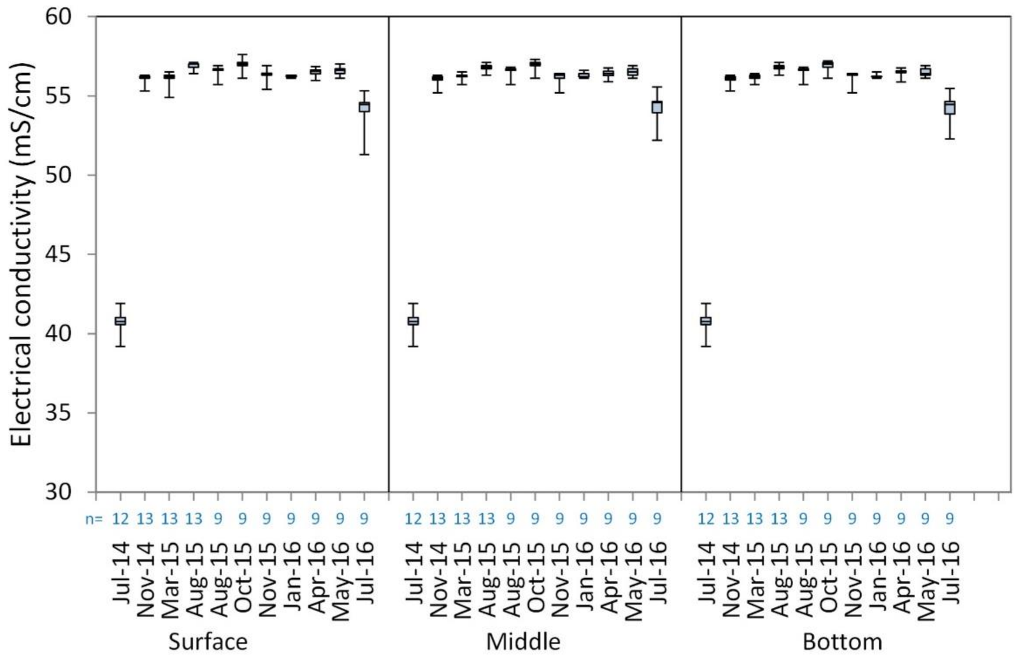


Figure 3.1 Water temperature box plots recorded: (a) the three depth horizons during each survey (sites pooled); and (b) the three depth horizons for each survey (survey pooled)

A)



B)

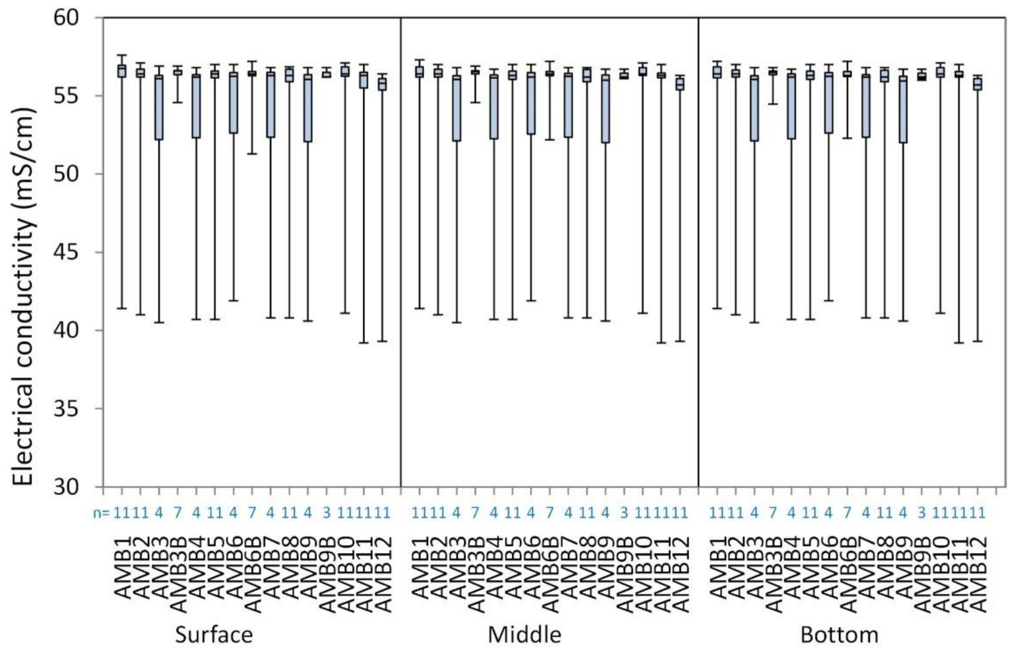


Figure 3.2 Salinity box plots recorded: (a) three depth horizons during each survey (sites pooled); and (b) the three depth horizons for each survey (survey pooled)

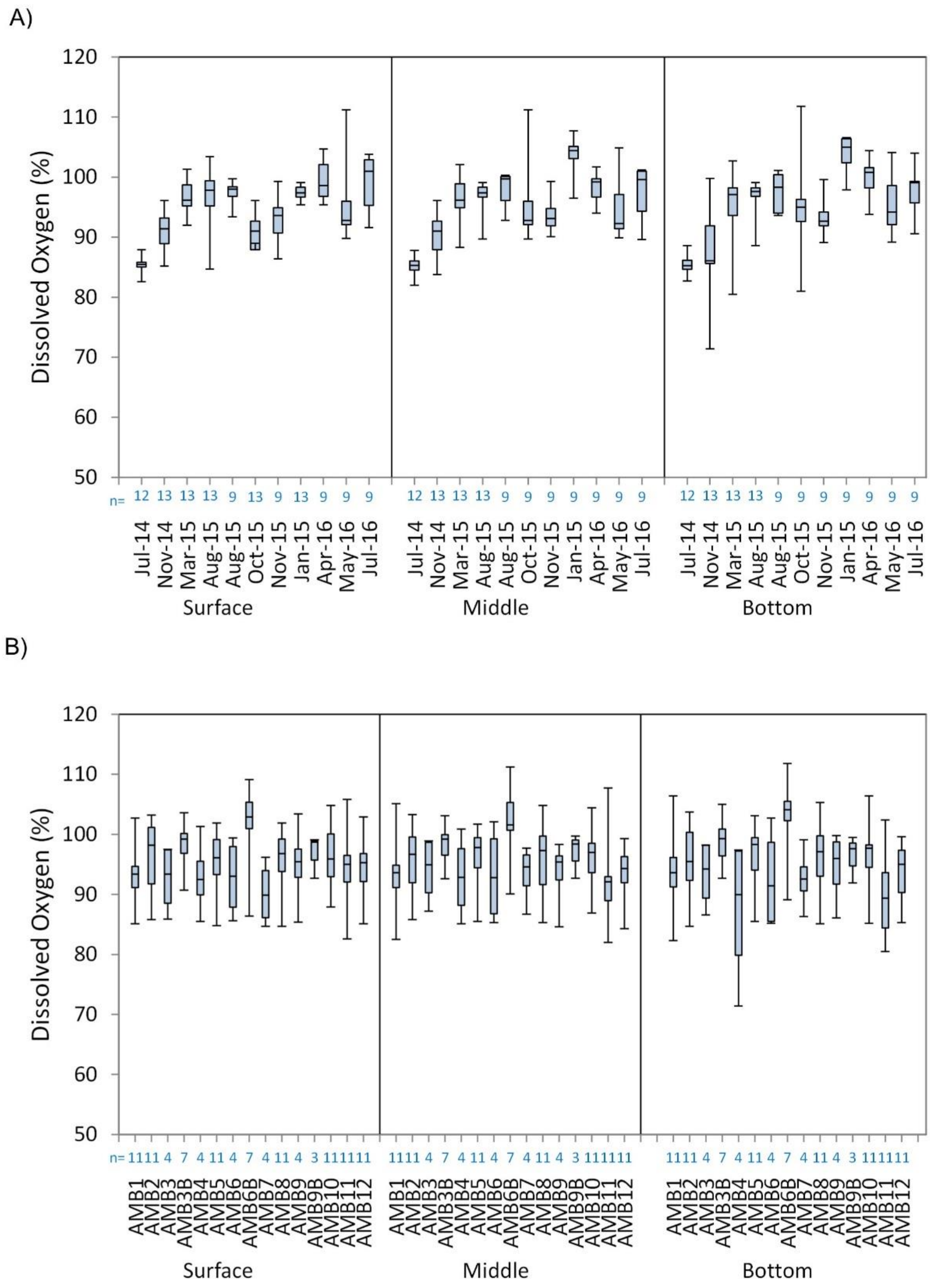


Figure 3.3 Dissolved oxygen box plots recorded: (a) three depth horizons during each survey (sites pooled); and (b) the three depth horizons for each survey (survey pooled)

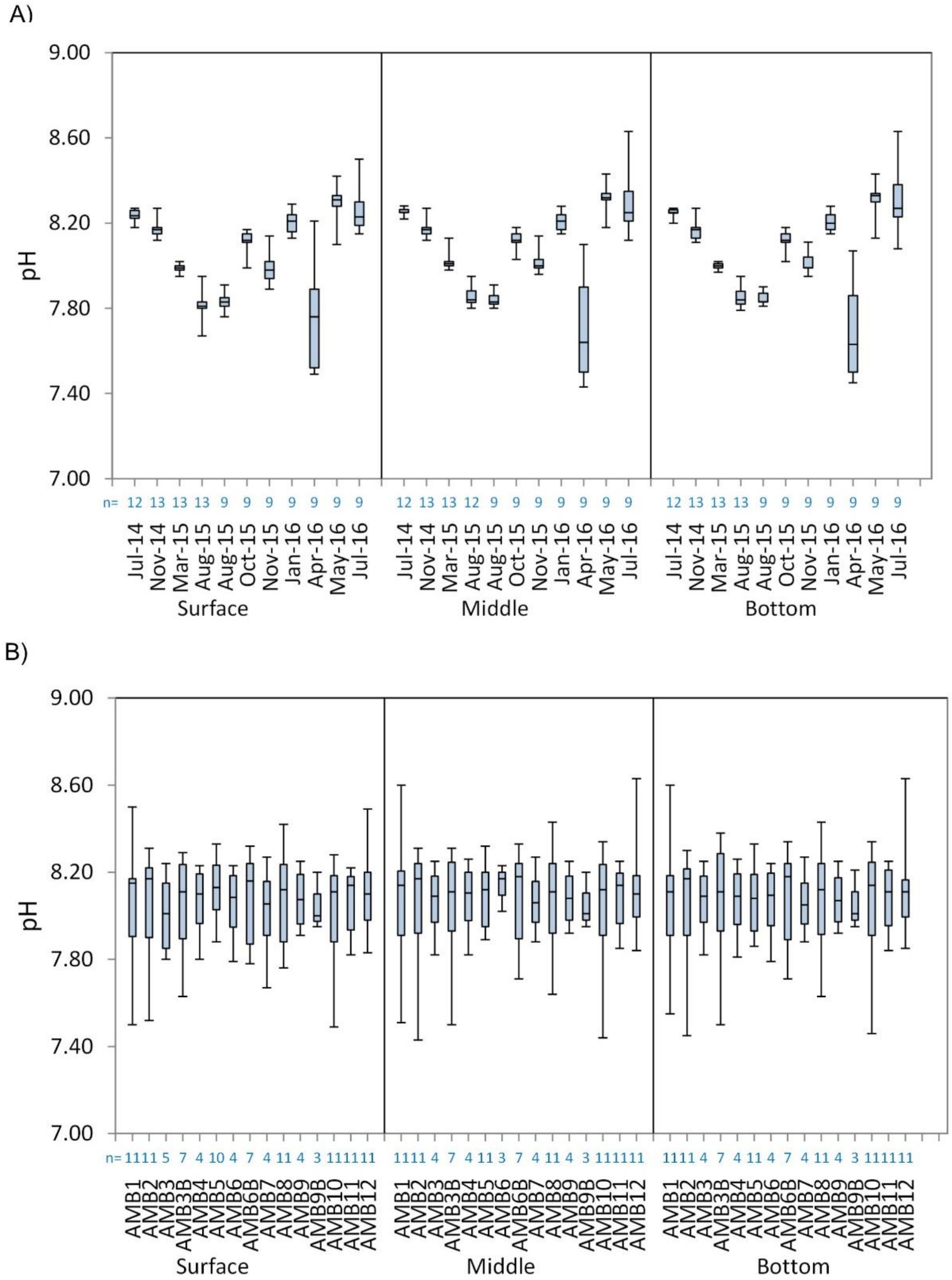


Figure 3.4 pH box plots recorded: (a) three depth horizons during each survey (sites pooled); and (b) the three depth horizons for each survey (survey pooled)

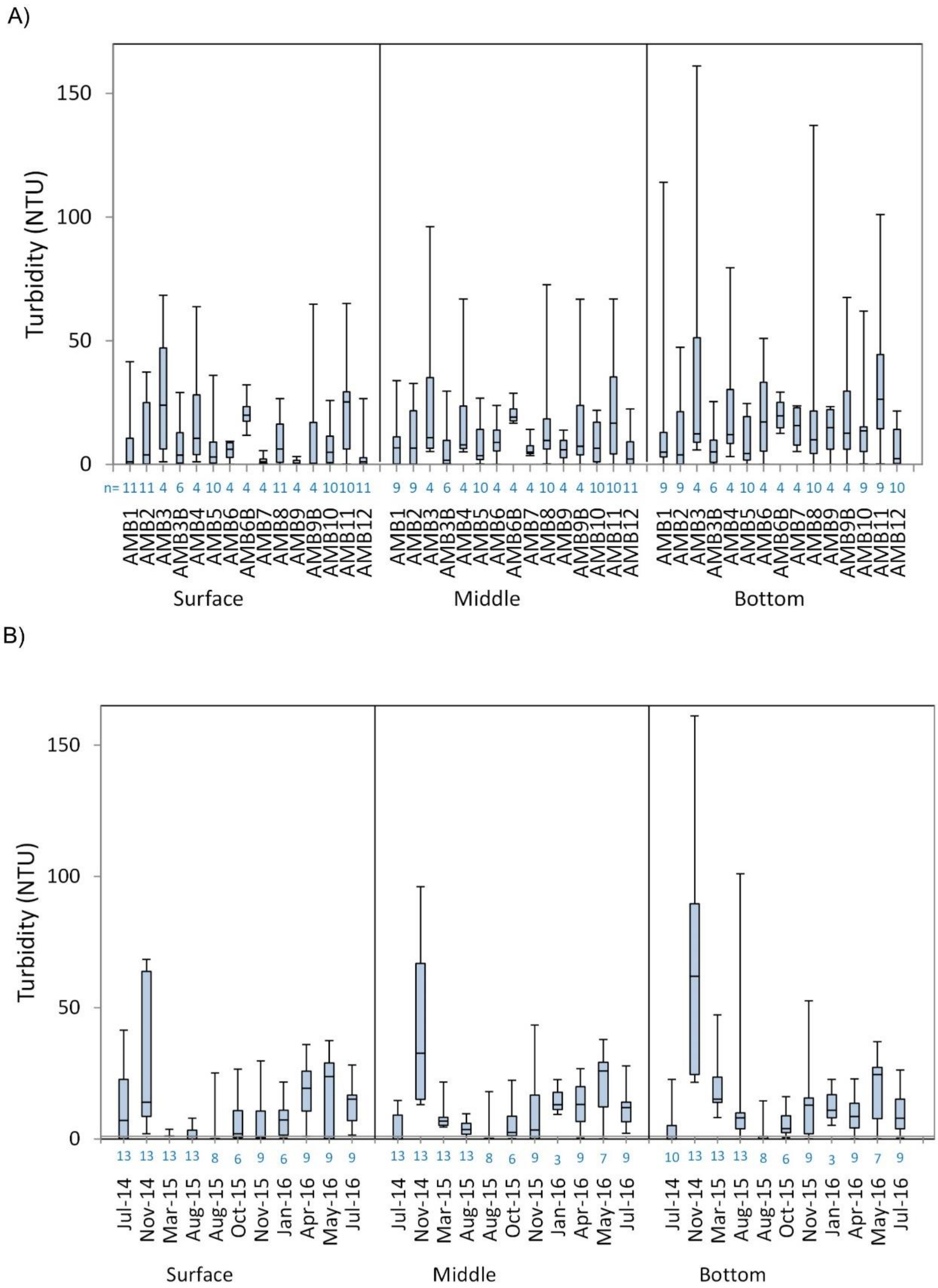
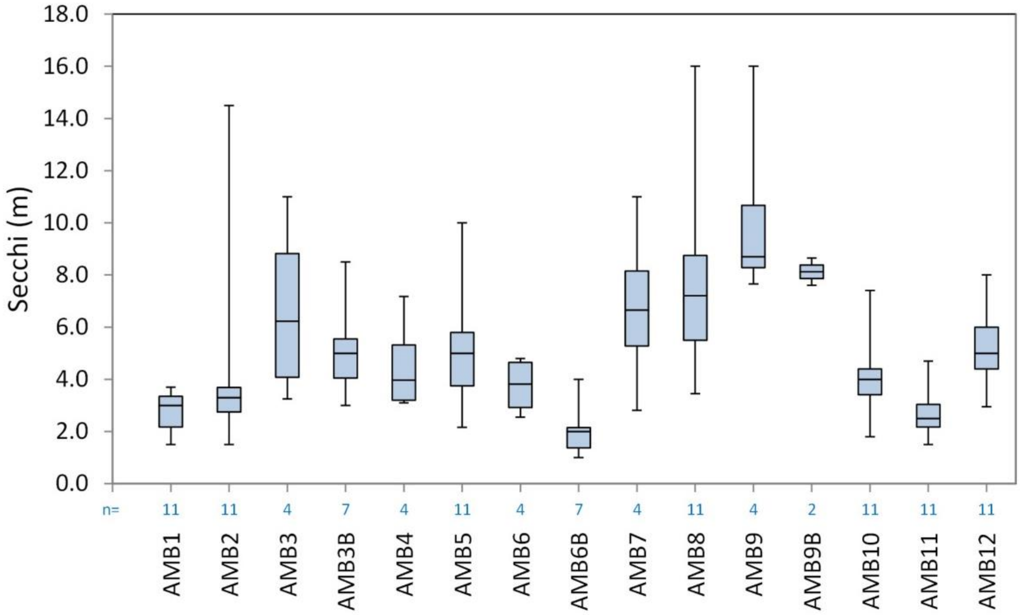


Figure 3.5 Turbidity box plots recorded: (a) three depth horizons during each survey (sites pooled); and (b) the three depth horizons for each survey (survey pooled)

A)



B)

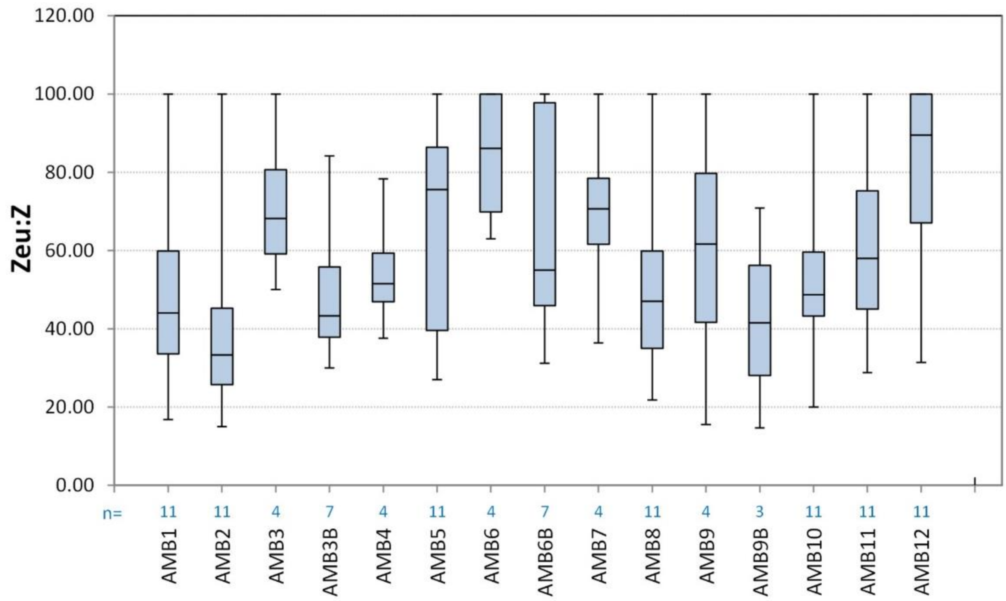


Figure 3.6 (A) water secchi disk depth for all sites (surveys pooled); and (b) light attention depth to depth ratio (Zeu:Z) for sites (survey pooled)

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). In the case for particular nitrogen (Figure 3.7), concentrations exceeded guideline during both the October and November 2015 surveys – the highest recorded concentrations in this program (Figure 3.7a). 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 rives 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. Following November 2015, PN concentrations were generally lower, complying with the guidelines despite several elevated concentrations.

Particulate phosphorus concentrations continue to be variable from survey to survey and site to site (Figure 3.8). While concentrations continue to be within the QWQG (2010), in many instances concentrations exceed the Mackay-Whitsunday water quality objective values (Folker et al., 2014). Both Relocation grounds (AMB 8), and Mackay Marina (AMB 11) seem to be more regularly exceeding the guidelines, possibly due to local site conditions (AMB8 is offshore and might be influenced by algal blooms), while Mackay Marina (AMB 11) is located in the marina and influenced by local stormwater runoff. Overall, there seems to be no consistent pattern in the PP concentrations from survey to survey (Figure 3.8b), whereby in 2016 alone the January and May surveys had lower concentrations compared to the data recorded during the March survey.

Chlorophyll-*a* concentrations were generally close to, or elevated above the guidelines (Figure 3.9). The highest chlorophyll-*a* concentrations continue to be recorded at Dudgeon reef (AMB 6B) and Mackay Marina (AMB 11), and could be influenced by local site conditions (AMB6B might be influenced by river flow from Sarina, while Mackay Marina (AMB 11) might be influenced by activities in the marina). In fact, chlorophyll-*a* concentrations recorded during October 2015 were among the highest recorded during since the monitoring program commenced. The highest concentrations were recorded during both the October and November 2015 surveys, which interesting corresponded with highest PN and PP (Figure 3.7 and 3.8), possibly suggesting some causal relationship. While this elevated period occurred once, and there is no apparent trend, it highlights the point that local water quality conditions can be variable.

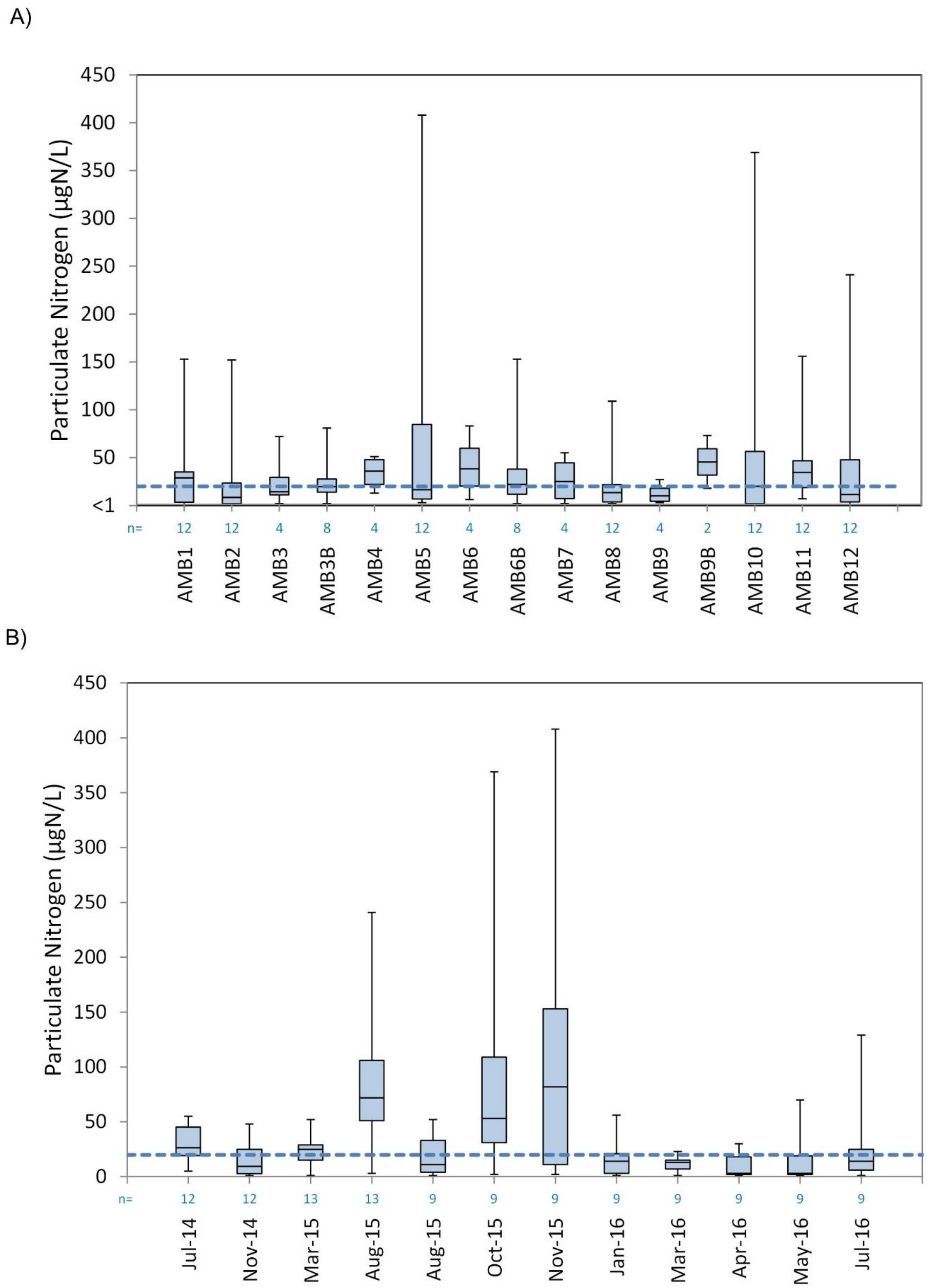


Figure 3.7 Particulate nitrogen box plots: (a) during each survey between July 2014 and July 2016 (sites pooled); and (b) at each site over this same survey period (surveys pooled)

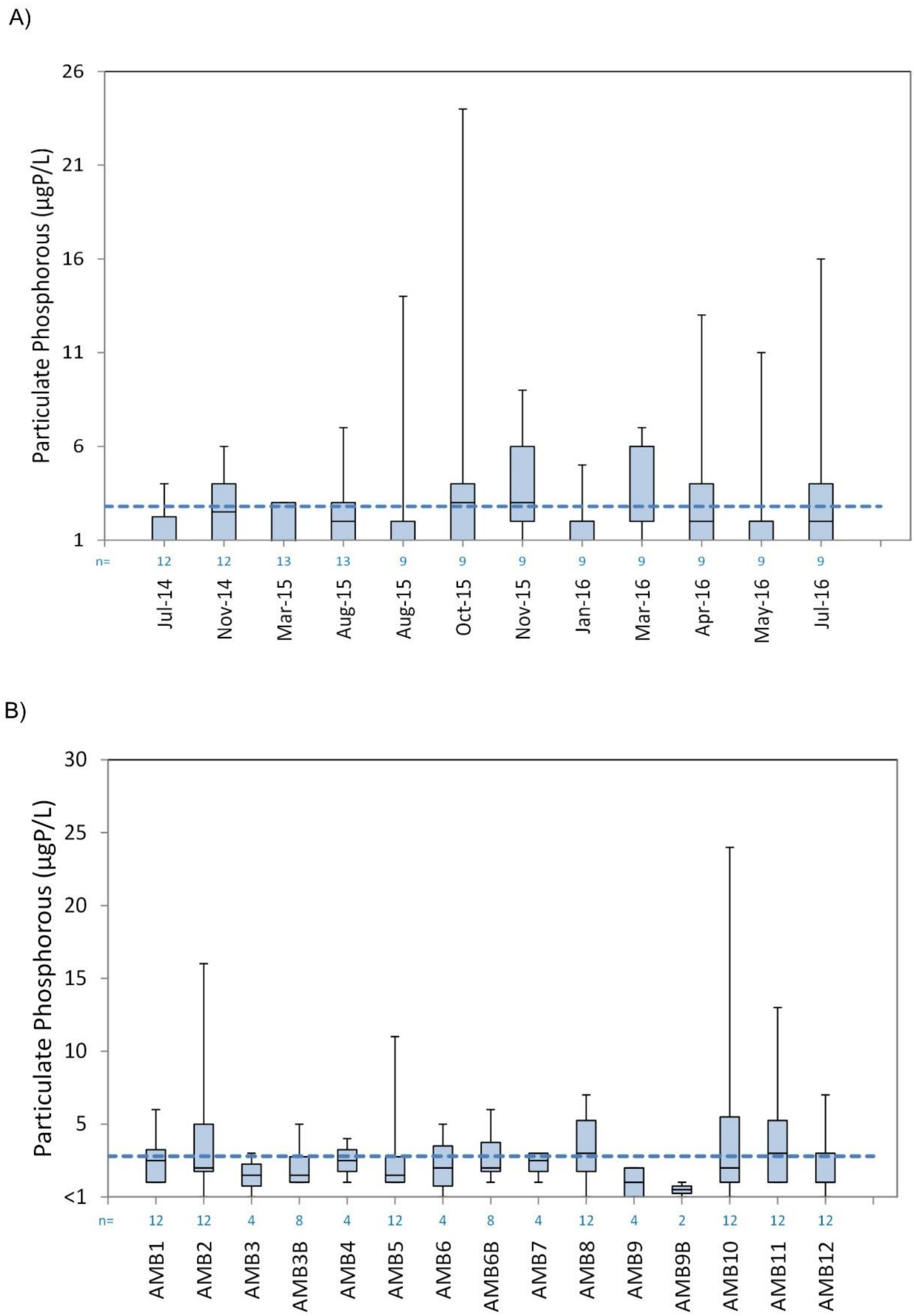
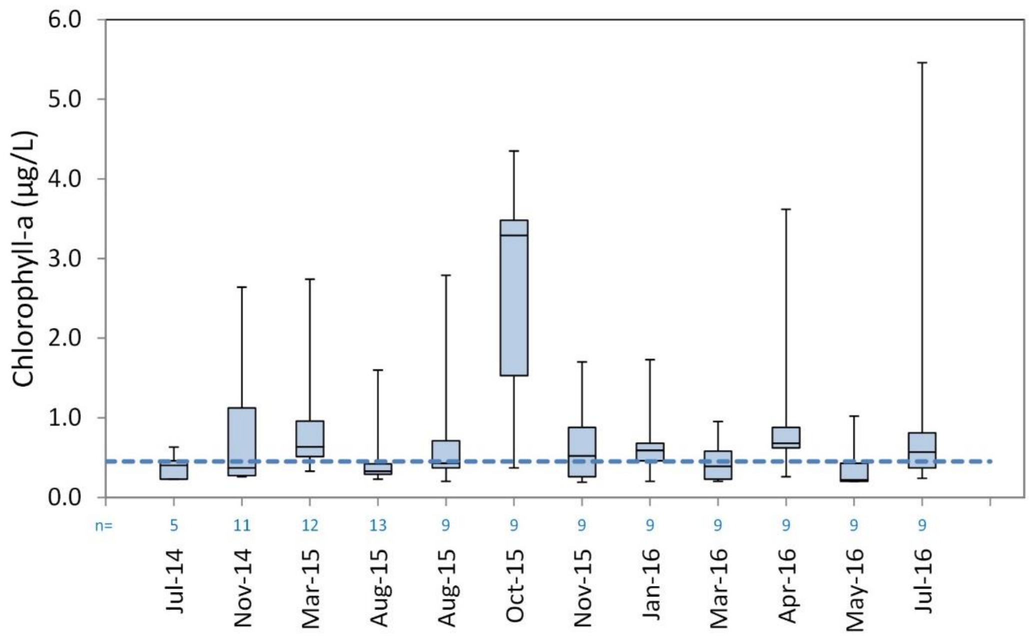


Figure 3.8 Particulate phosphorus box plots: (a) during each survey between July 2014 and July 2016 (sites pooled); and (b) at each site over this same survey period (surveys pooled)

A)



B)

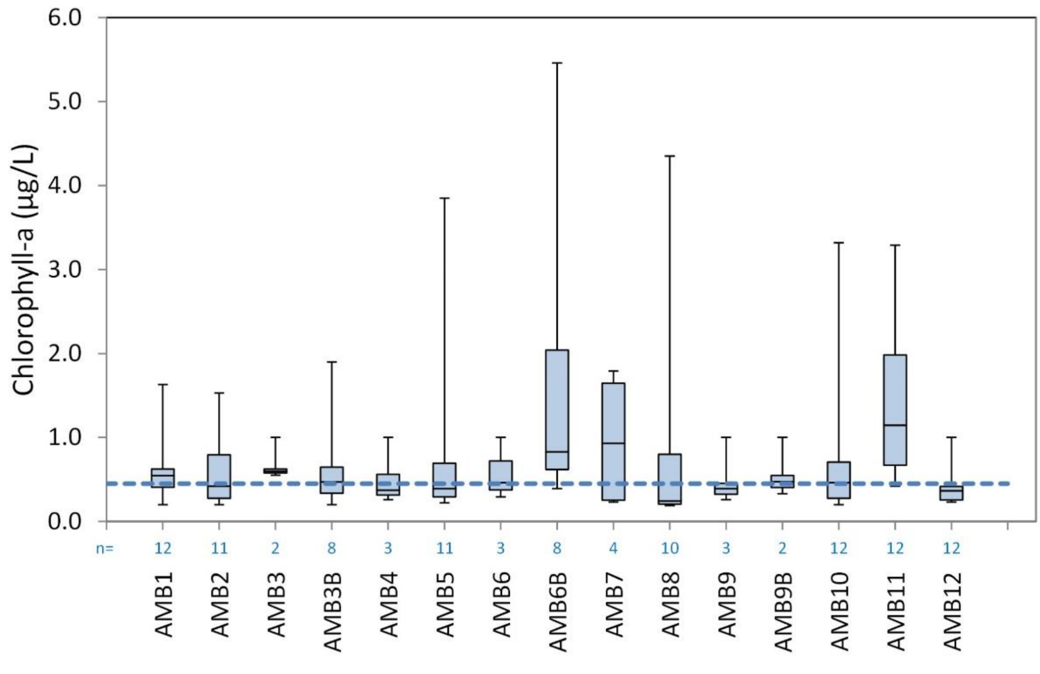


Figure 3.9 Chlorophyll-a box plots: (a) during each survey between July 2014 and July 2016 (sites pooled); and (b) at each site over this same survey period (surveys pooled)

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 95%	**ID**	**5.5**	**1.3**	**4.4**	**70**	**1.4**	**15**	**0.4**	**6**
Jul-14	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	-
	Mean	1.45	<0.2	<1	0.25	<0.5	<0.1	<5	<0.0001	-
Nov-14	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
	Mean	1.28	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Mar-15	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
	Mean	1.68	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Aug-15	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
	Mean	1.22	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
Nov-15	Min	1.60	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	-
	Max	1.90	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	-
	Mean	1.74	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	-
Mar-16	Min	1.40	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	-
	Max	1.70	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	-
	Mean	1.67	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	-
Overall	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
	Mean	1.46	<0.2	1.5	0.25	<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). Pesticides and herbicides that were detected include Diazinon, Hexazinone, Propconazole, Tebuconazole, Diuron, Atrazine and Simazine. 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 were detected during the November 2015 (dry season) survey. These herbicides were detected at sites AMB1, AMB2 and AMB6B, which are all coastal sites located near to river systems; these 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 did not contain an average wet season and therefore runoff was minimal. Consequently, again this year, these values continue to not fully characterise concentrations that might be expected in the region during an average or above average rainfall year.

Table 3.2 Summary statistics for pesticides/herbicides recorded at all sites during the program. 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 – 2016

		LOR	Guidelines (GBRMPA)	WQO's (WQIP, 2014)	Dry 2014 (July)			Wet 2015 (March)			Dry 2015 (November)			Wet 2015 (March)			Overall		
					Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Chlorpyrifos	**µg/L**	**0.0010**	0.009	0.01	<0.002	<0.002	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.00128	0.001	0.002
Malathion	**µg/L**	**0.0010**		0.01	<0.002	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.00128	<0.001	0.002
Diazinon	**µg/L**	**0.0002**	0.01	0.01	0.0027	0.0006	0.0072	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.0006	<0.0002	0.0072
Pirimiphos-methyl	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.00026	<0.0002	0.0004
Thiobencarb	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.0003	<0.0002	0.0004
Pendimethalin	**µg/L**	**0.0010**		0.01	<0.002	<0.002	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0013	<0.001	0.0020
Hexazinone	**µg/L**	**0.0002**	1.2	0.01	0.0006	0.0004	0.0008	0.0003	0.0003	0.0004	0.0022	<0.0002	0.0139	<0.0002	<0.0002	<0.0002	0.0007	<0.0002	0.0139
Propiconazole	**µg/L**	**0.0002**		0.01	0.0013	0.0004	0.0048	0.0004	<0.0002	0.0006	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0004	<0.0002	0.0048
Hexaconazole	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.0003	<0.002	0.0004
Difenoconazole	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0004
Tebuconazole	**µg/L**	**0.0002**		0.01	0.0014	0.0014	0.0014	0.0006	0.0006	0.0006	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0014
Flusilazole	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0004
Penconazole	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.0003	<0.002	0.0004
Diuron	**µg/L**	**0.0002**	1.6	0.01	0.0070	0.0020	0.0213	0.0045	0.0018	0.0115	0.0055	<0.0002	0.0220	<0.0002	<0.0002	<0.0002	0.0037	<0.0002	0.0220
Ametryn	**µg/L**	**0.0002**	1.0	0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0007	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0007
Atrazine	**µg/L**	**0.0002**	1.4	0.01	0.0006	0.0004	0.0008	0.0004	<0.0002	0.0007	0.0041	<0.0002	0.0294	<0.0002	<0.0002	<0.0002	0.0011	<0.0002	0.0294
Cyanazine	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0004
Prometryn	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0004
Propazine	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0004
Simazine	**µg/L**	**0.0002**	3.2	0.01	0.0016	0.0016	0.0016	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0005	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0016
Terbuthylazine	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0004
Terbutryn	**µg/L**	**0.0002**		0.01	0.0010	0.0009	0.0010	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	0.0003	<0.0002	0.0010

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. Unfortunately, in-situ measurements were not recorded during the April 2016 survey.

Exploratory statistical examination of the data collected to date using multidimensional scaling (nMDS) reveals a consistent significant difference (i.e. interaction is not significant) in water quality conditions with from survey to survey, and with water depth (Table 3.3). The ordination pattern supports this conclusion (Figure 3.10).

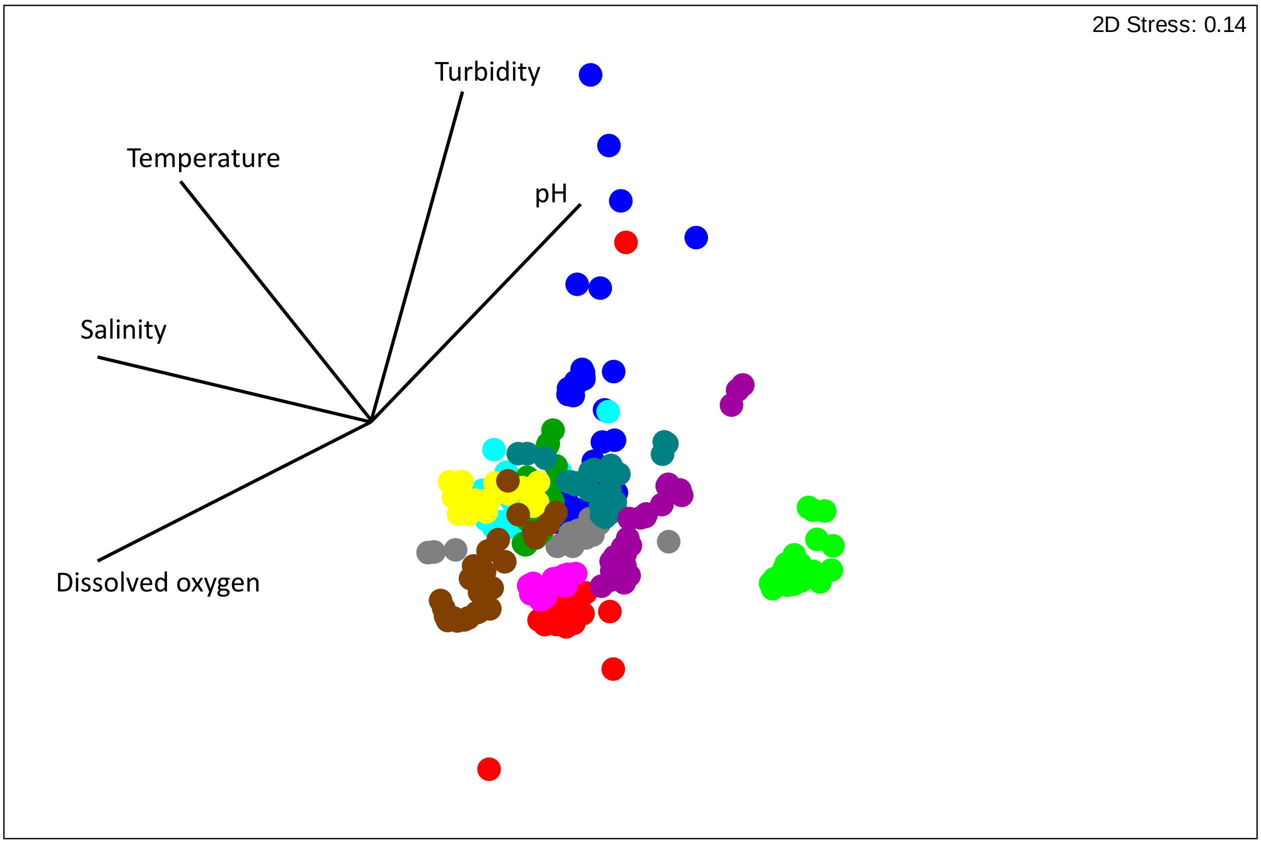


Figure 3.10 Non-dimensional ordination plot using field in-situ measurements for all surveys. Included in this ordinate are surface, mid-depth and bottom horizon, but are not shown in the colour coding. Data has been 4th root transformed on the Euclidean distance matrix (Clarke & Gorley 2006). Light green – July 2014; dark blue – November 2014; light blue – March 2015; red – early August 2015; pink – late August 2015; grey – October 2015; dark green – November 2015; yellow – January 2016; brown – April 2016; navy – May 2016; dark purple – July 2016

Table 3.3 PERMANOVA table of results relating to Figure 3.10

Source	df	SS	MS	Pseudo-F	P(perm)
Surveys	10	1260	126.06	96.776	**0.0001**
Depth	2	5.7658	2.8829	2.2132	**0.045**
De x Su	20	32.337	1.6169	1.2413	0.1168
Res	309	402.49	1.3026		
Total	341	1707			

When only focusing on surface water quality conditions (including PN, PP, chlorophyll-a turbidity, and ZeuZ) (Figure 3.11) the nMDS ordination revealed is compliable with Figure 3.10. Again there is a significant with different in surface water quality conditions among surveys (Table 3.4).

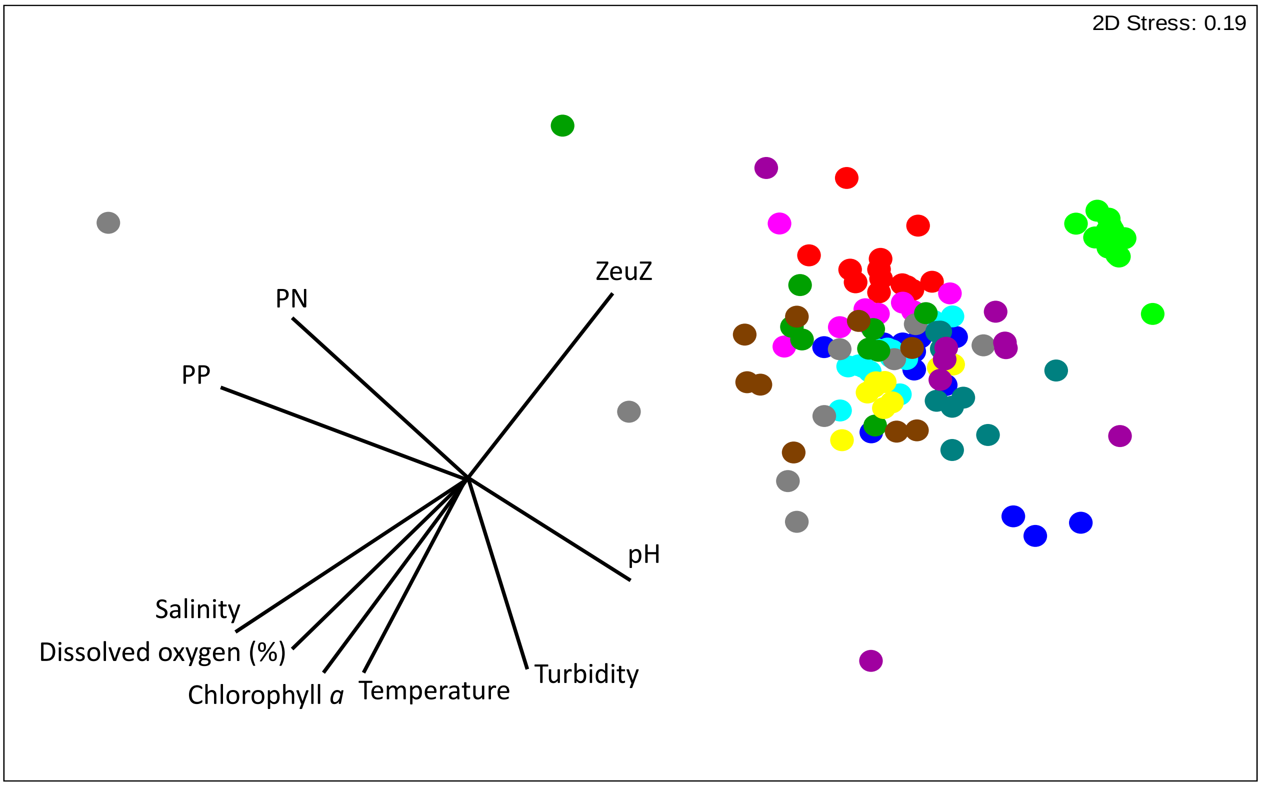


Figure 3.11 Non-dimensional ordination plot using field *in-situ* surface measurements for all surveys. Labels are shortened site names. Stress is 0.09. Data has been 4th root transformed on the Euclidean distance matrix. Survey colours match Figure 3.10

Table 3.4 PERMANOVA table of results relating to Figure 3.11

Source	df	SS	MS	Pseudo-F	P(Perm)
Survey	10	514.48	51.489	10.65	**0.001**
Residual	102	493.11	4.8345		
Total	112	1008			

3.2 Plankton communities

Plankton samples have been collected on two occasions across the study area: November 2015 (dry season), and March 2016 (wet season). A total of 44 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*. Dudgeon Point (AMB 6B) had the highest species diversity (23 species), while Victor Inlet (AMB 10) had the lowest species diversity (17 species). Of the cyanobacteria species, *Trichodesmium spp* was the most widespread species, and is regularly recorded during field trips to the region (see Figure 2a). For zooplankton, a total of 33 different species were recorded, including a single group of fish larvae/eggs. Several species were recorded at all sites, including *Flaccisagitta enflata*, *Favella serrata*, and Siphonophorae. Dudgeon Point (AMB 6B) again had the highest diversity of species (19 species), but not during the March 2016 survey where richness was lowest, while sites Mackay Marina (AMB 11) and Round Top Island (AMB 3B) both recorded the lowest (12 species).

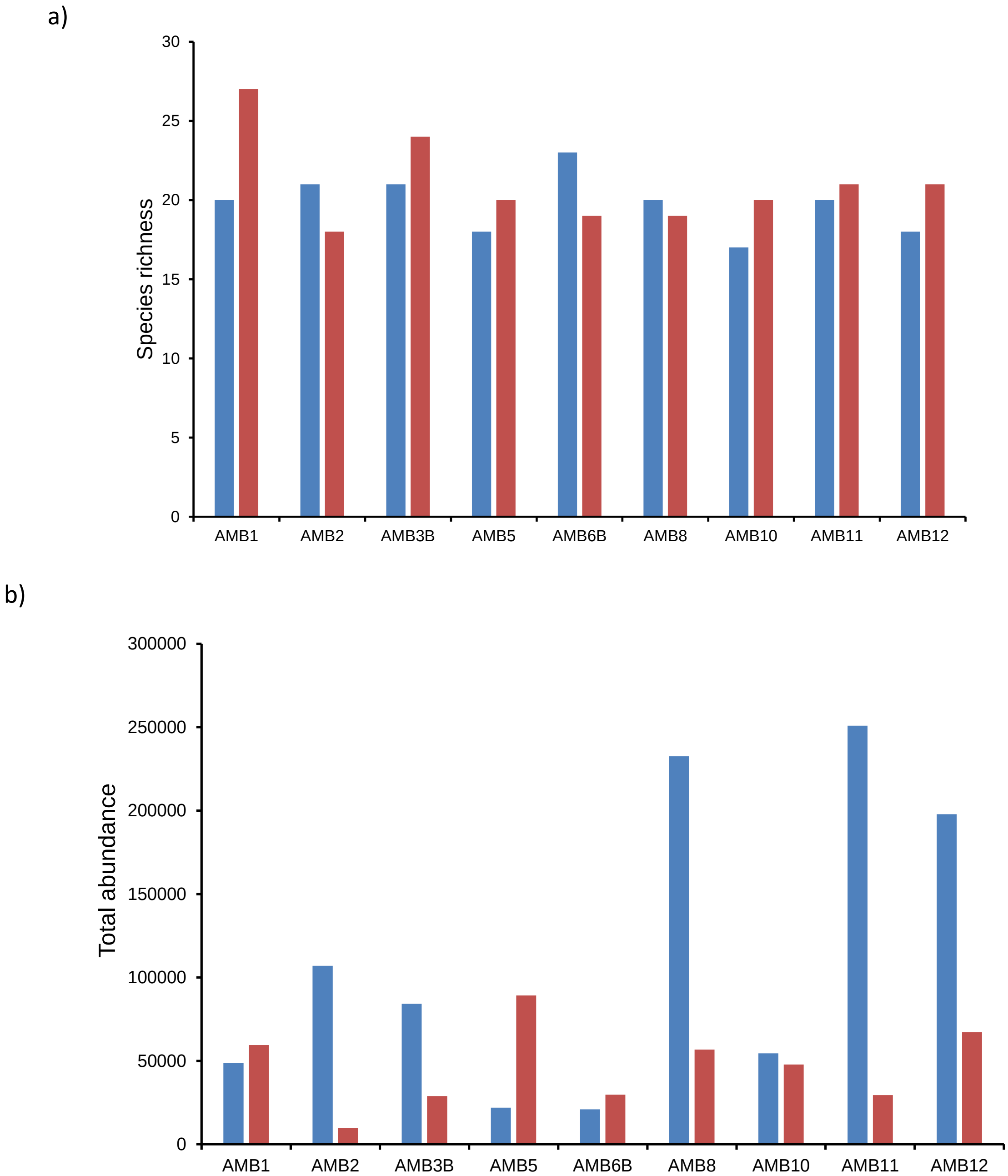


Figure 3.12 a) Species richness of phytoplankton; and b) total species count of phytoplankton at sites, during dry season November 2015 (blue bars); and wet season April 2016 (red bars)

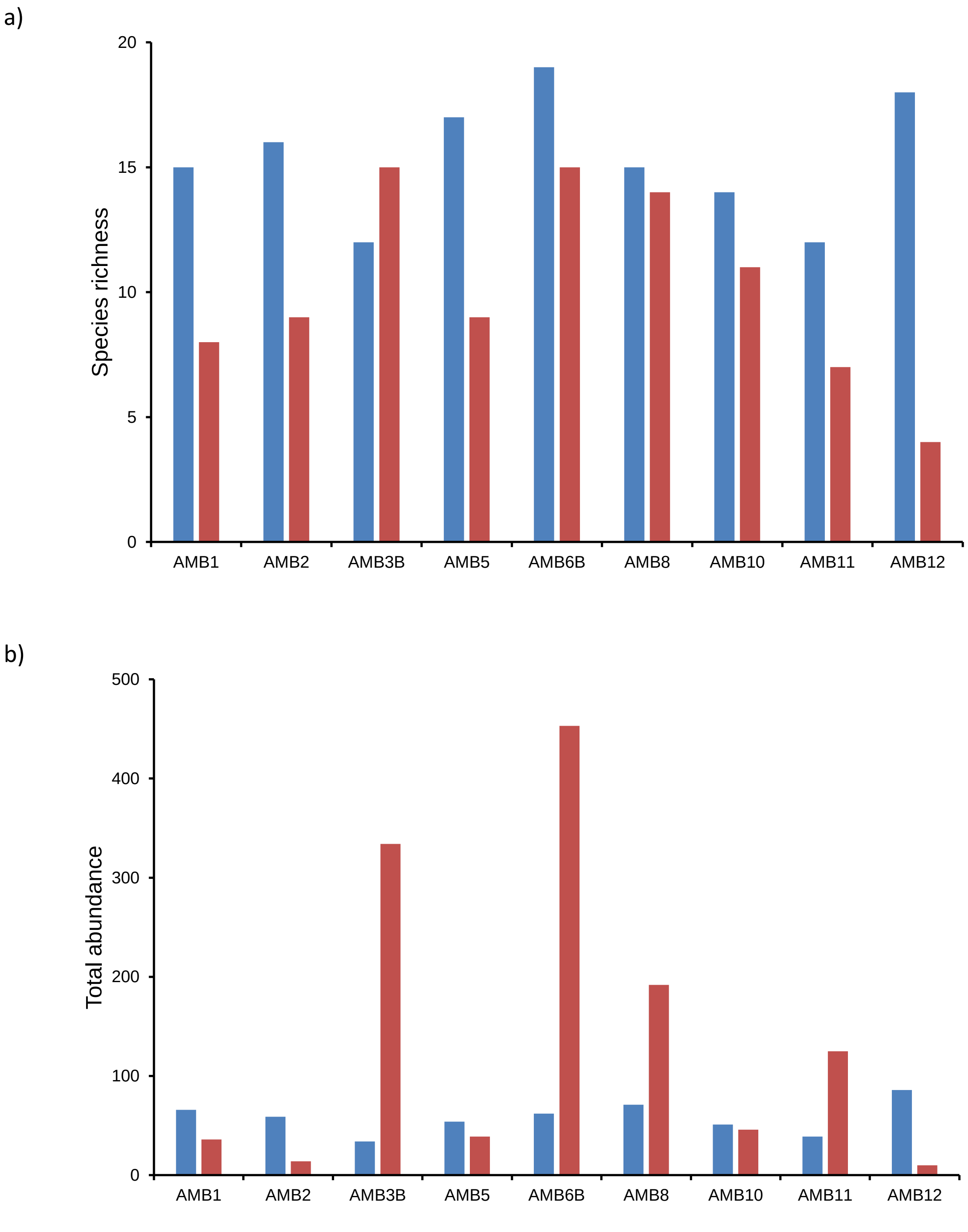


Figure 3.13 a) Species richness of zooplankton; and b) total species count of zooplankton at sites, during November 2015 (blue bars) and April 2016 (red bars)

3.2.1 Plankton ordinations

Despite only two surveys, exploratory statistical analysis of the plankton using non-dimensional scaling (nMDS) reveals a separation between survey for both phytoplankton (Figure 3.14) community and the zooplankton community (Figure 3.15). In these ordination plots, the obvious separation is mostly due to differences in species composition between surveys 1 and 2, as the square root transformation (applied in these figures) did not change when applying a presence/absence transformation (which is a more aggressive data transformation that focuses on species present or not; Clarke and Gorley 2006). The pattern emerging seems to be a seasonal effect between winter and summer, and should continue to be examined in future years. There are too few data points to complete any meaning statistical analyses.

An interesting point in these data were that both plankton communities recorded in survey 1 were more closely associated, while in survey 2 sites were more wide spread suggesting local differences among sites. This is most evident with Keswick Island (AMB 12), which was well separated during survey 2 from other sites, and that Round Top Island (AMB 3B), Dudgeon Point (AMB 6B), Relocation grounds (AMB 8) and Mackay Marina (AMB 11) were more similar (these sites are located surround the Pioneer River nearshore area.

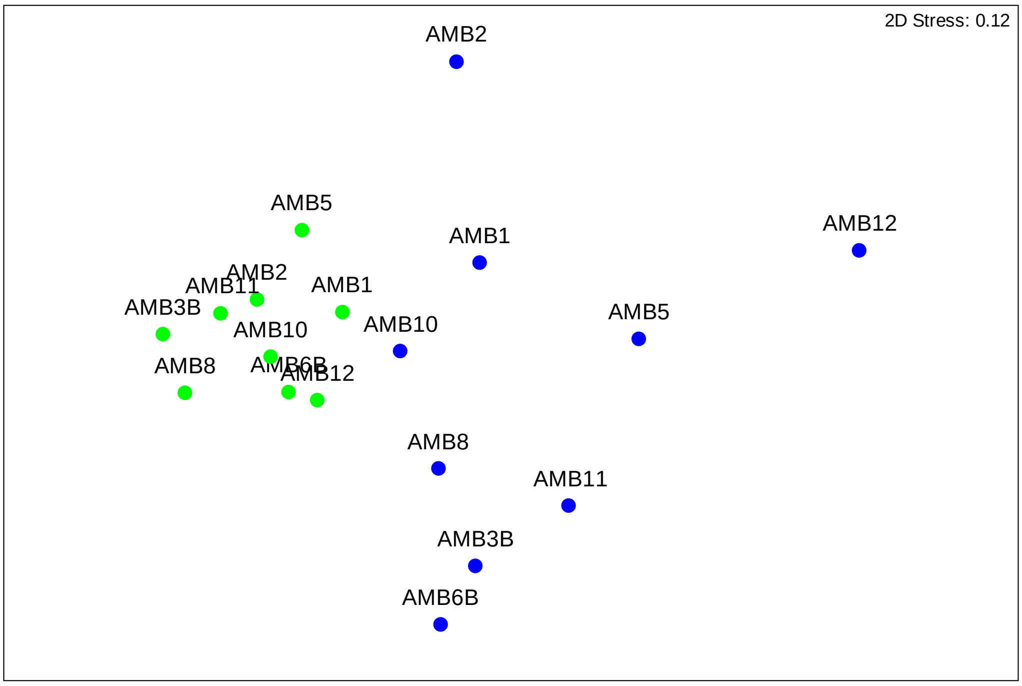


Figure 3.14 Non-dimensional ordination plot for phytoplankton collected during survey 1 (green, November 2015) and survey 2 (blue, April 2016). Data has been squared root transformed (presence/absence transformation was also completed however did not provide a different ordination plot) on the Bray Curtis distance matrix (Clarke and Gorley 2006)

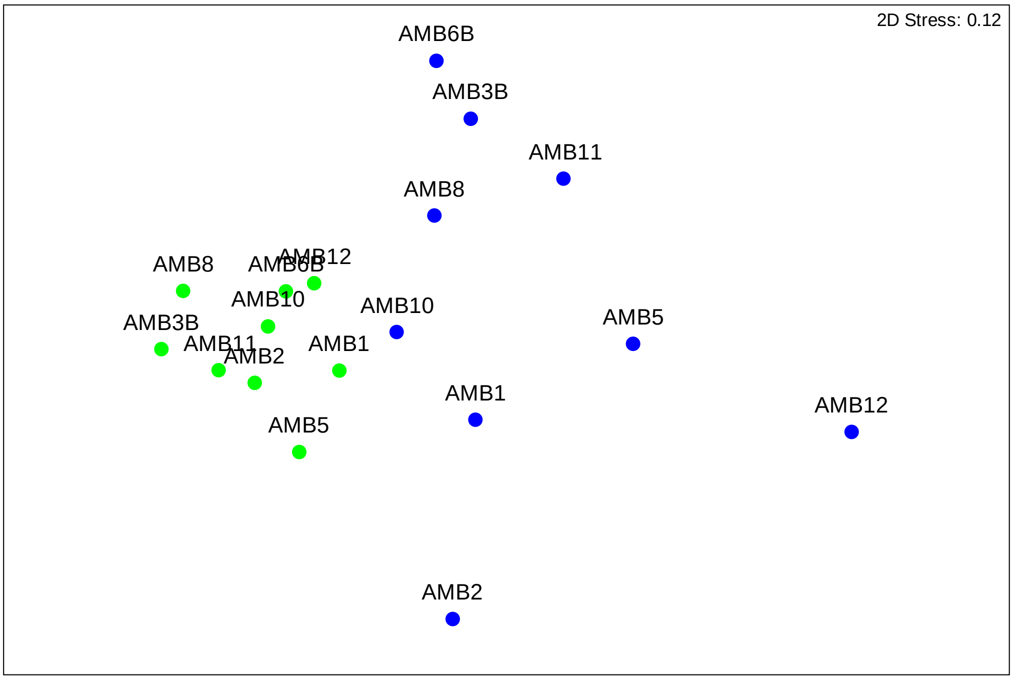


Figure 3.15 Non-dimensional ordination plot for zooplankton collected during survey 1 (green, November 2015) and survey 2 (blue, April 2016). Data has been squared root transformed (presence/absence transformation was also completed however did not provide a different ordination plot) on the Bray Curtis distance matrix (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 2015 to July 2016 (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, and in attached appendices, 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 (mg/cm^2/day), water temperature (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 event and during non-event periods differs among sites due to differences in a sites exposure to wave energy and the water depth of the site. The RMS water height data from this survey year shows the sites can be categorised into three relative groups. Figure 3.16 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) (Table 3.4). This site had much lower RMS values than all other sites with a median RMS water height of 0.008 and the lowest variance in RMS values (10th percentile = 0.003, 90th percentile = 0.031). 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 0.022 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. This is important to note as the Hay Reef (AMB 2) 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 = 0.036, AMB 5: RMS = 0.042) than the five other sites. Round Top Island (AMB 3) 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 relatively shallow site (mean depth of 8.95m) yet because of its exposure to wave energy it had the highest RMS water height values.

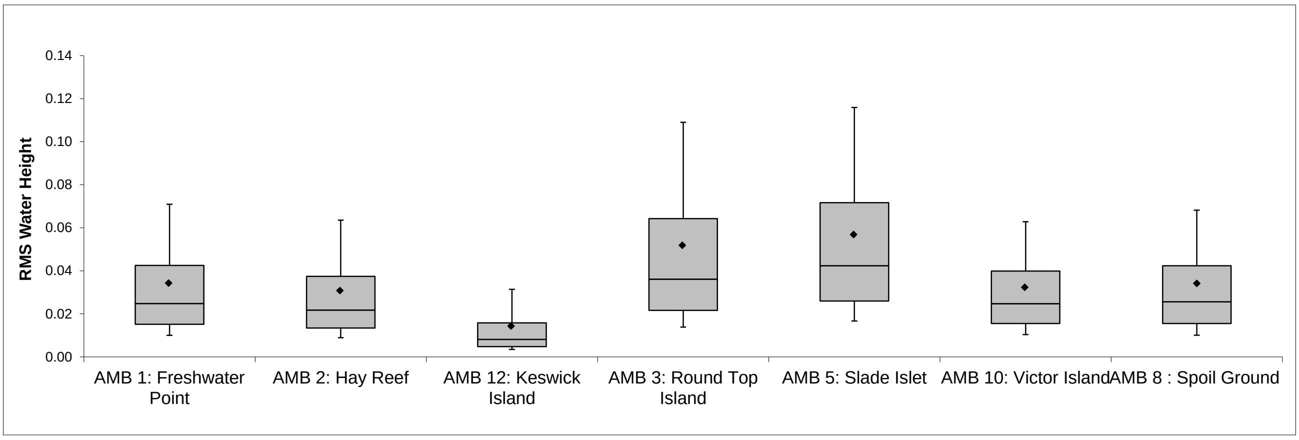


Figure 3.16 Box plot of RMS water depth (m) at 7 sites for the year deployment commencing in July 2015 through to July 2016

Table 3.4 RMS water depth (m) statistics at sites for the monitoring period between July 2015 and July 2016

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	0.034	0.031	0.014	0.052	0.057	0.032	0.03
median	0.025	0.022	0.008	0.036	0.042	0.025	0.03
min	0.000	0.000	0.000	0.000	0.000	0.000	0.00
lower quartile	0.015	0.013	0.005	0.022	0.026	0.015	0.02
upper quartile	0.043	0.037	0.016	0.064	0.072	0.040	0.04
max	0.354	0.396	0.333	0.730	0.487	0.478	0.35
90^{th} percentile	0.071	0.064	0.031	0.109	0.116	0.063	0.07
10^{th} percentile	0.010	0.009	0.003	0.014	0.017	0.010	0.01
n	51712	49546	39634	37118	53302	53295	52212
St. Dev	0.030	0.028	0.019	0.048	0.047	0.027	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 (Figure 3.17) in RMS water height were attributed to changes in water depth due to tidal change which can alter the wave dynamics of a site. Figures 3.17 and 3.18 provide an example of when weather driven wave energy in combination with tide are evident in the RMS data. Figure 3.17 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 3.18 is a shorter time period of the same event and enables the RMS water height data to be studied more closely. 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.

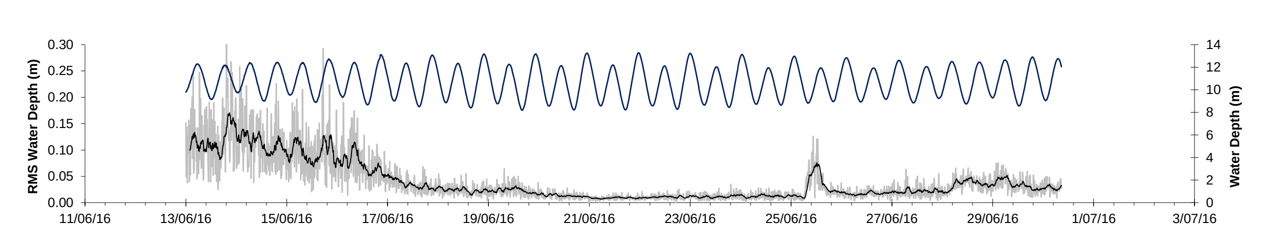


Figure 3.17 Hay Point (AMB 2) RMS water depth (grey), 12 point averaged RMS trend line (black) and water depth (blue). Data shows a wave event followed by a calmer period

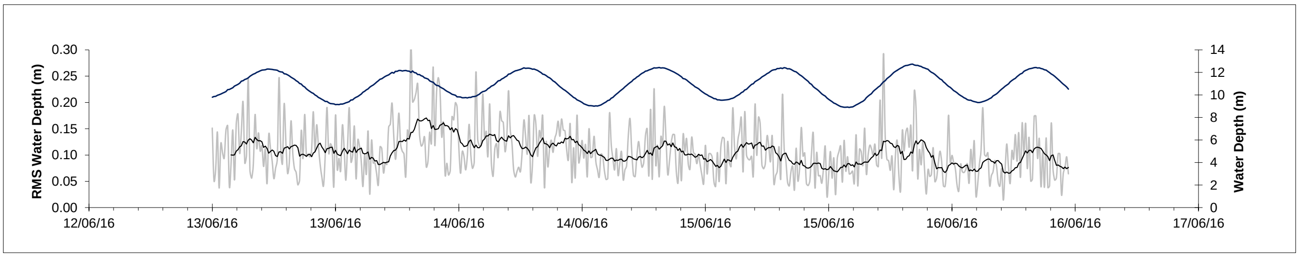


Figure 3.18 Hay Point (AMB 2) RMS water depth (grey), 12 point averaged RMS trend line (black) and water depth (blue). A closer inspection of data from wave event shown in Figure 3.17

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 report (Waltham et al. 2015), and data collected in similar 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 may result from variation in influencing factors such as RMS water height, site depth, benthic geology, hydrodynamics and sediment type.

Of the seven sites, three (Keswick Island AMB 12, Round Top AMB 3, and Relocation ground AMB 8) had median SSC values below 2mg/L and the least variance in NTUe/SSC. All three were positioned much further from the mainland than the other sites, at approximately 5, 8 and 26 km, respectively. Exposure to cleaner oceanic water is the common factor between these sites, although site specific factors such as sediment size and wave shear stress (RMS water height) that are also major influences on NTUe/SSC were different. Site AMB 12 Keswick Island showed the lowest median (0.89 mg/L) and lowest variance (SD = 1.22, 10^{th} percentile = 0.35 mg/L, 90^{th} percentile = 2.30 mg/L) values in NTUe/SSC. This is due to: a) the site being sheltered from the trade south east weather systems (see Figure 3.16 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. This site is also exposed to currents with cleaner oceanic water. The Relocation grounds (AMB 8) site is the deepest site (mean depth 16.97m) in this program, situated kilometres from shallow water where sediment is more readily resuspended and open to clean oceanic water. Local re-suspension in response to the measured moderate RMS water height values and finer muddy sediment did not influence site NTUe/SSC, as expected.

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 3.19; Table 3.5). The location of these sites classifies them as open ocean sites (Water Quality Guidelines for the Great Barrier Reef Marine Park, 2010) subject to relevant trigger limit guidelines. However, these inshore coastal waters are in contrast to these guidelines and are high in suspended solids from the re-suspension of sediment that dominates this environment. 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.

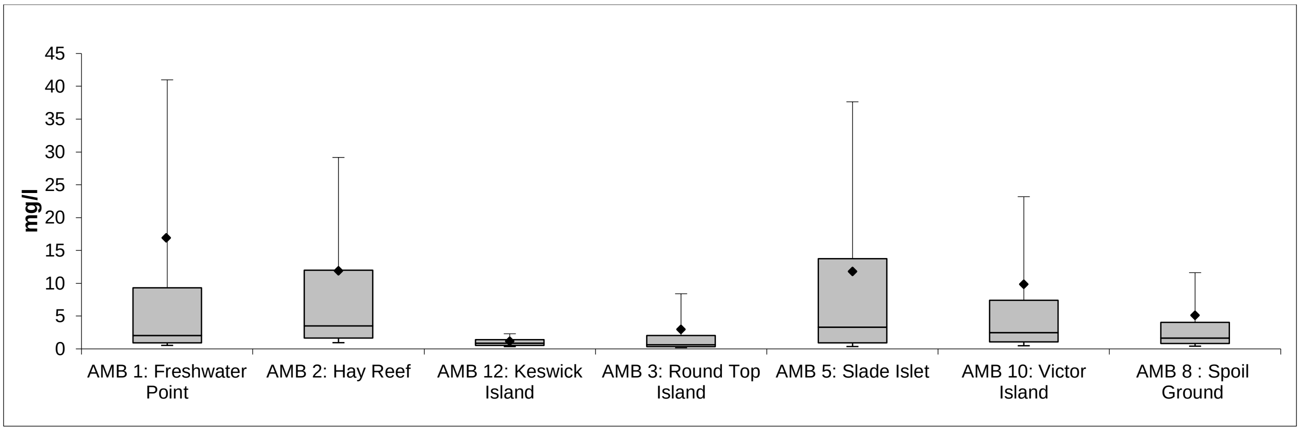


Figure 3.19 Box plot of SSC sites for the period July 2015 to September 2016

Table 3.5 Summary statistics for SSC at sites for the period July 2015 to September 2016

	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	16.93	11.87	1.16	2.95	14.46	9.84	5.10
median	2.03	3.52	0.89	0.61	3.31	2.47	1.65
min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
lower quartile	0.94	1.66	0.55	0.36	0.91	1.07	0.82
upper quartile	9.30	11.97	1.41	2.03	13.74	7.38	4.02
max	1377.19	447.15	89.15	162.60	487.65	501.50	450.28
90th percentile	40.99	29.16	2.30	8.40	37.64	23.19	11.61
10th percentile	0.54	0.95	0.35	0.22	0.36	0.48	0.41
n	49574	42331	31979	32387	50226	43345	49200
St. Dev	53.43	24.60	1.22	6.64	31.90	25.24	13.62
St. Error	0.24	0.12	0.01	0.04	0.14	0.12	0.06

To demonstrate the connection between increases in wave energy and increases in suspended sediment Figure 3.20 presents RMS water height and SSC data from the inshore site Hay Reef (AMB 2) in a time series format. 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.

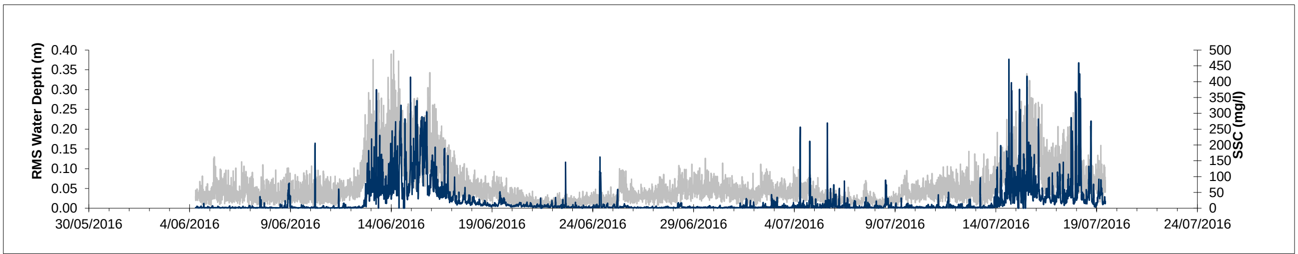


Figure 3.20 Spikes in SSC (blue) and RMS water height (grey) at Hay Reef (AMB 2)

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 height, the variation in NTUe/SSC also increases which is likely a function of a more dynamic environment. The example shown (Figure 3.21) is of data from Relocation grounds (AMB 8), however, the pattern is similar for all sites in the program. These two figures support 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. 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. Using the median values for analysis it can be seen that three sites (AMB 12, AMB 3 and AMB 8) had median values below 2.00 mg/L and AMB 1 only just above, at 2.03 mg/L. Sites AMB 2, 5 and 10 had annual median SSC values of 3.52, 3.31 and 2.47 mg/L, respectively. This is important to highlight as it shows that the median values of these sites are above the mean trigger limit values set by GBRMPA (2010). However, these values are not considerably larger and in combination with the variation among sites it suggests that these sites provide an accurate representation of typical coastal water quality and the inherent variation between sites.

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.

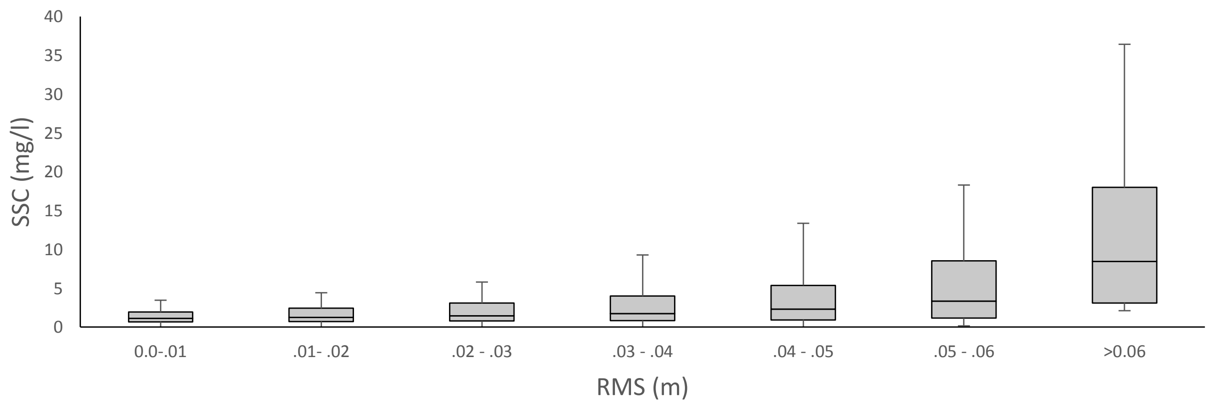


Figure 3.21 Box plot distribution of SSC at RMS water depth intervals using the data from Relocation ground (AMB 8)

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 keep it suspended. The monitoring of sediment deposition rates and any changes from a natural state are an important aspect of marine environmental monitoring. The Water Quality Guidelines for the Great Barrier Reef Marine Park (2010) references De'ath and Fabricius 2008 in noting that 10mg/cm^2/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/cm^2/day and a daily maximum of 15 mg/cm^2/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 3.6. The data indicates that Keswick Island (AMB 12), had the greatest deposition with a mean and median daily average deposition rate of 11.79 mg/cm^2/day and 3.06 mg/cm^2/day respectively. Again it is suggested that the median rather than the mean values be used in analysis to provide an un-skewed value of the data. The median daily average deposition rate ranged from 0.68 – 2.37 mg/cm^2/day at the 6 other 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/cm^2 is equivalent to a layer of sediment of thickness less than 35 µm, assuming a sediment density of 1.5 g/cm^3.

A comparison of the deposition statistics to the RMS water depth and NTUe/SSC statistics reveals that while the Keswick Island (AMB 12) site has the highest deposition rate, it also has the lowest NTUe/SSC and RMS water depth values, with annual medians of 0.89 mg/L and 0.01 m respectively. The lower wave energy at the site enables a greater amount of transported sediment to be deposited, a pattern found in the previous year monitoring (Waltham et al. 2015).

It was interesting that the reference site (Freshwater Point, AMB 1) had a mean deposition rate similar to sites close to the port facilities, and near to the entrance of Pioneer River. This was the second highest value for the region, after Keswick Island (AMB 12) (Figure 3.23).

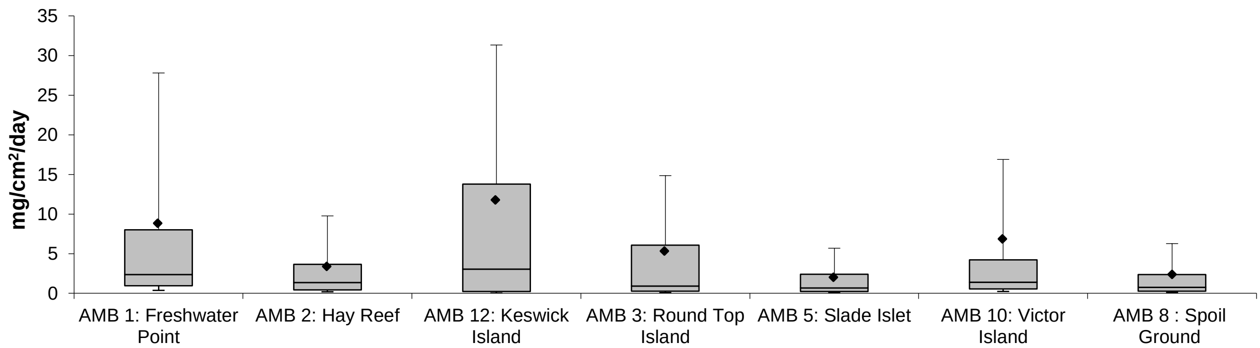


Figure 3.22 Box plot of daily deposition rate at sites for the year deployment commencing in July 2015 to July 2016

Table 3.6 Daily average deposition rate statistics at 7 sites for the year deployment commencing in July 2015 to July 2016

ASSD 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	8.84	3.39	11.79	5.34	2.02	6.89	2.41
median	2.37	1.35	3.06	0.92	0.68	1.37	0.76
min	0.04	0.06	0.00	0.01	0.01	0.04	0.01
lower quartile	0.94	0.41	0.22	0.25	0.22	0.53	0.28
upper quartile	8.02	3.66	13.77	6.08	2.41	4.23	2.38
max	75.22	34.36	192.10	59.32	24.81	170.86	40.79
90^{th} percentile	27.79	9.76	31.32	14.84	5.68	16.88	6.26
10^{th} percentile	0.36	0.19	0.02	0.08	0.07	0.23	0.11
n	261	337	248	243	301	349	341
St. Dev	15.24	5.25	22.14	9.63	3.24	18.71	5.10
St. Error	0.94	0.29	1.41	0.62	0.19	1.00	0.28

It can be seen in the time series deposition data (see appendix) that deposition tends to peak 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 was the case in the 2014/2015 Port of Hay Point and Mackay ambient marine water quality monitoring report, water temperature data matched closely among all sites. Seasonal changes in water temperature were apparent, peaking between December and March at approximately 29.5 -30.5 ^{o}C (Figure 3.23); a factor that was also observed in the field *in-situ* water temperature surveys. Lowest temperatures were observed in July, where values dropped to 18.8 – 22.9 ^{o}C. Both the highest maximum temperature and the lowest minimum temperature across all seven sites occurred at Freshwater Point (AMB 1) (Table 3.7). 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).

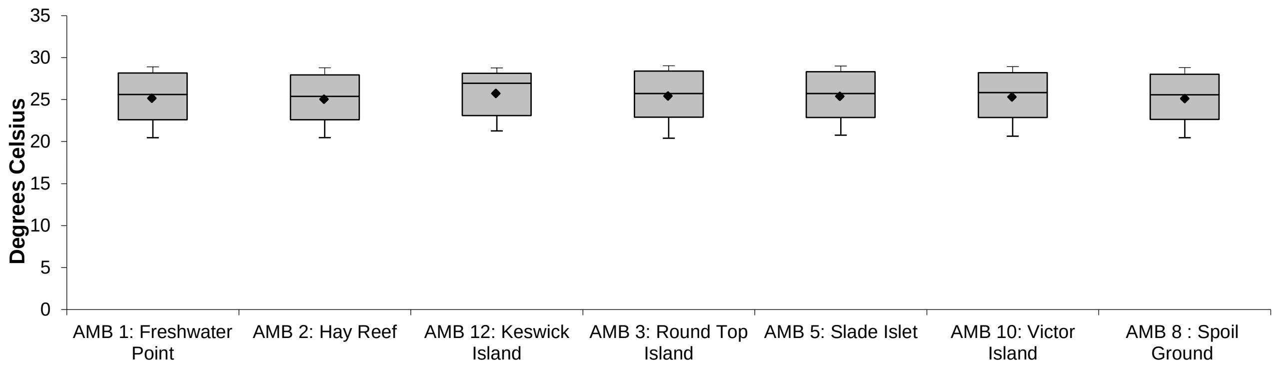


Figure 3.23 Box plot of temperature at sites for the deployment between July 2015 and July 2016

Table 3.7 Temperature statistics at sites for the deployment between July 2015 and July 2016

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	25.17	25.04	25.72	25.41	25.39	25.31	25.14
median	25.64	25.40	26.97	25.75	25.75	25.86	25.57
min	18.80	19.32	19.98	19.40	19.59	19.22	19.26
lower quartile	22.62	22.61	23.09	22.92	22.86	22.88	22.65
upper quartile	28.18	27.95	28.15	28.40	28.33	28.20	28.03
max	30.48	30.03	29.45	30.16	30.37	30.30	30.02
90^{th} percentile	28.91	28.80	28.78	29.04	29.01	28.94	28.82
10^{th} percentile	20.47	20.48	21.28	20.41	20.77	20.65	20.47
n	51699	49534	39597	36928	53278	53274	51969
St. Dev	3.19	3.07	2.86	3.11	3.08	3.09	3.04
St. Error	0.01	0.01	0.01	0.02	0.01	0.01	0.01

3.3.5 Photosynthetically active radiation (PAR) logging

Benthic photosynthetically active radiation (PAR) was monitored at 7 sites from July 2015 and July 2016 (Figure 3.24). 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).

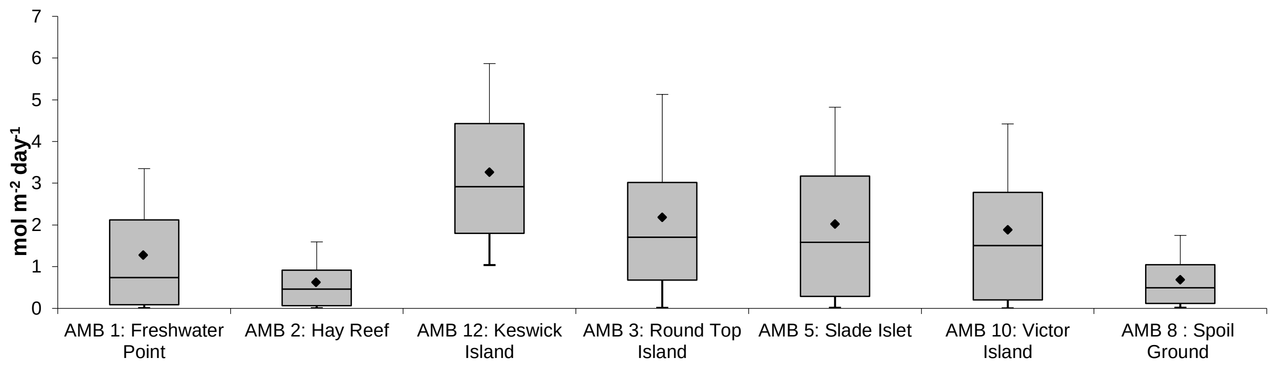


Figure 3.24 Box plot of total PAR (mol photons /m²/day) at sites for the deployment between July 2015 and July 2016

Table 3.8 Summary statistics for total PAR (mol photons /m²/day) recorded at sites during the program (July 2015– July 2016)

Daily PAR 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	1.27	0.63	3.27	2.18	2.02	1.88	0.69
median	0.74	0.46	2.92	1.70	1.58	1.51	0.49
min	0.00	0.00	0.08	0.00	0.00	0.00	0.00
lower quartile	0.09	0.06	1.80	0.68	0.29	0.20	0.12
upper quartile	2.12	0.91	4.43	3.01	3.17	2.78	1.04
max	5.93	3.12	9.35	8.59	8.47	9.19	3.26
90th percentile	3.35	1.59	5.87	5.13	4.82	4.42	1.75
10th percentile	0.01	0.00	1.04	0.01	0.01	0.00	0.02
n	359	343	275	270	371	370	363
St. Dev	1.37	0.67	1.90	2.01	1.89	1.93	0.69
St. Error	0.07	0.04	0.11	0.12	0.10	0.10	0.04

Benthic PAR was highly variable within sites throughout the year, with peaks and troughs occurring both regularly and intermittently over time (Figure 3.25). Semi-regular oscillations between low and high PAR levels were overridden by larger episodic events caused by storm or rainfall events, where PAR levels were generally much lower across the region. Shallow water sites such as Slade Islet (AMB 5) and Victor Islet (AMB 10) displayed much greater variation in daily PAR compared to deeper sites further off shore such as Round Top Island (AMB 3) and Relocation grounds (AMB 8). Keswick Island, which is located 26 km from the mainland, showed a noticeably different and less variable pattern in variation of PAR compared to the other sites.

Investigating examples of monthly variation among sites show an initial period of increasing daily PAR levels from July to August 2015, with levels dropping around October 2015 across all three representative sites. This is similar to the pattern of greater daily PAR levels seen in the previous year (Waltham et al. 2015), from July 2014 through to December 2014 at the same sites. The shallow and deeper coastal sites (e.g. Victor Island, AMB 10; and Round Top Island, AMB 3) show similar general patterns in monthly PAR throughout the year with

February and March 2016 having the lowest PAR values. The offshore Keswick Island site (Figure 3.26c) showed light peaking between October 2015 and December 2015 and lower levels around March and April 2016. This is in contrast to the previous year, which showed light peaking between November 2014 and March 2015 and lower levels around June 2015. PAR levels were similar in May, June and July 2016 to the previous annual period (2015) across all sites.

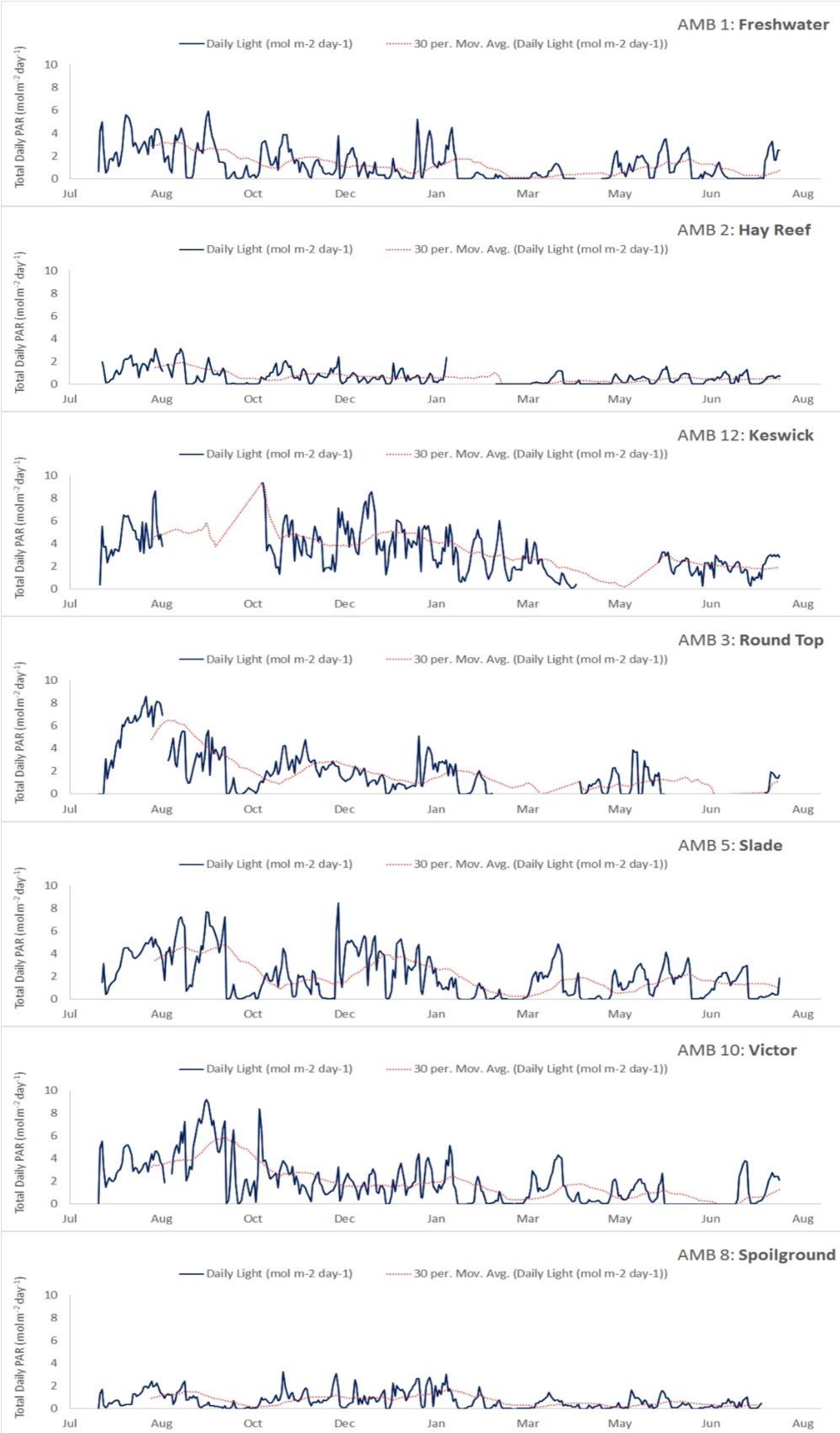


Figure 3.25 Time series of mean total daily photosynthetically active radiation (PAR) (mol photons /m^2/day) recorded at all sites during the second year of the program (July 2015 - July 2016). 30 day moving average trend line depicted in red

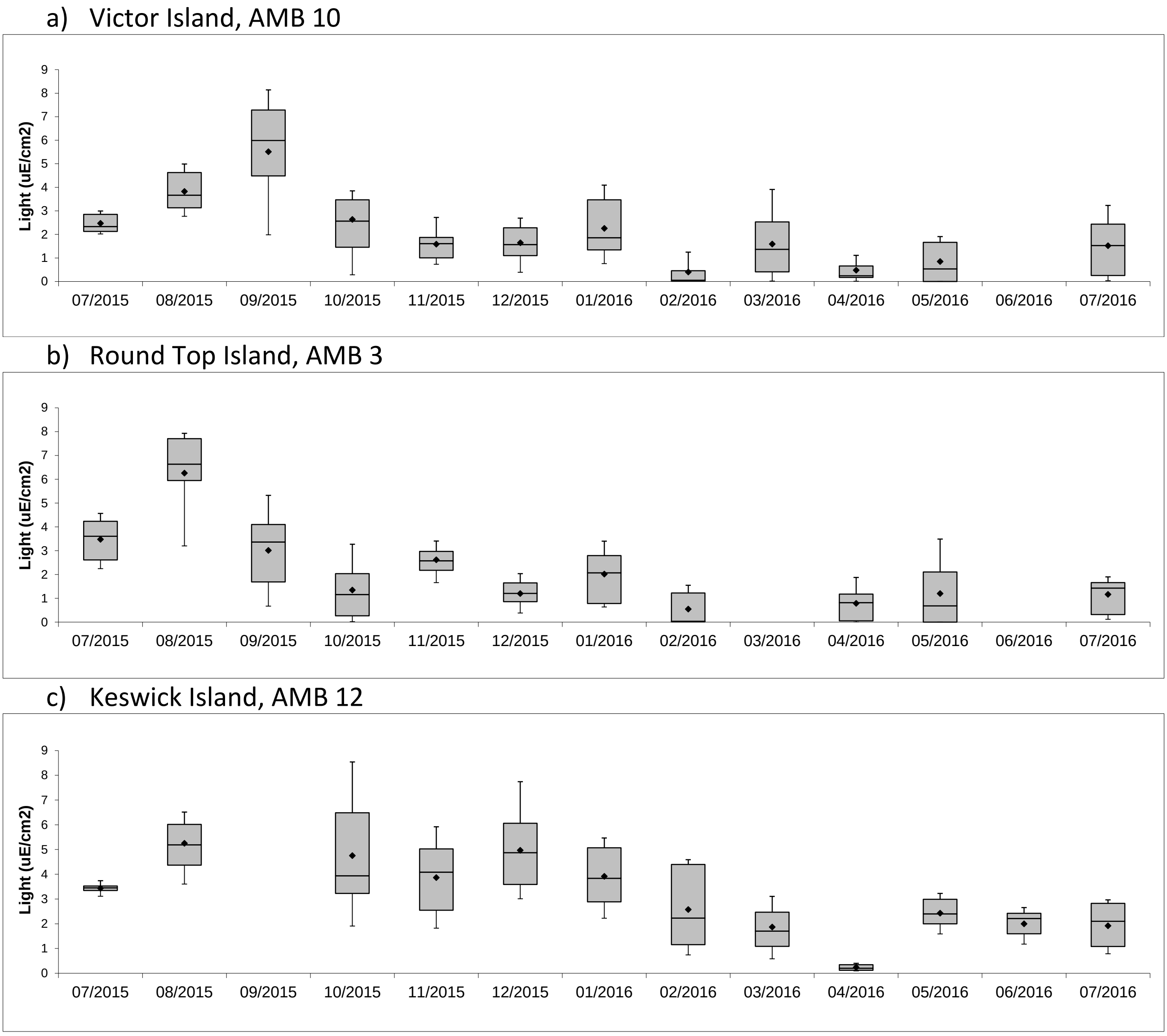


Figure 3.26 Monthly means and variation in total daily photosynthetically active radiation (PAR) (mol photons m^2/day) at a representative inshore site: a) Victor Islet, AMB 10; b) representative deeper coastal site (Round Top Island, AMB 3); and c) offshore site (Keswick Island, AMB 12) during the second year of the program

3.3.6 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 3.27). The strength of the linear relationship between sites was measured using an R^2 value shown on each pairwise scatterplot.

Figure 3.27 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. Victor Islet and Freshwater sites R^2 = 0.47). There were also strong similarities between distant coastal sites that were located in similar environments (e.g. Victor Islet and Slade Islet, R^2 = 0.47, which are both located on the northern sides of islands). As was found in the previous report (2014/2015), 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.

3.3.7 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 provide 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),

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

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 3.28 where during periods of high SSC, light is attenuated and when SSC exceeds approximately 10 mg/L, light extinction occurs.

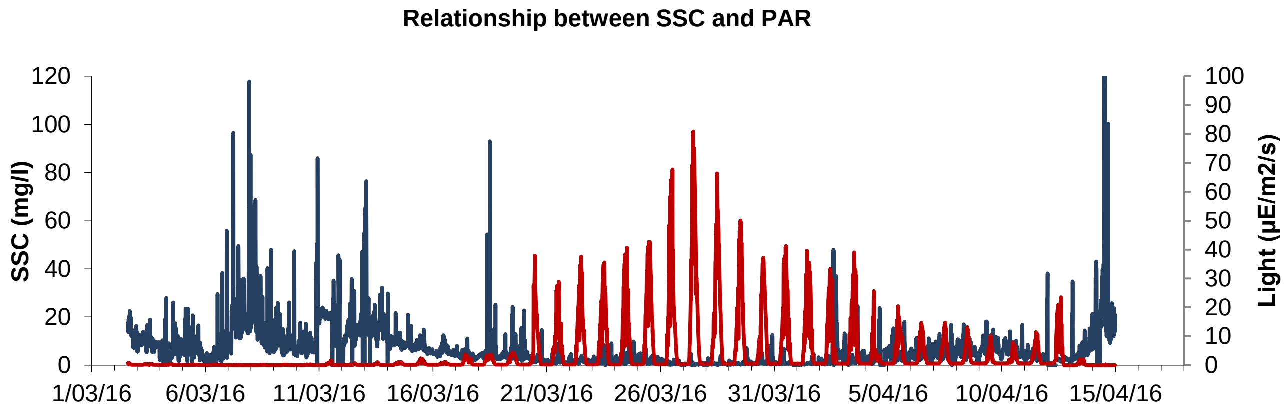


Figure 3.28 A typical example of the relationship between SSC and PAR light, showing light levels decreasing as SSC increases during March-April 2016 at Relocation grounds (AMB 8)

3.3.8 Current meter

Current meter data was collected at five sites; Round Top Island (AMB 3), Slade Islet (AMB 5), Relocation grounds (AMB 8), Victor Islet (AMB 10), and Keswick Island (AMB 12). Marotte HS current meter instruments were deployed for periods of between 2 and 3 months. The current meter data indicates the prominent current direction and velocity at each site during the monitored periods. 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 (21/10/15 to 18/2/16) is predominantly in a SSW direction at an average velocity of 0.2 m/s (Figure 3.29 and Figure 3.30). This indicates that a coastal current dominates this site. Changes in current velocity are likely the result of tidal current influence.

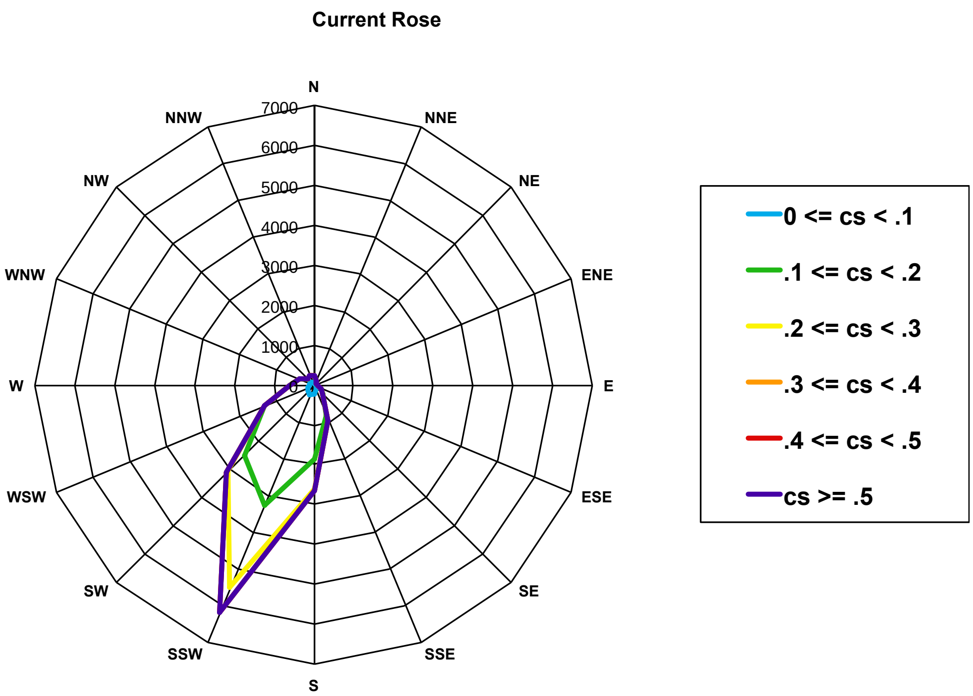


Figure 3.29 Current rose at Slade Island (AMB 5). The legend shows the cs (m/s), current speed, ranges and the number of recorded values are labelled on the radar axis

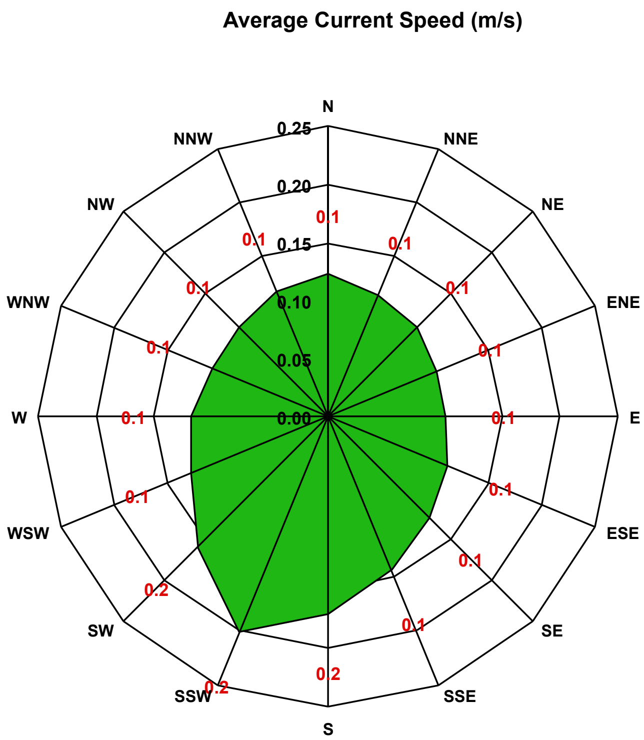


Figure 3.30 Average current speed rose at Slade Island (AMB 5). Red numbers indicate average current speed (m/s) at specified direction. Average current speed (m/s) is labelled on the radar axis. Green area shows the recorded average current speed data

Keswick Island (AMB 12) current meter data

Current at Keswick Island (15/1/16 to 25/2/16), situated in the channel between Keswick and St Bees Islands, is mainly in a NNE direction with an average velocity of 0.3 m/s. Figure 3.31 and Figure 3.32 show that the largest numbers of data points were observed at over 0.5 m/s in the NNE direction. Again, a coastal current dominates this site and tidal current influences its velocity and the channel between Keswick and St Bees Islands influences the direction of the current. This site had the highest average current speed of the recorded sites, most likely due to the funnelling between the Islands.

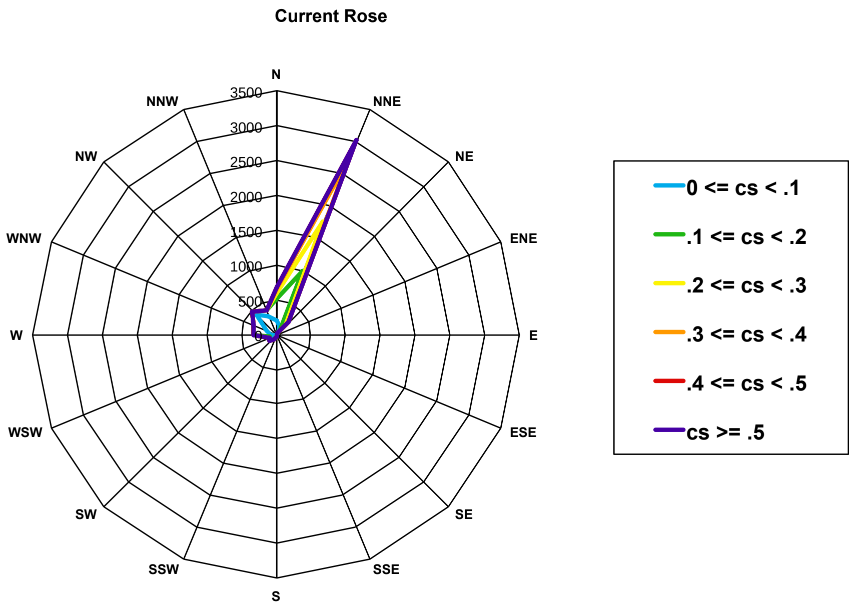


Figure 3.31 Current rose at Keswick Island (AMB 12). The legend shows the cs (m/s), current speed, ranges and the number of recorded values are labelled on the radar axis

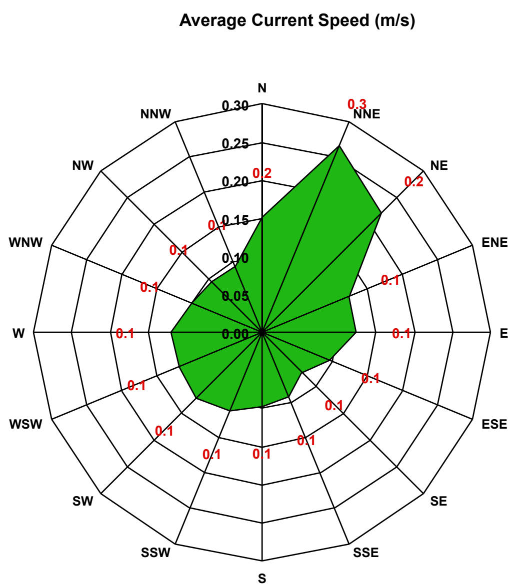


Figure 3.32 Average current speed rose at Keswick Island (AMB 12). Red numbers indicate average current speed (m/s) at specified direction. Average current speed (m/s) is labelled on the radar axis. Green area shows the recorded average current speed data

Round Top Island (AMB 3) current meter data

At Round Top Island (15/1/16 to 17/2/16) the current is dominant in the NNE and ESE direction (Figure 3.33). Both directions of current have an average velocity of 0.2 m/s. Current over 0.5 m/s is recorded approximately 25% more in the NNE direction than in the ESE direction (Figure 3.34). Change in tidal current is the change in current direction observed in the current meter data.

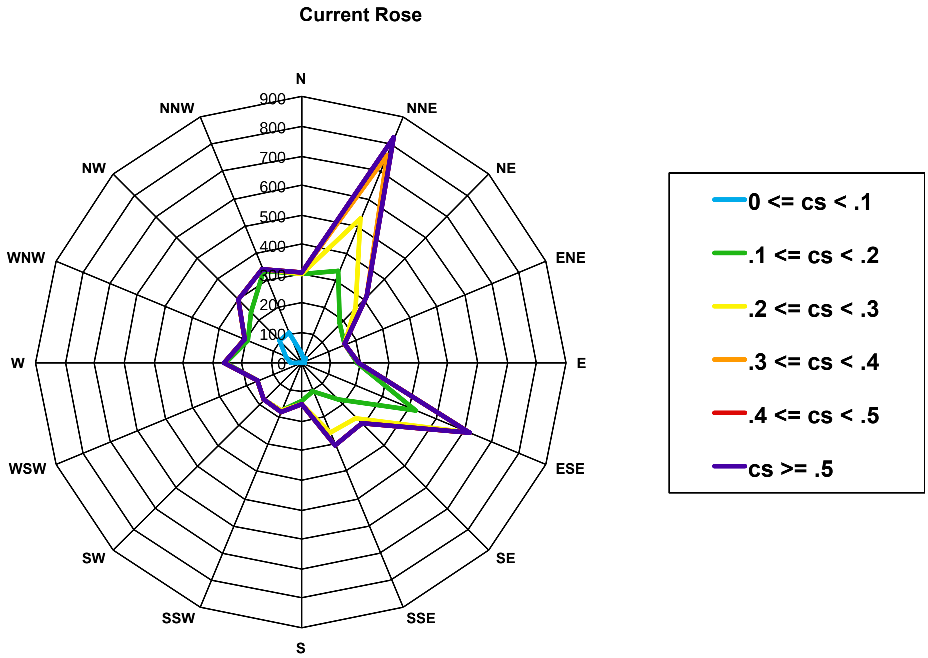


Figure 3.33 Current rose at Round Top Island (AMB 3). The legend shows the cs (m/s), current speed, ranges and the number of recorded values are labelled on the radar axis

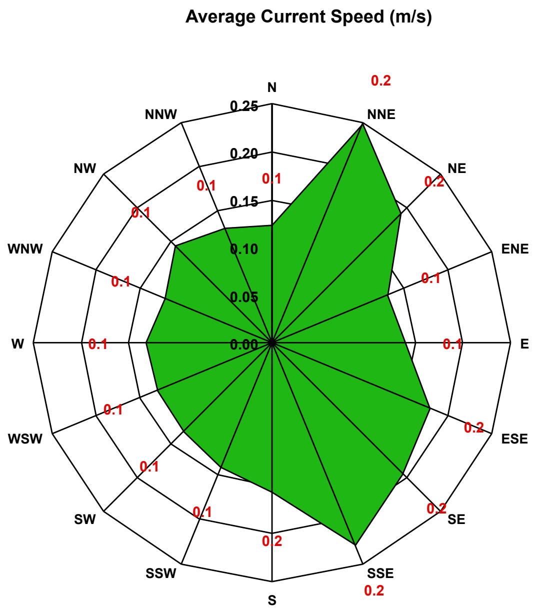


Figure 3.34 Average current speed rose at Round Top Island (AMB 3). Red numbers indicate average current speed (m/s) at specified direction. Average current speed (m/s) is labelled on the radar axis. Green area shows the recorded average current speed data

Relocation grounds (AMB 8) current meter data

The two current directions (18/1/2016 to 11/04/2016) that dominate at Relocation grounds (AMB 8) are in the N and SW directions (Figure 3.35). An average current velocity of 0.2 m/s was recorded in both the N and SW 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 3.36). Again the change in direction is likely explained by changes in tidal current direction.

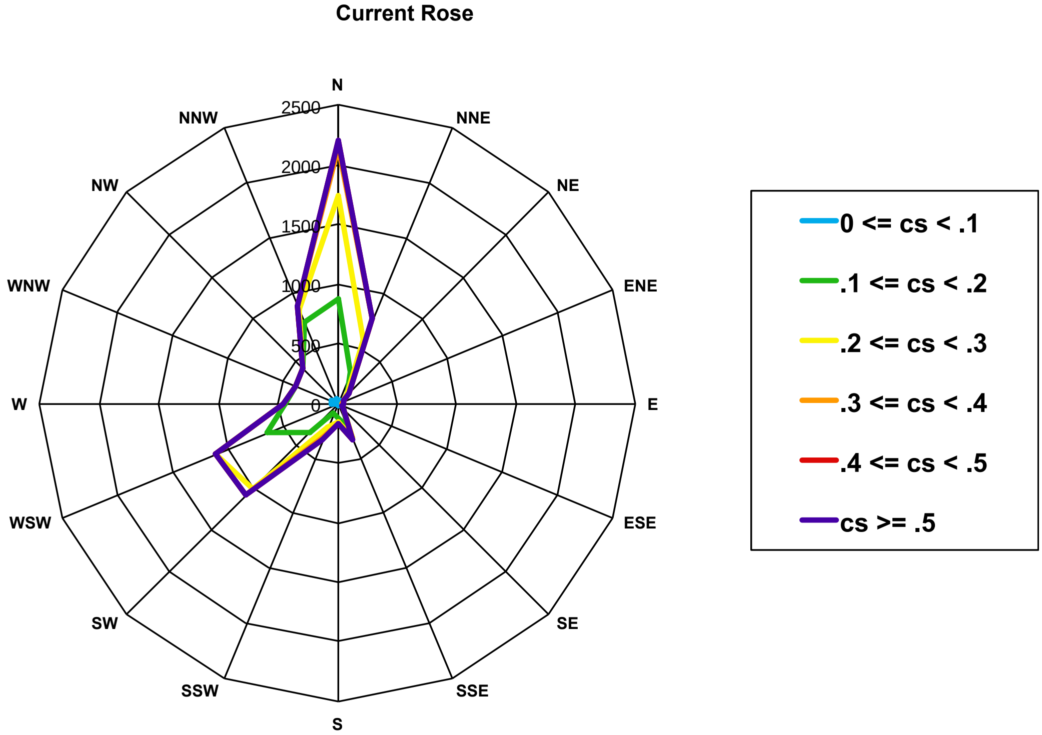


Figure 3.35 Current rose at Relocation grounds (AMB 8). The legend shows the cs (m/s), current speed, ranges and the number of recorded values are labelled on the radar axis

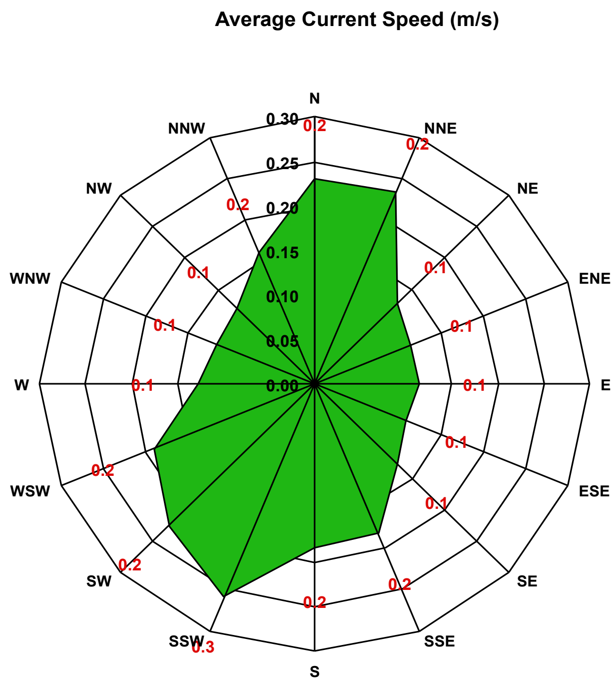


Figure 3.36 Average current speed rose at Relocation grounds (AMB 8). Red numbers indicate average current speed (m/s) at specified direction. Average current speed (m/s) is labelled on the radar axis. Green area shows the recorded average current speed data

Victor Islet (AMB 10) current meter data

Current at Victor Island (21/10/2015 to 03/12/2015) (AMB 10) is predominantly in the SSW and NNE directions (Figure 3.37). The average current velocity is 0.2 m/s in both directions (Figure 3.38). The tidal change in current is a 180-degree change in current direction.

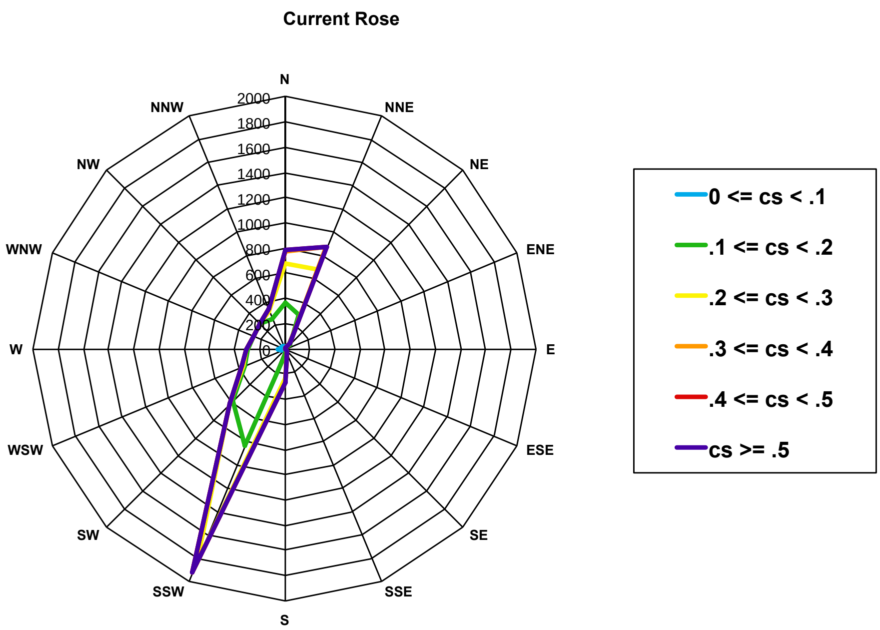


Figure 3.37 Current rose at Victor Islet (AMB 10). The legend shows the cs (m/s), current speed, ranges and the number of recorded values are labelled on the radar axis

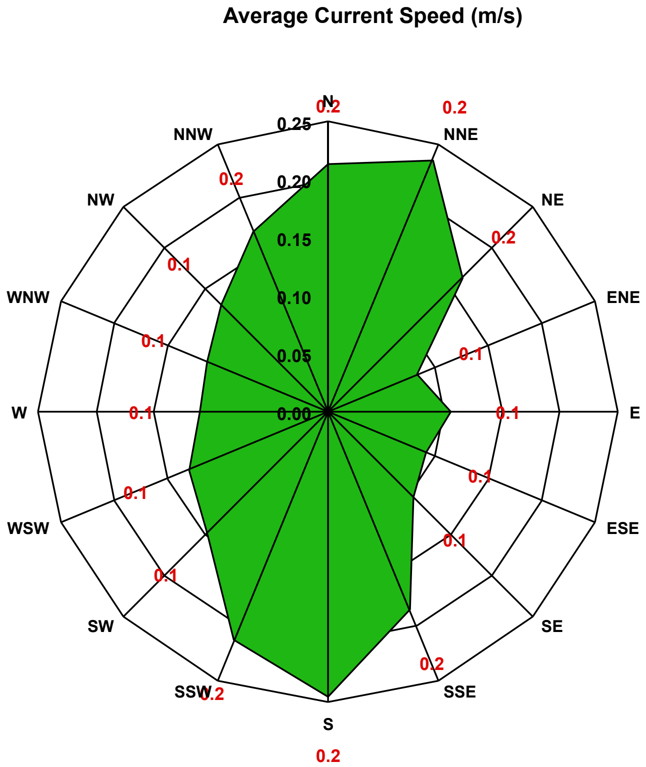


Figure 3.38 Average current speed rose at Victor Islet (AMB 10). Red numbers indicate average current speed (m/s) at specified direction. Average current speed (m/s) is labelled on the radar axis. Green area shows the recorded average current speed data

3.4 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.

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

Equation 2 - where $\hat{T}(t)$ is the predicted daily turbidity, α1-6 and β1-5 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 3.39 – 3.45). 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 2014 through to June 2015 to fit the parameters and data from July 2015 through to July 2016 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 3.9). These R^2 values show that the models performed well when tested and with the continuation of *in-situ* data collection these predictive models will only increase in their predictive accuracy.

The R^2 values for the fit period will generally be higher than for the prediction period because the model parameters are adjusted to force the model result to match as closely as possible to the data. When the model is run for the prediction, variation that the model does not represent becomes evident as an increased divergence between the model and the data.

Table 3.9 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	Hay Reef (AMB 2)	Freshwater Point (AMB 1)	Keswick Island (AMB 12)	Round Top Island (AMB 3B)	Slade Islet (AMB 5)	Victor Island (AMB 10)	Relocation grounds (AMB 8)
Fit period	0.70	0.66	0.60	0.61	0.63	0.59	0.63
Test period	0.69	0.33	0.16	0.42	0.36	0.32	0.02

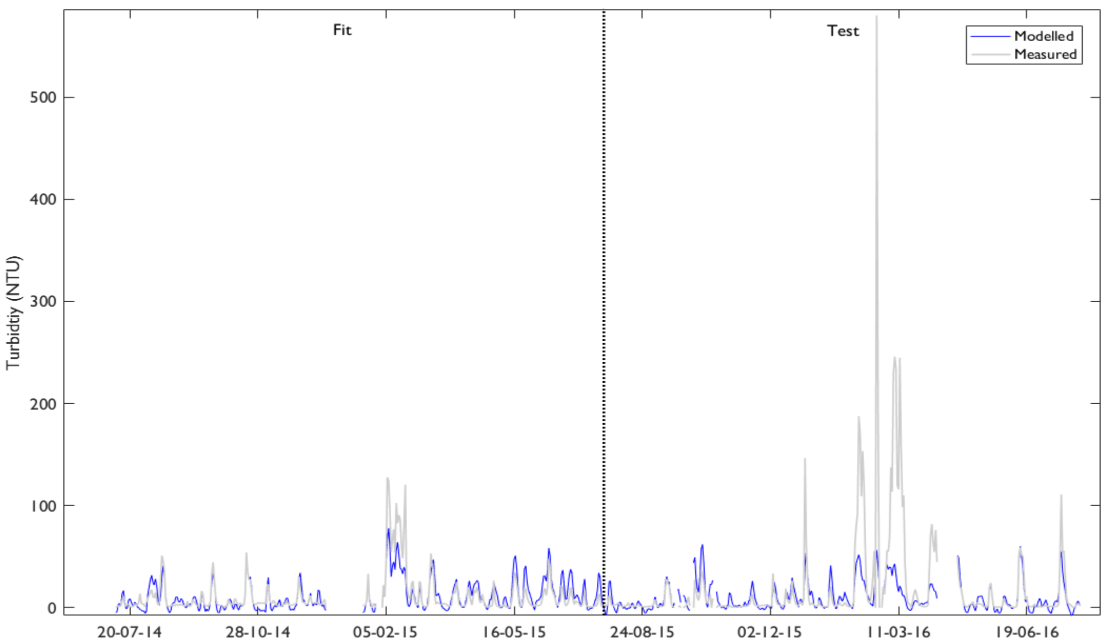


Figure 3.39 Freshwater Point (AMB 1) predictive NTUe/SSC model. The model was generated using the first twelve months of data (July 2014 to July 2015) and tested on the remaining data (August 2015 to July 2016)

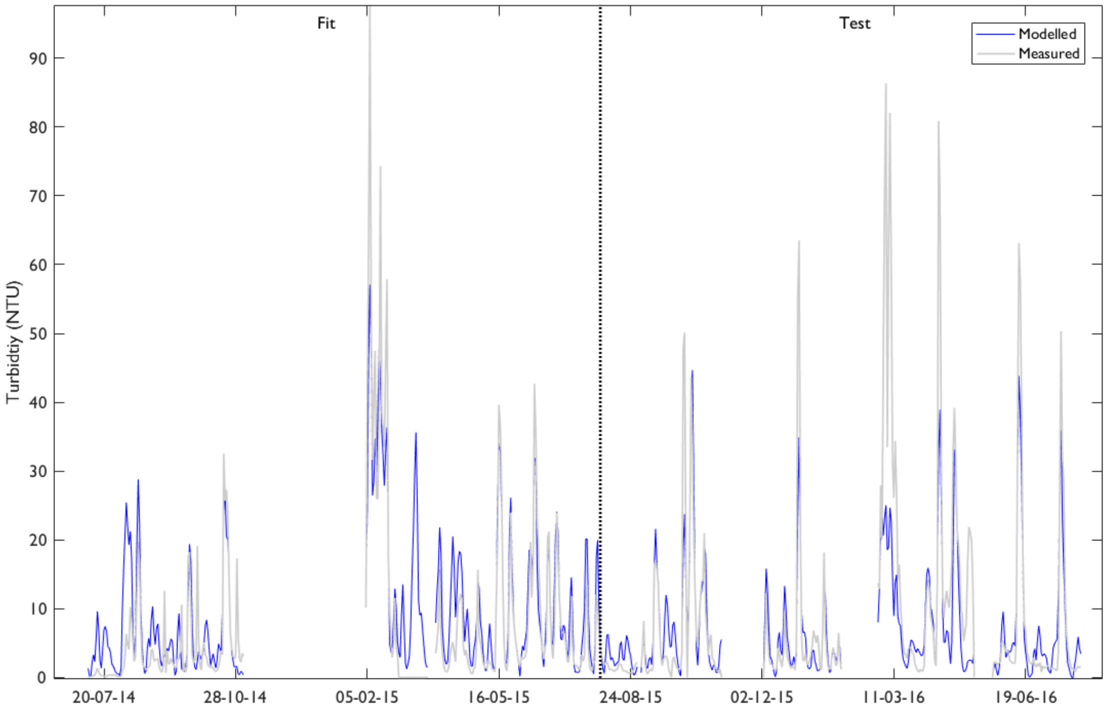


Figure 3.40 Hay Reef (AMB 2) predictive NTUe/SSC model. The model was generated using the first twelve months of data (July 2014 to July 2015) and tested on the remaining data (August 2015 to July 2016)

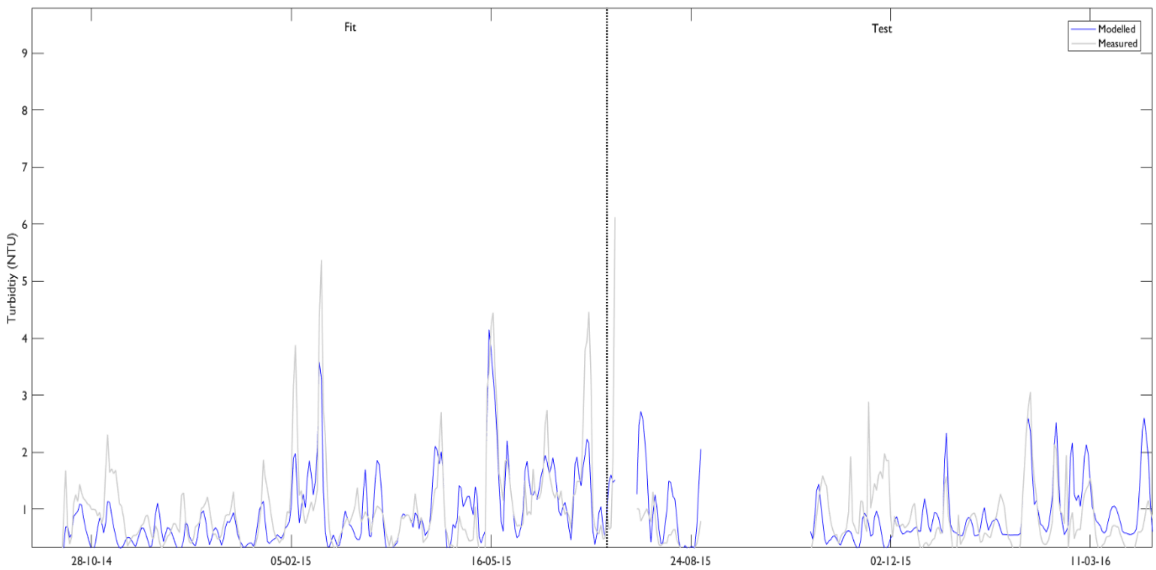


Figure 3.41 Keswick Island (AMB 12) predictive NTUe/SSC model. The model was generated using the first twelve months of data (July 2014 to July 2015) and tested on the remaining data (July 2015 to July 2016)

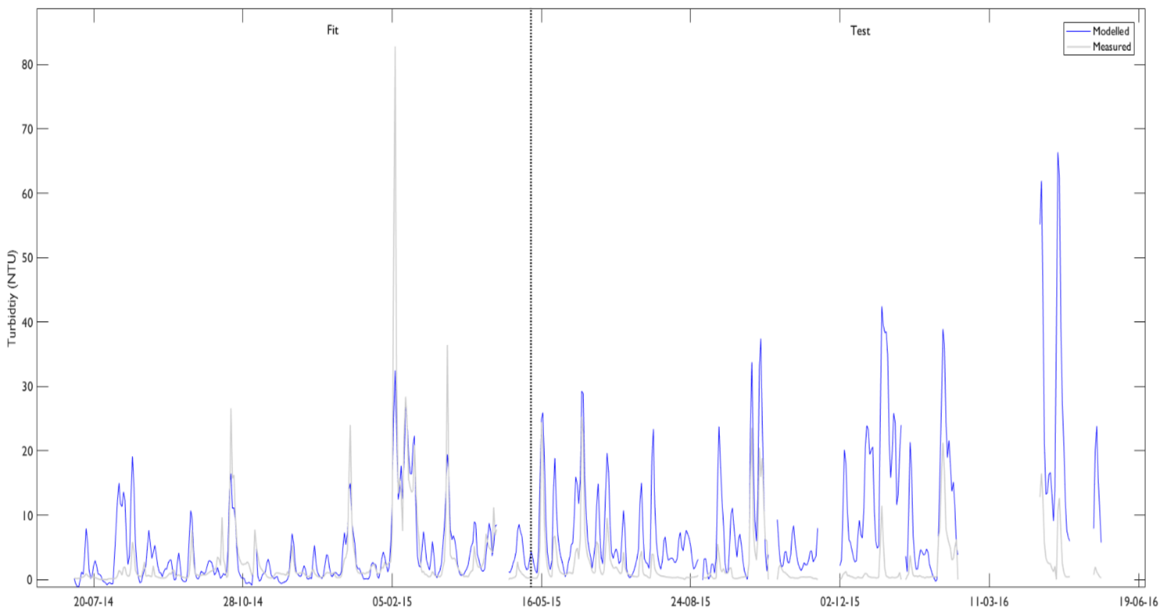


Figure 3.42 Round Top Island (AMB 3) predictive NTUe/SSC model. The model was generated using the first ten months of data (July 2014 to May 2015) and tested on the remaining data (May 2015 to July 2016)

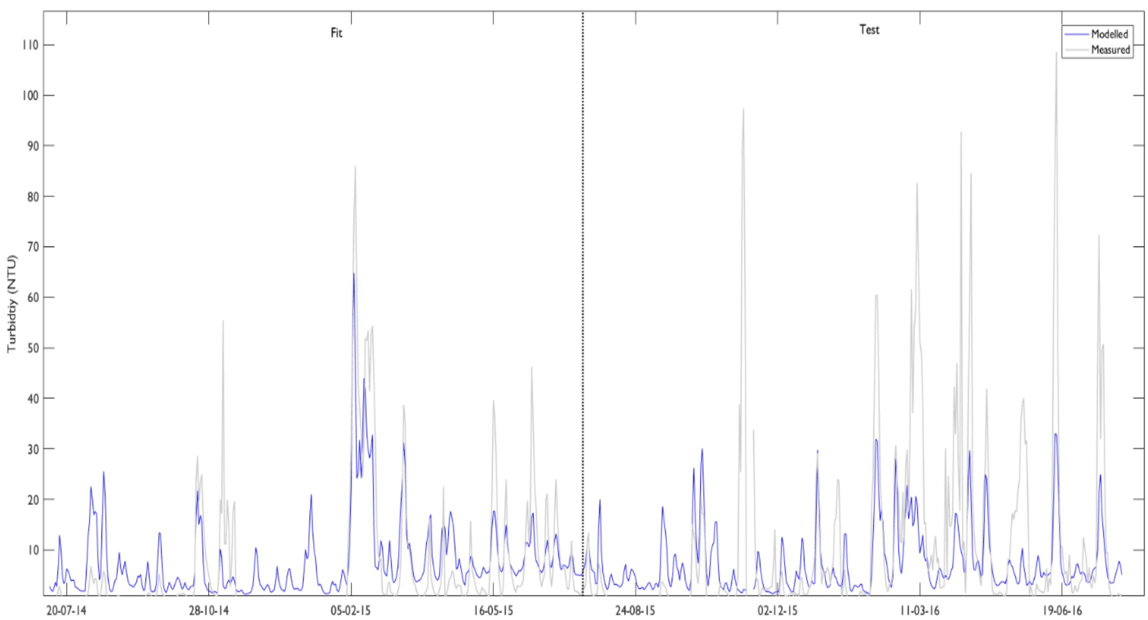


Figure 3.43 Slade Islet (AMB 5) predictive NTUe/SSC model. The model was generated using the first twelve months of data (July 2014 to July 2015) and tested on the remaining data (July 2015 to July 2016)

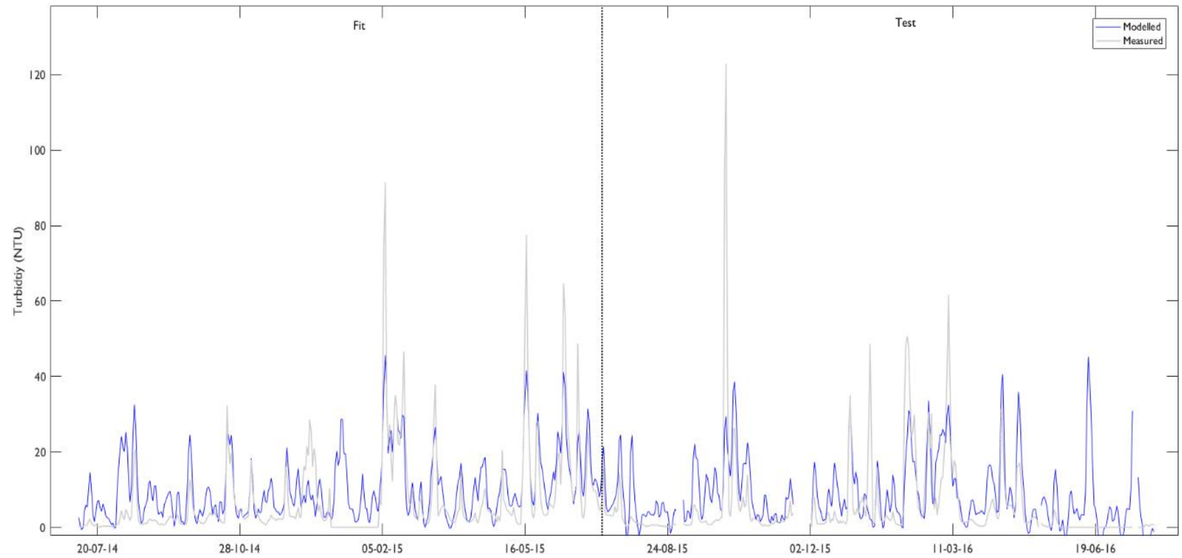


Figure 3.44 Victor Islet (AMB 10) predictive NTUe/SSC model. The model was generated using the first twelve months of data (July 2014 to July 2015) and tested on the remaining data (July 2015 to July 2016)

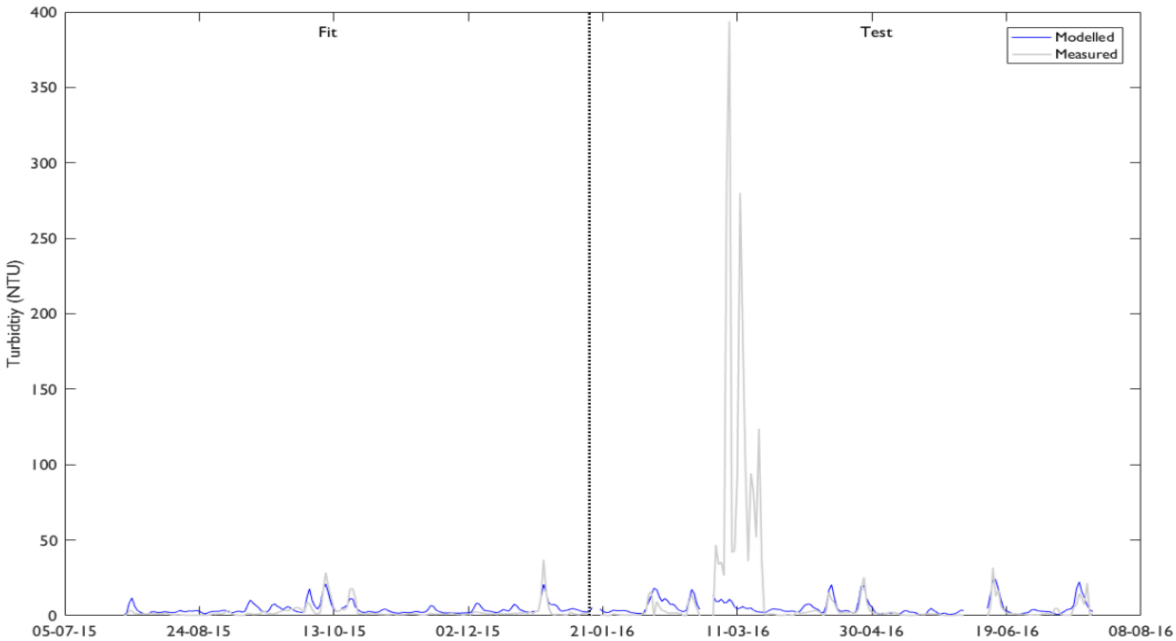


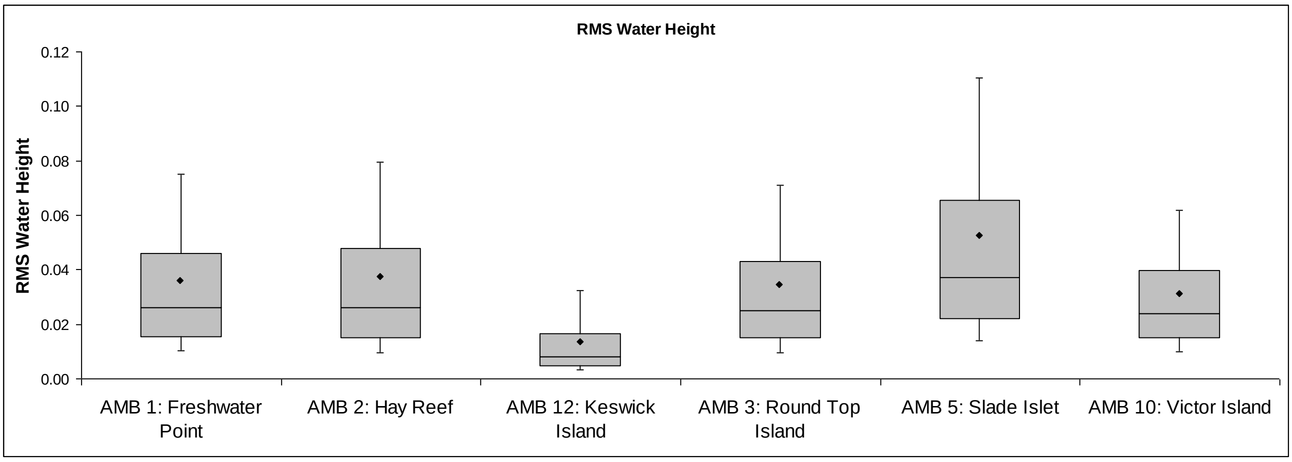
Figure 3.45 Relocation grounds (AMB 8) predictive NTUe/SSC model. The model was generated using the first six months of data (July 2015 to January 2016) and tested on the remaining data (January 2016 to July 2016)

3.6 Data comparison: 2014/2015 to 2015/2016

Comparison of the 2014/2015 and 2015/2016 statistics provides a larger 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 system. Results are expected to have small variations year to year due to natural variation in weather and oceanographic systems.

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 recorded or change in weather events for the year. The figures below are box plots of RMS water height from 2014/2015 and 2015/2016 (Figure 3.46). Inspection of trends in the figures features very similar results between the years. As expected, sites with low RMS values in 2014/2015 have remained low in 2015/2016 and the same for sites with high RMS water height values. On closer inspection, there are subtle differences among sites, of which the only worth noting is in Round Top Island (AMB 3) data. This site showed an increase in RMS water height values from 2014/2015 to 2015/2016. These differences are attributed to a small change to a more exposed location of this site. Other slight differences in the data are most likely the result of weather variances from year to year.

a)



b)

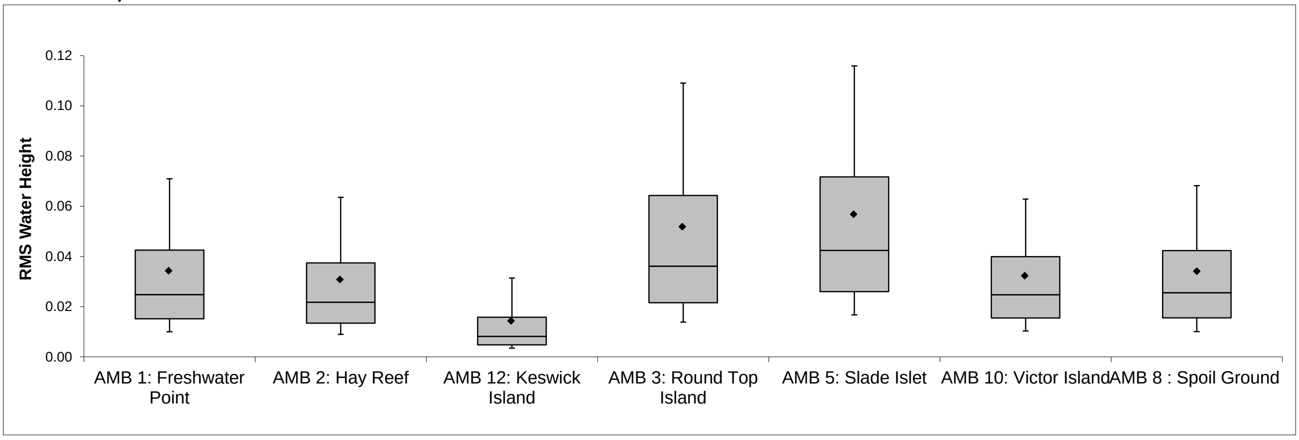
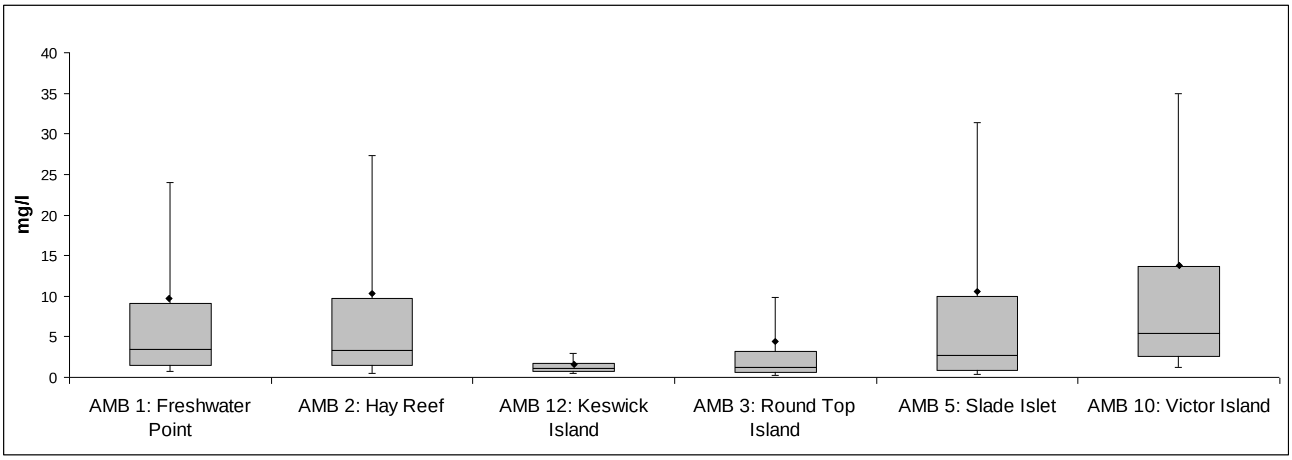


Figure 3.46 RMS water height (m) box plots for: a) 2014/15; and b) 2015/16

SSC

SSC values show similar values in yearly statistical results (Figure 3.47). Keswick Island (AMB 12) and Round Top Island (AMB 3) have SSC data showing very low values. Freshwater Point (AMB 1) had a much more variance in the second year of data. A large SSC event that includes very high spikes is present in the 2015/2016 data and is reason the variance is shown to have increased for this year. Victor Island (AMB 10) has notably larger SSC values for the 2015/2016 data set. A closer analysis of the data is required before any statements on the driving forces behind this increase can be made.

a)



b)

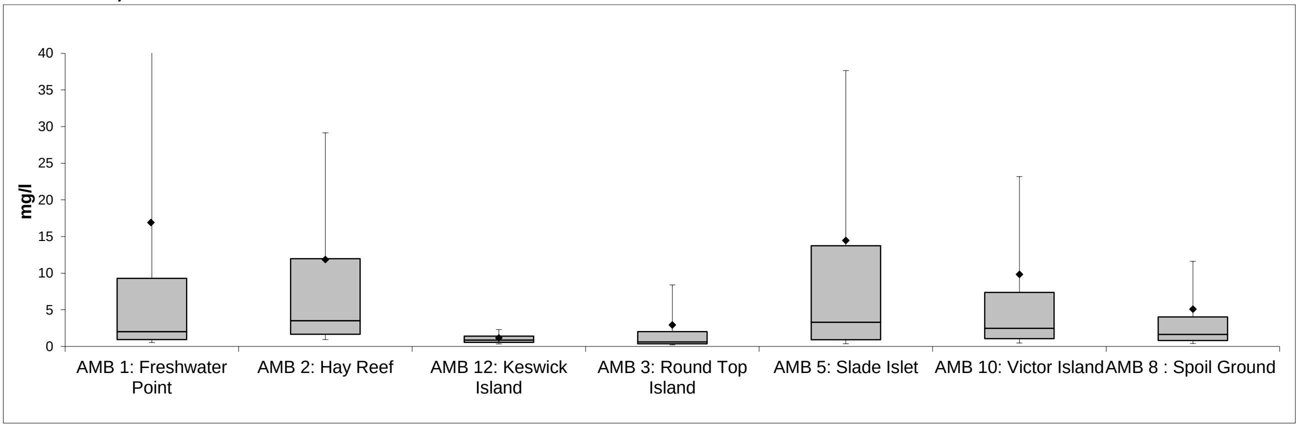
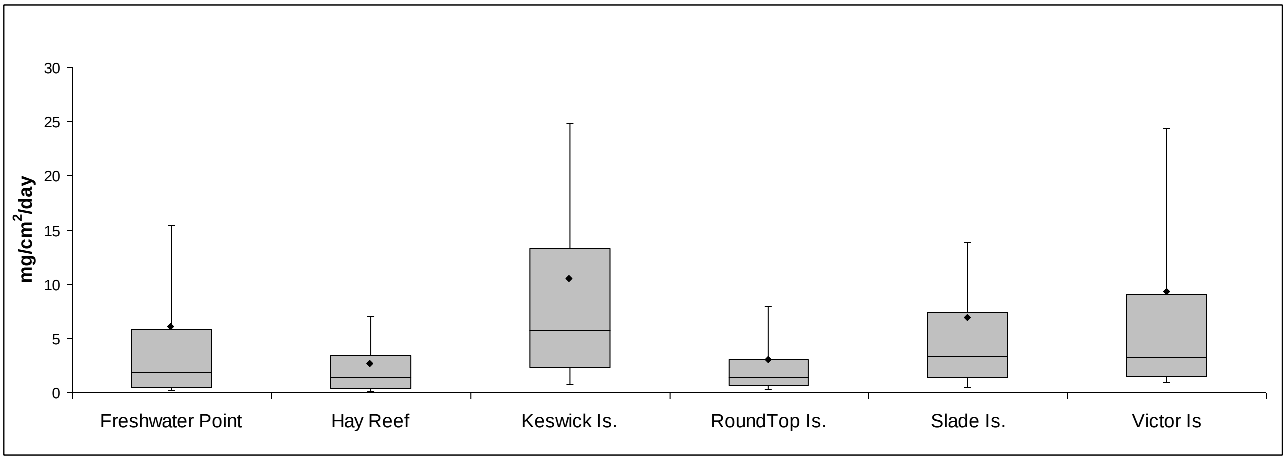


Figure 3.47 Suspended sediment concentration box plots for: a) 2014/15; and b) 2015/16

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 3.48). Slade Island (AMB 5) and Victor Island (AMB 10) showed more obvious decreases in deposition rate in the 2015/2016 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.

a)



b)

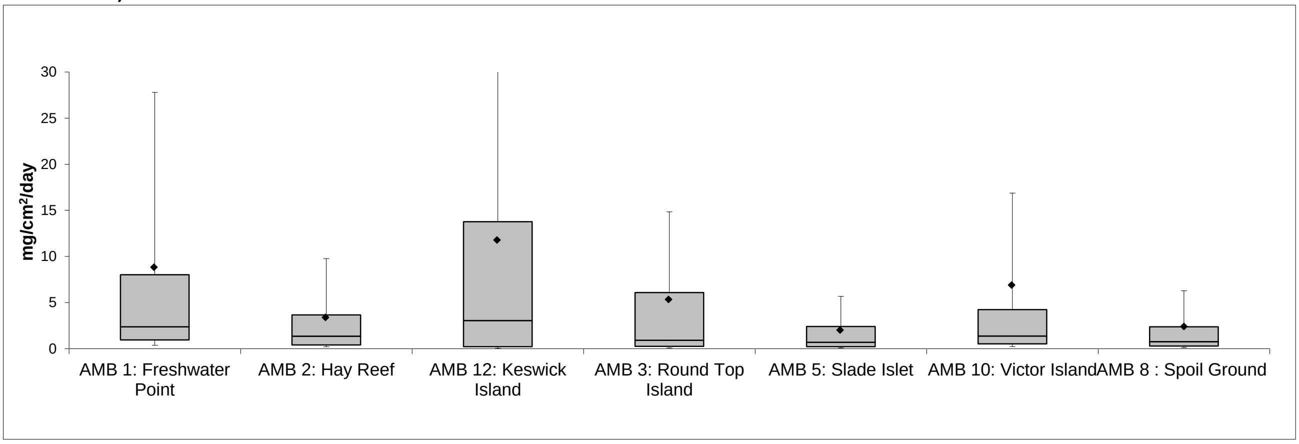


Figure 3.48 2hr deposition rate box plots for: a) 2014/15; and b) 2015/16

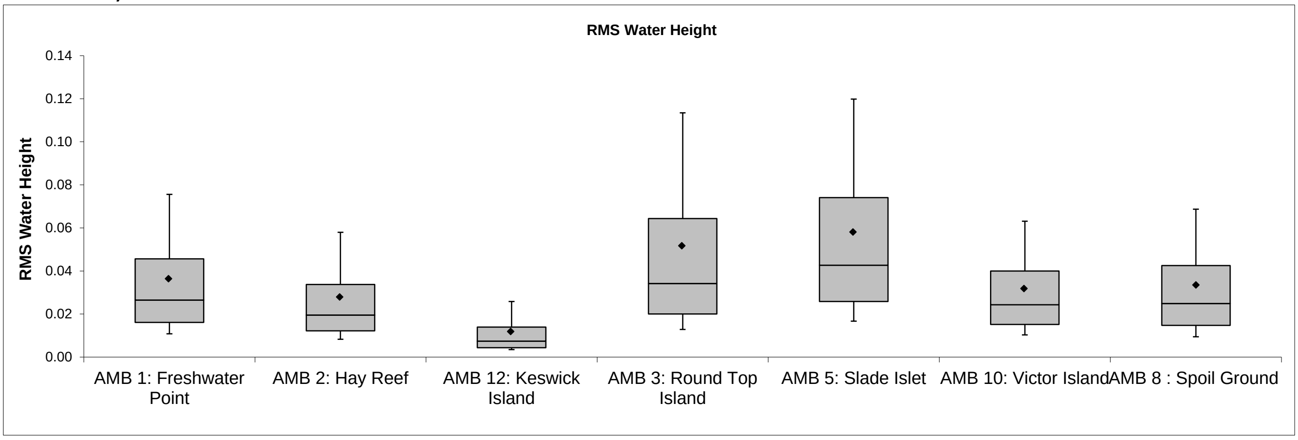
3.7 Seasonal variation: wet vs dry

Seasonal variation of all marine water properties is often assumed. The following comparison of wet (November through March) and dry (April through October) season statistics at all monitored sights shows there to be much less variation than may be expected.

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. The results from the 2015/2016 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 3.49).

a)



b)

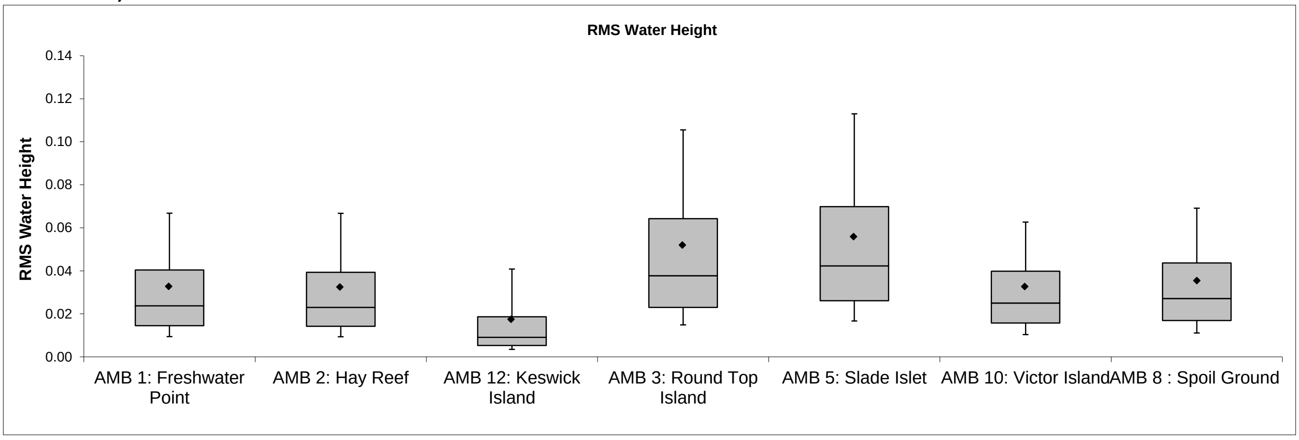


Figure 3.49 2015/16 RMS water height (m) box plots for: a) wet season; and b) dry season

SSC

For some sites small differences in the statistical SSC results, between the wet and dry seasons, have been found (Figure 3.50). Median values were larger by approximately 1 mg/L at Freshwater Point (AMB 1) and Victor Islet (AMB 10) during the wet season. The Slade Islet (AMB 5) wet season median SSC was approximately 2 mg/L greater than in the dry season. The other sites had either slightly higher or lower values when comparing median values between wet and dry season. Higher variance during the wet season at Freshwater Point (AMB 1) is present, although this is likely due to one large event that is identified in the raw data set. Overall the SSC values do not change considerably between the wet and dry season statistics.

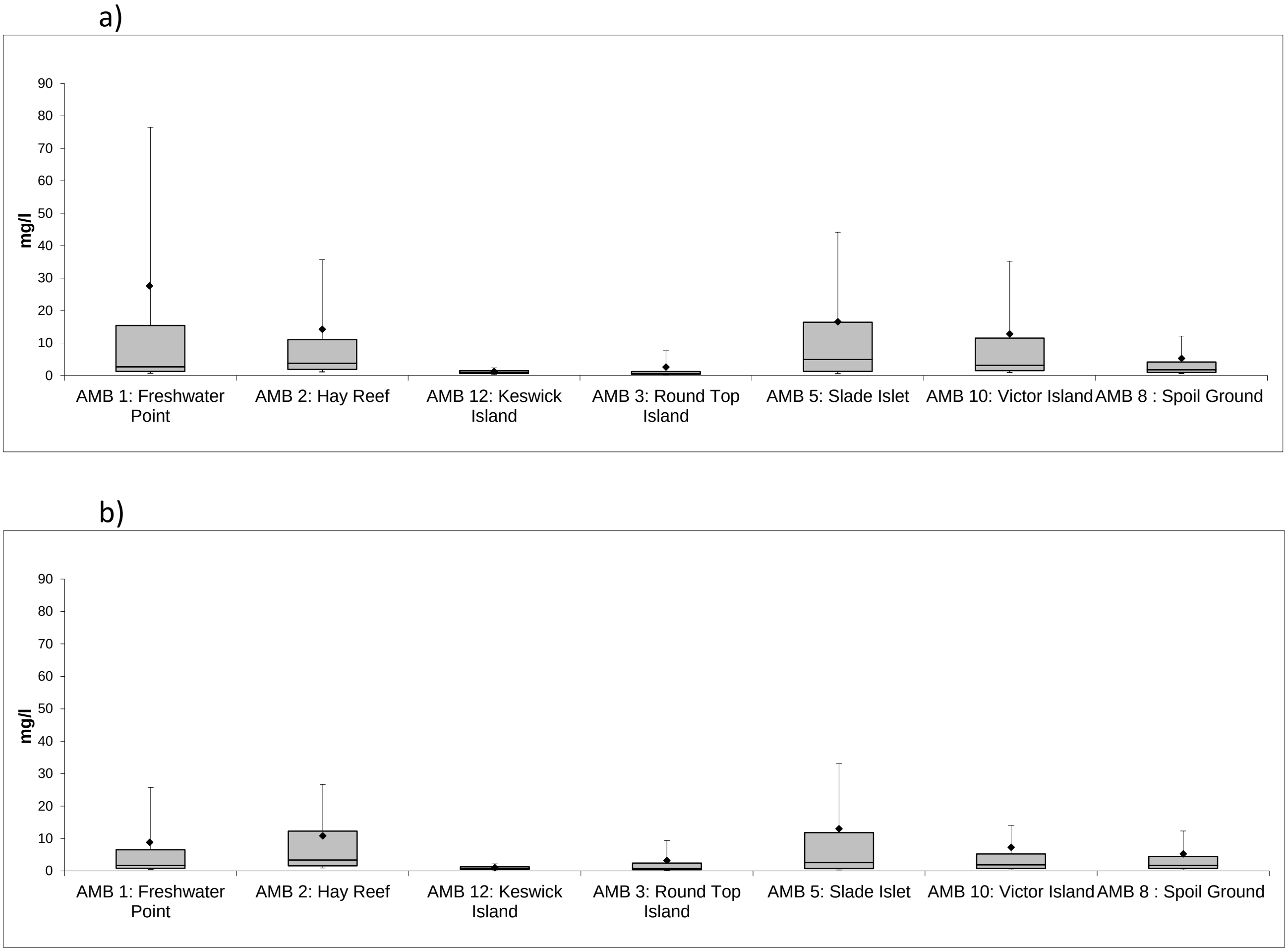
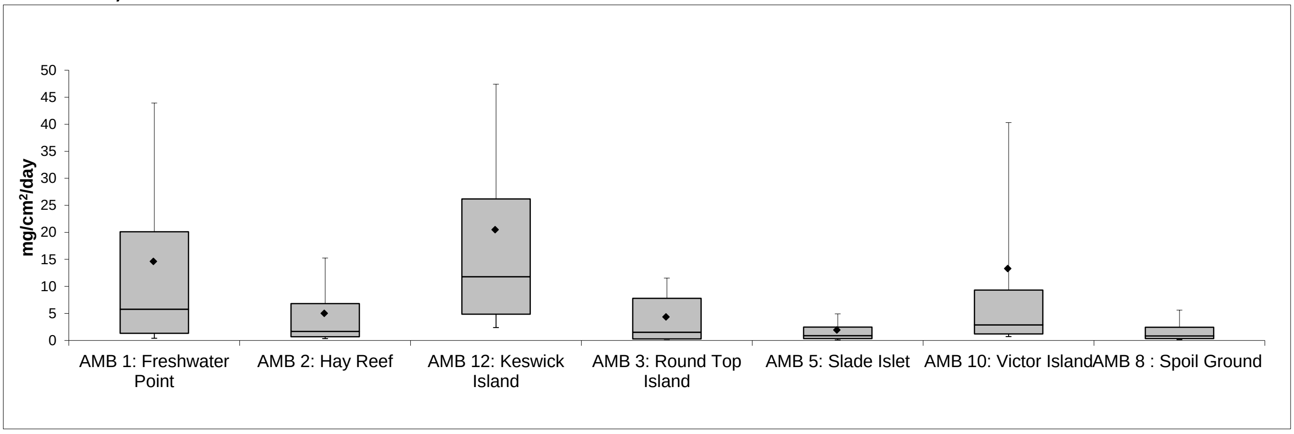


Figure 3.50 2015/16 SSC box plots for: a) wet season; and b) dry season

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) and Victor Islet (AMB 10) (Figure 3.51). These three sites show increases in the median and variance values during the wet season period. Keswick Island (AMB 12) had a very large deposition event that is likely the main cause of the difference observed, rather than a continuous increase in deposition rate. 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 2015/2016 results.

a)



b)

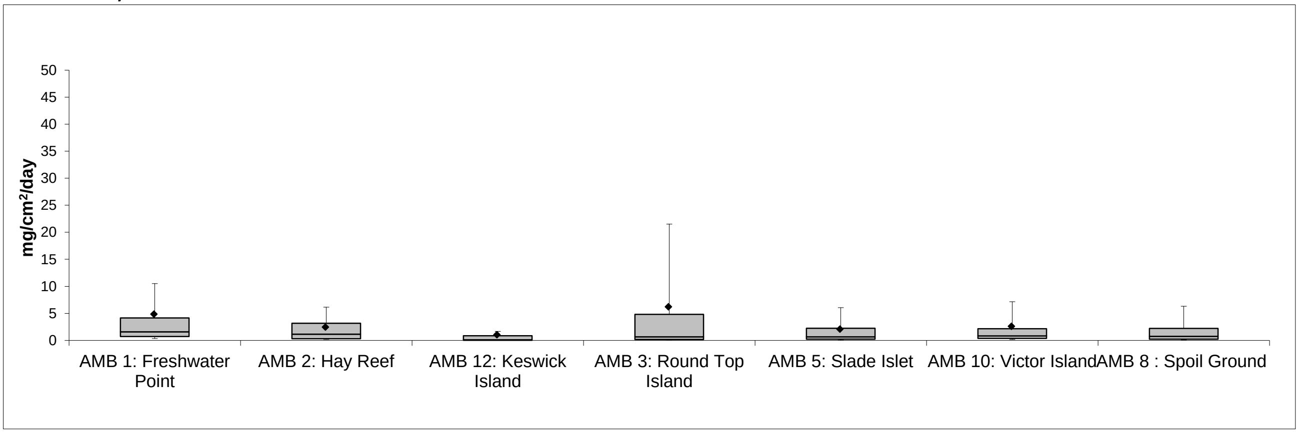


Figure 3.51 2015/16 2hr deposition rate box plots for: a) wet season; and b) dry season

Total daily PAR

Daily total PAR values appear very similar between the wet and dry season statistics (Figure 3.52). Some sites show increased total daily PAR during the wet season while others have increased total daily PAR during the dry season. It may have been expected that the wet season data would show increased total daily PAR due to the longer daylight hours, although the data shows that there is no indication of this being an influential factor in the statistical results.

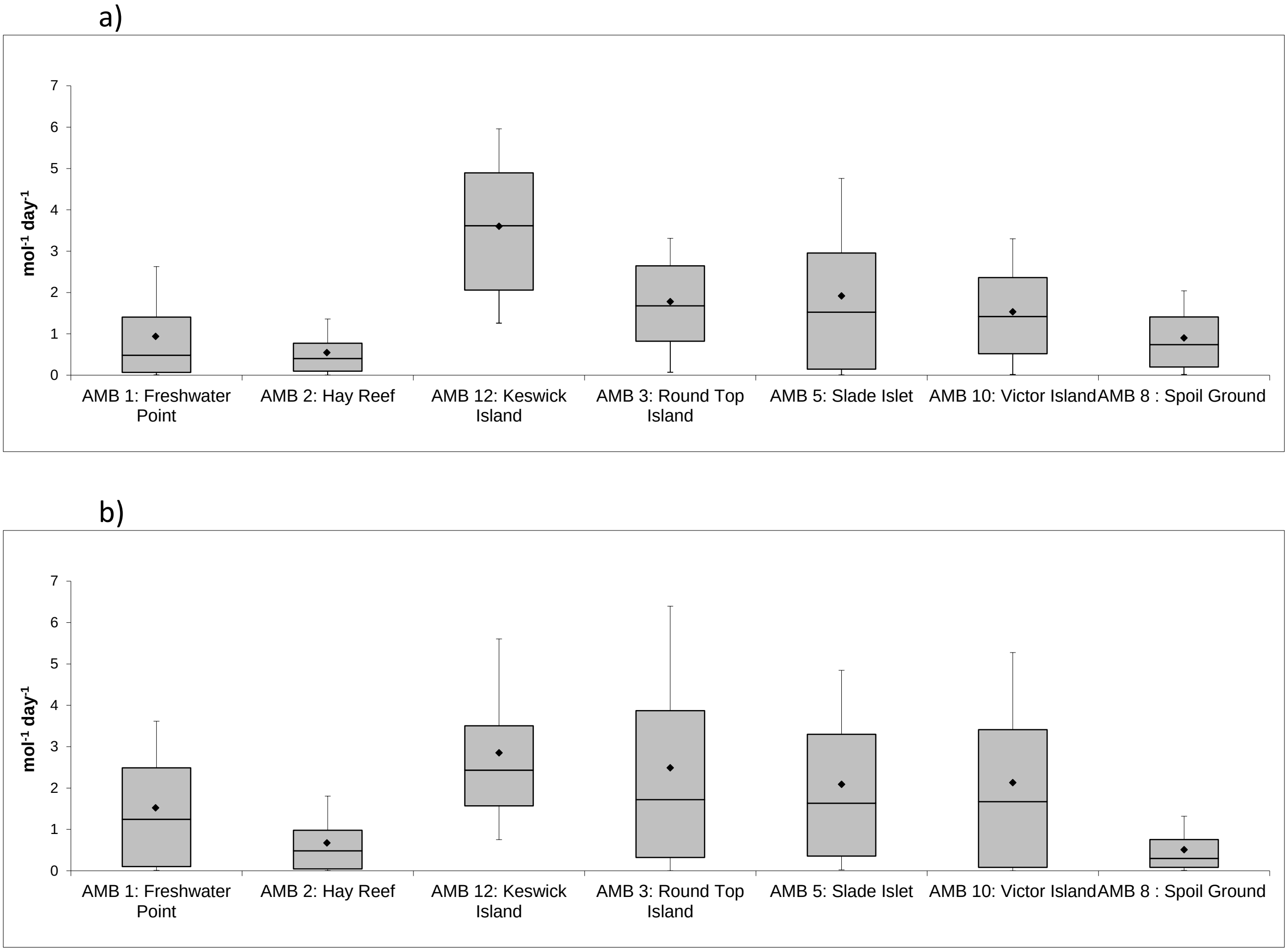
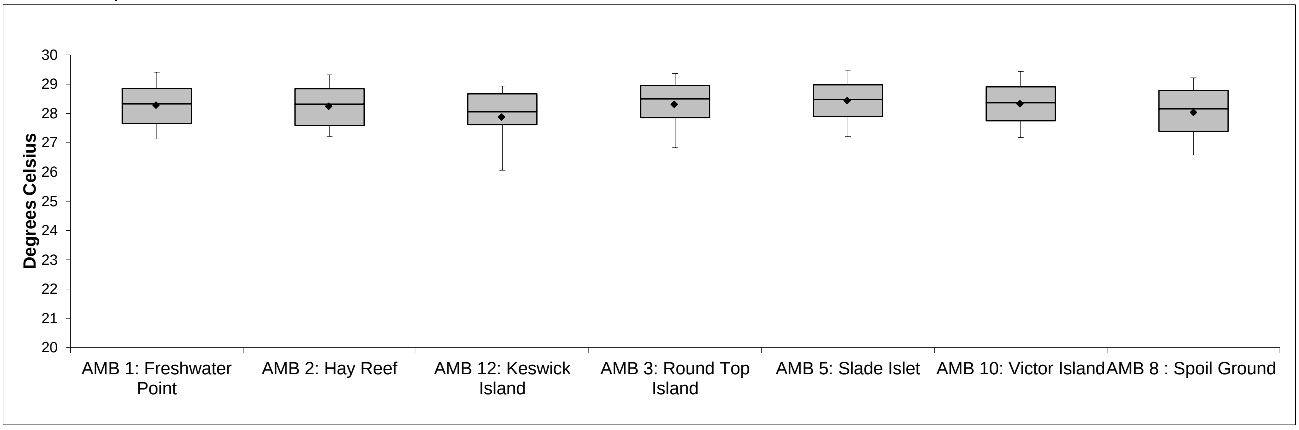


Figure 3.52 2015/16 PAR box plots for a) wet season; and b) dry season

Water temperature

There is a clear pattern of differences in water temperature between the wet and dry season (Figure 3.53). 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. Interestingly the deepest site, Relocation grounds (AMB 8), had the highest median temperature during the dry season. A possible explanation is that water temperature at the site was less influenced by atmospheric changes in temperature.

a)



b)

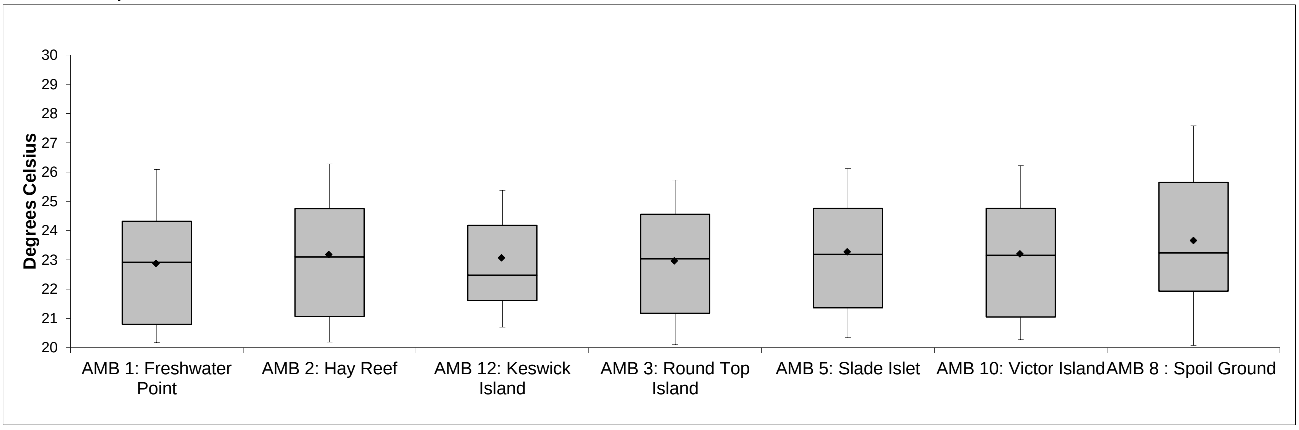


Figure 3.53 2015/16 water temperature box plots for a) wet season; and b) dry season

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 74% 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 the NWSE wind component. Together these two variables explained about 62% of SSC variability at Freshwater Point (Figure 3.54). NESW wind component, Sandy River discharge and tide amplitude combined explained around 12% of SSC variability. Results of the partial effects plots (Figure 3.55) 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 Sandy River discharge 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 2014-2015 monitoring of Freshwater Point. The only difference between the two monitoring periods being that Pioneer River discharge was replaced by the Sandy river discharge in this years' model.

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

Coefficients

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	5.733275	0.461840	12.414	< 2e-16 ***
Log (RMS)	1.795489	0.118036	15.211	< 2e-16 ***
Log (Sandy + 1)	0.169216	0.027141	6.235	1.52e-09 ***
wind_NESW	0.029214	0.007770	3.760	0.000204 ***
Wind_NWSE	-0.032947	0.008069	-4.083	5.68e-05 ***
Amplitude	0.276245	0.046053	5.998	5.67e-09 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.8161 on 303 degrees of freedom
Multiple R-squared: 0.7428, Adjusted R-squared: 0.7386
F-statistic: 175 on 5 and 303 DF, p-value: < 2.2e-16

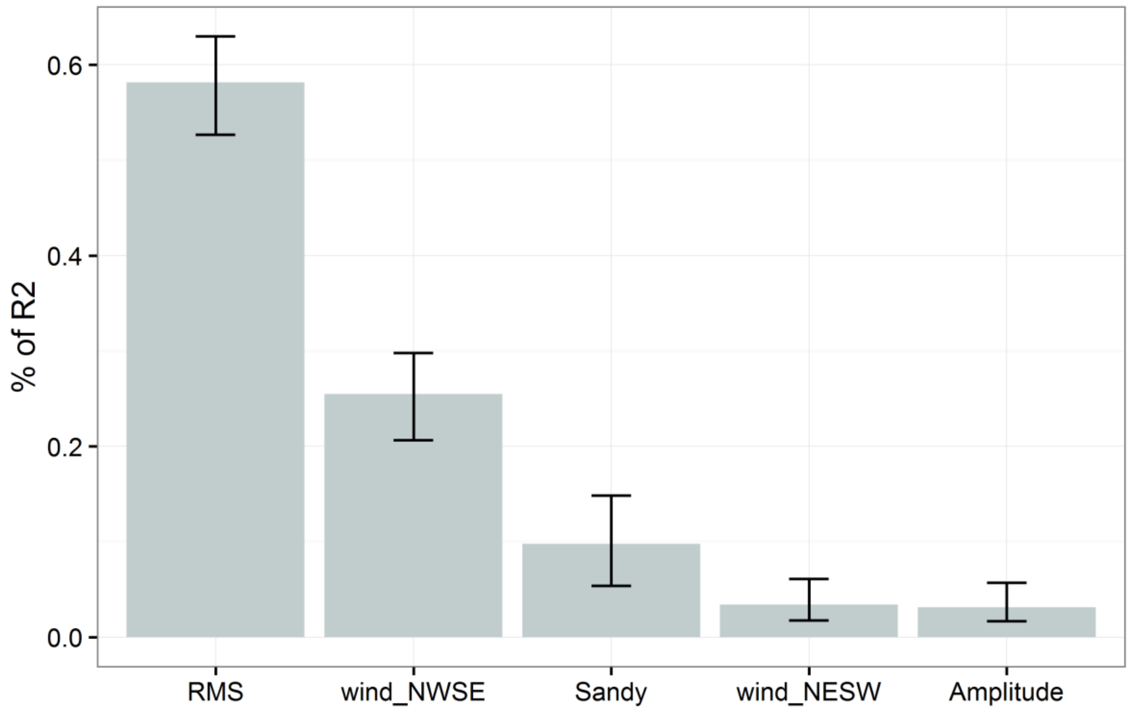


Figure 3.54 Freshwater Point bootstrapping relative importance analysis following a stepwise multiple regressionanalysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall R^2 = 0.74

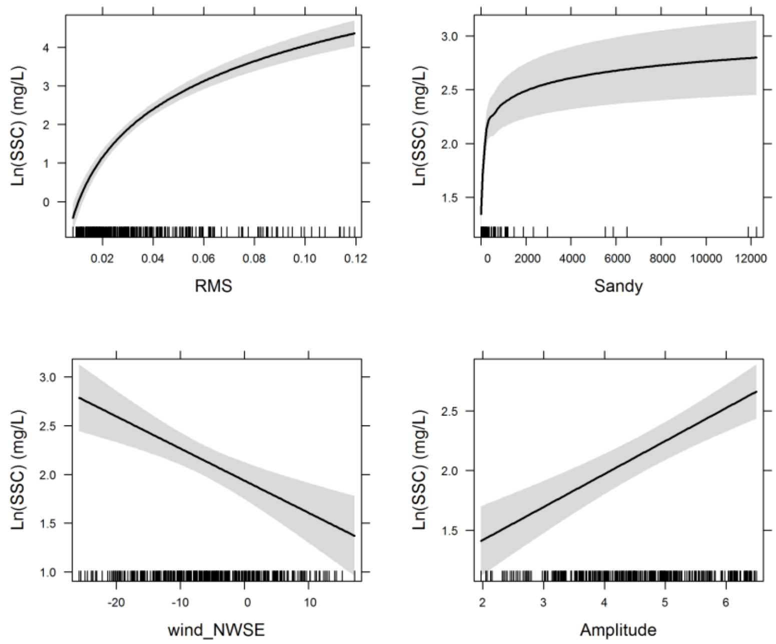


Figure 3.55 Partial effect plots for Freshwater Point parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

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, the wind component NESW, tide amplitude and the Pioneer River discharge explained 68% 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 48% of the SSC variability at Hay Point reef (Box 2). NESW wind component, Pioneer River discharge, wind component NESW and tide amplitude combined explained around 20% of SSC variability (Figure 3.56). Results of the partial effects plots (Figure 3.57) 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. The stronger the winds coming from the east (i.e. positive values for wind_NESW) the higher the SSC readings were. These results are similar to the Hay Point Reef site specific outputs for the 2014-2015 monitoring. The only difference being that Pioneer River discharge was 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)	4.682956	0.324967	14.411	< 2e-16 ***
Log (RMS)	1.394433	0.072537	19.224	< 2e-16 ***
Log (Pioneer + 1)	0.230062	0.025464	9.035	< 2e-16 ***
wind_NESW	0.028358	0.005324	5.327	2.04e-07 ***
Amplitude	0.177470	0.037490	4.734	3.48e-06 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.6759 on 284 degrees of freedom
Multiple R-squared: 0.6806, Adjusted R-squared: 0.6761
F-statistic: 151.3 on 4 and 284 DF, p-value: < 2.2e-16

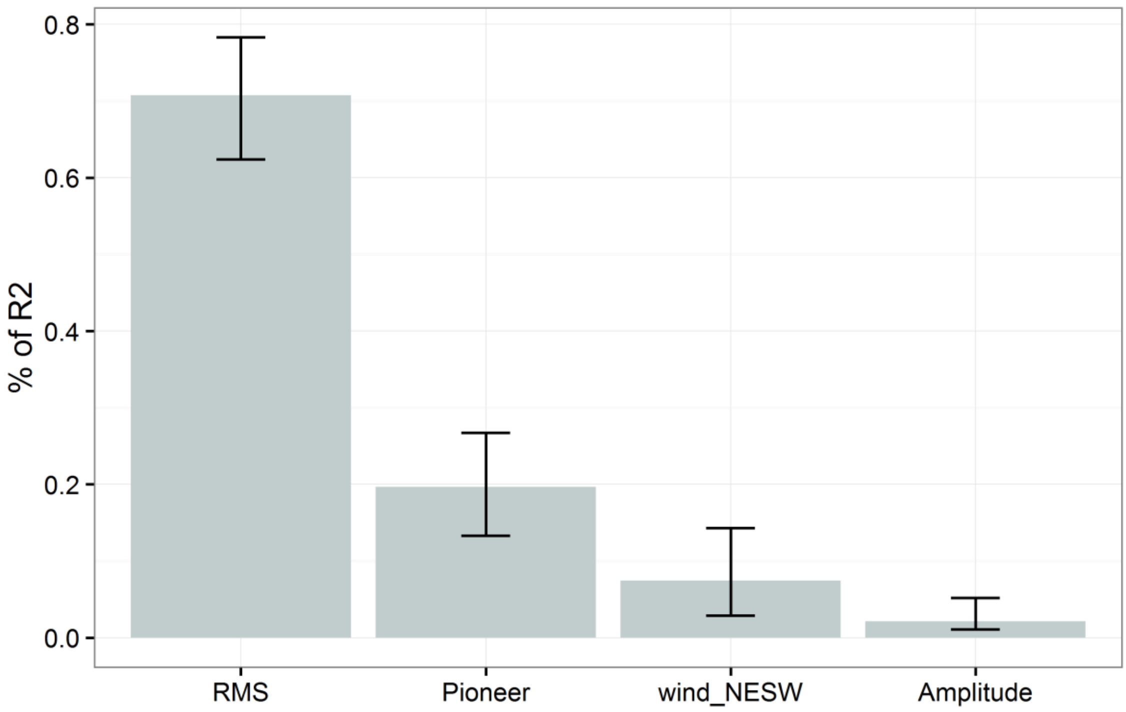


Figure 3.56 Hay Point Reef bootstrapping relative importance analysis following a stepwise multiple regressionanalysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall R^2 = 0.68

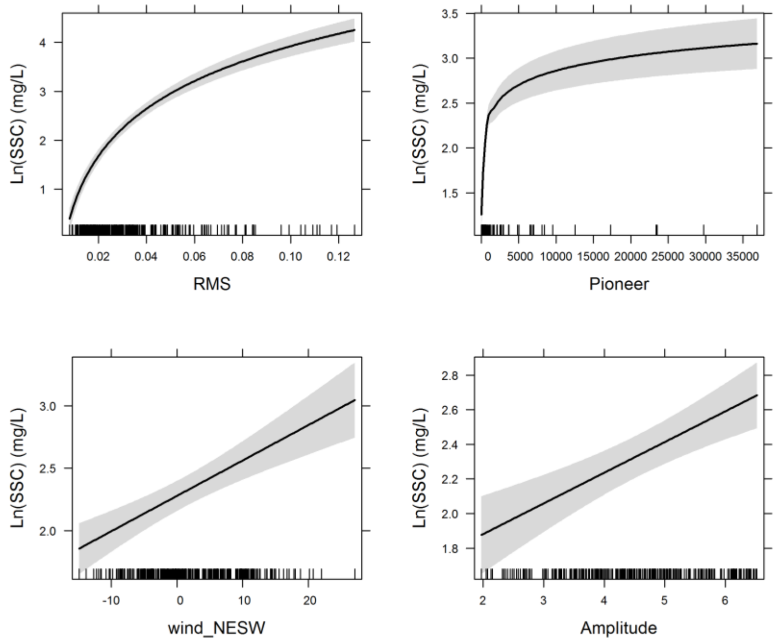


Figure 3.57 Partial effect plots for Hay Point Reef parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

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 40% of the SSC variability (Box 3). The relative importance analysis suggested that RMS of water depth and tidal amplitude were the most influential parameters on SSC, explaining about 31% of the SSC variability at Keswick Island (Box 3). The NWSE wind component and, Pioneer River and Sandy river discharges combined explained around 9% of SSC variability (Figure 3.58). Results of the partial effects plots (Figure 3.59) generally followed expected trends for SSC in relation to each environmental parameter selected in the model. The exception was the relationship between Pioneer River discharge and SSC which showed a weak negative relationship. Overall, an increase in SSC was observed with increases in the environmental predictors. The stronger the winds coming from the west (i.e. positive values for wind_NWSE) the higher the SSC readings were. These results are in accordance with last years' monitoring results in which a positive relationship was found between SW winds and SSC and is probably a function of the location of Keswick Island which is protected from NE winds by Keswick Island and St Bees Island. As concluded in the 2014-15 monitoring report, the high influence of tidal amplitude for this site may be due to its location where tidal currents are amplified close to the channel between the islands.

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

Coefficients

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	2.298322	0.446134	5.152	5.68e-07 ***
Log (RMS)	0.619552	0.080460	7.700	4.39e-13 **
Log (Pioneer + 1)	-0.145545	0.035601	-4.088	6.07e-05 ***
Log (Sandy + 1)	0.100664	0.029939	3.362	0.00091 ***
wind_NWSE	0.016672	0.006437	2.590	0.01023 *
Amplitude	0.249199	0.031167	7.996	6.93e-14 ***

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

Residual standard error: 0.5086 on 223 degrees of freedom

Multiple R-squared: 0.4043, Adjusted R-squared: 0.391

F-statistic: 30.27 on 5 and 223 DF, p-value: < 2.2e-16

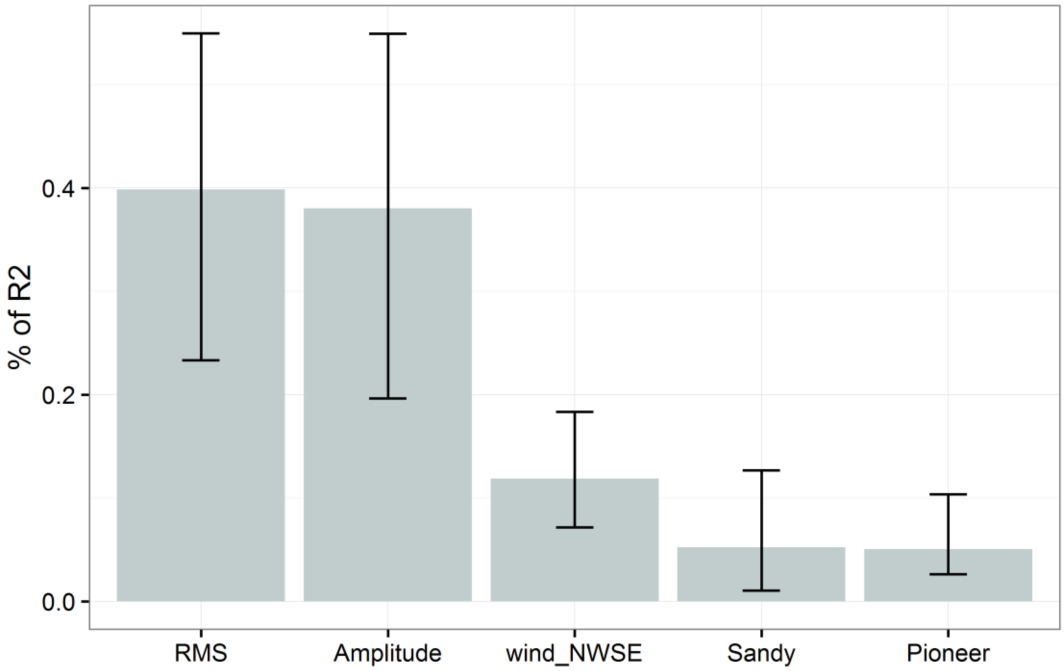


Figure 3.58 Keswick Island bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall R^2 = 0.40

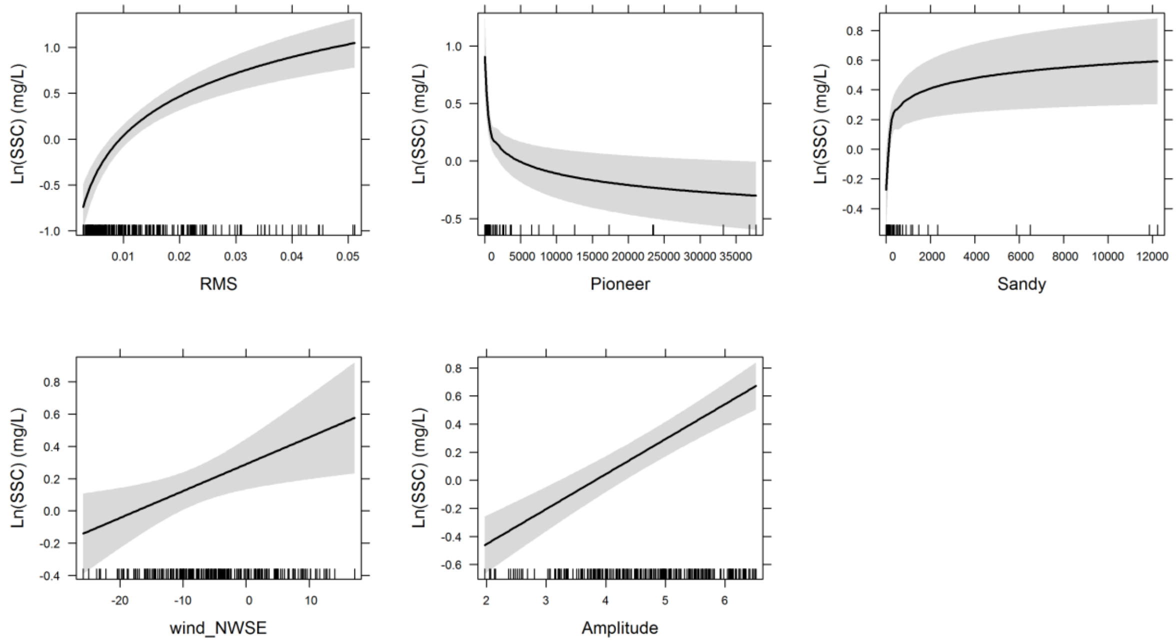


Figure 3.59 Partial effect plots for Keswick Island parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

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, Pioneer River discharge, both the wind components and tide amplitude together explained about 50% of the SSC variability (Box 4). The relative importance analysis suggested that RMS of water depth was the most influential parameter on SSC, explaining about 29% of the SSC variability at Round Top Island (Box 4). The remaining variables combined explained around 21% of SSC variability (Figure 3.60). Results of the partial effects plots (Figure 3.61) followed expected trends for SSC in relation to each environmental parameter selected in the model. Patterns in SSC were observed against all the environmental parameters with the Pioneer River discharge 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 consistent with the Freshwater Point site specific outputs as well as the models for Round Top Island reported for the 2014-2015 monitoring.

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

Coefficients

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	1.61270	0.61876	2.606	0.009813 **
Log (RMS)	1.05918	0.14402	7.354	4.35e-12 ***
Log (Pioneer + 1)	0.18963	0.04862	3.900	0.000130 ***
wind_NESW	0.03792	0.01067	3.553	0.000471 ***
wind_NWSE	-0.02077	0.00999	-2.079	0.038870 *
Amplitude	0.14511	0.06137	2.364	0.018979 *

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

Residual standard error: 0.8874 on 208 degrees of freedom

Multiple R-squared: 0.5087, Adjusted R-squared: 0.4969

F-statistic: 43.08 on 5 and 208 DF, p-value: < 2.2e-16

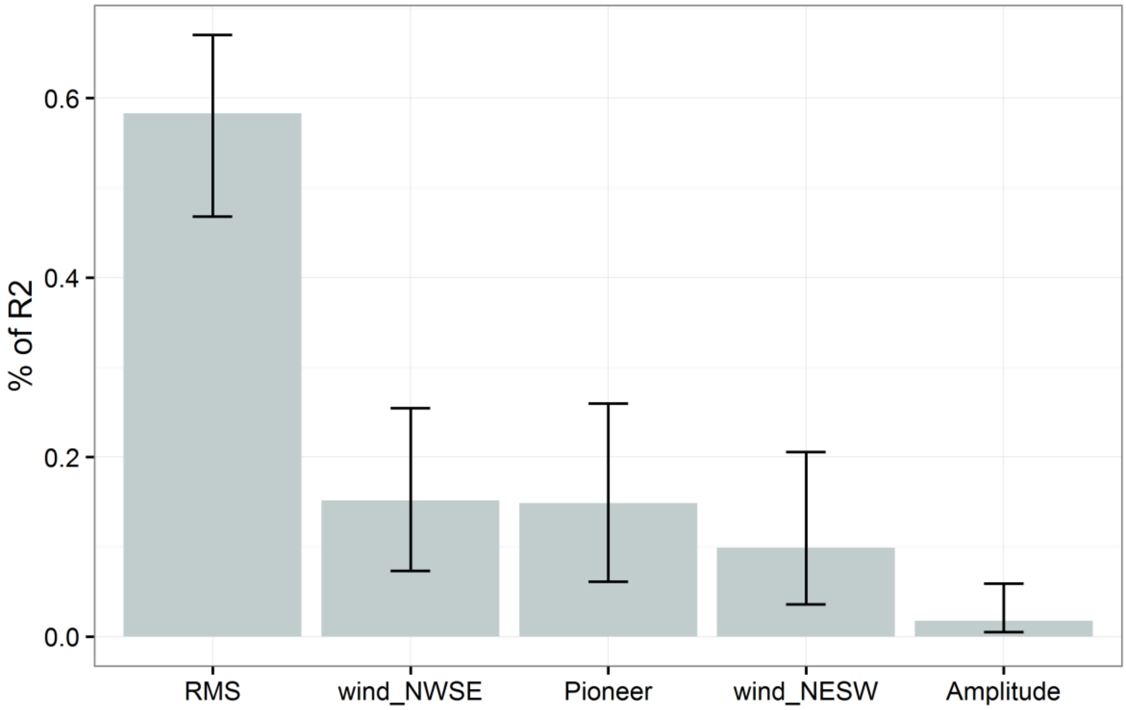


Figure 3.60 Round Top Island bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall $R^2 = 0.50$

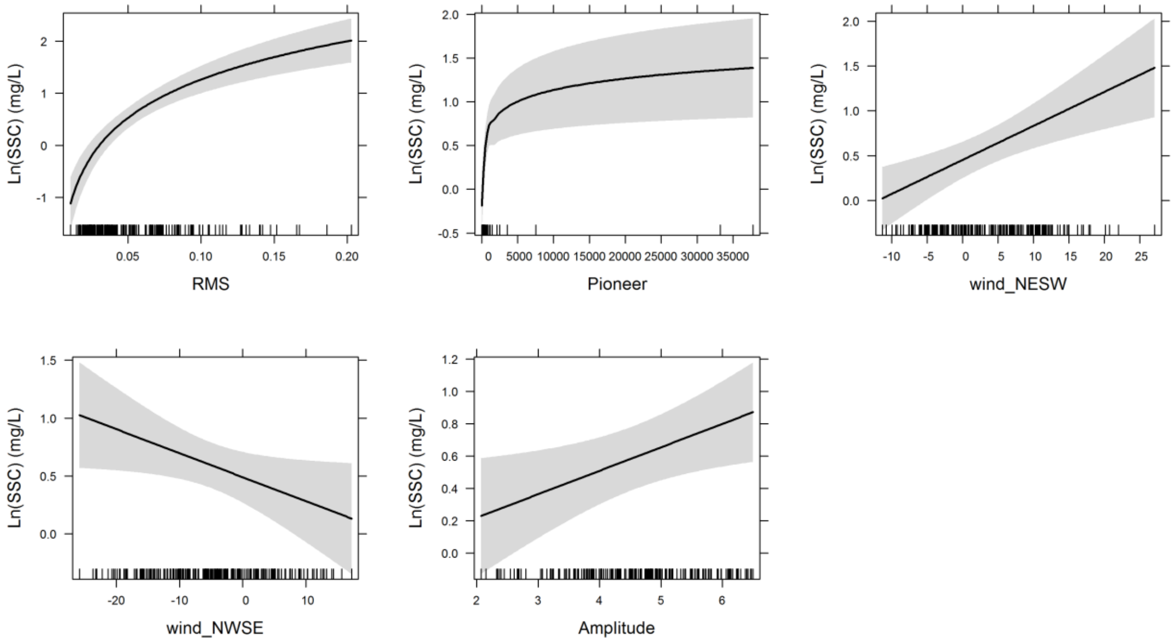


Figure 3.61 Partial effect plots for Round Top Island parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

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 and Sandy River discharges together explained about 36% 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 about 18 % of the SSC variability at Slade Islet (Box 5). The remaining discharge variables combined also explained around 18% of SSC variability (Figure 3.62). Overall, an increase in SSC was observed with increases in the environmental predictors although the discharge variables exhibiting wide confidence intervals (Figure 3.63). The results differ from the 2014-15 site specific monitoring with the discharge variables being influential in this years' model but neither of the wind components nor the tidal amplitude appeared to influence SSC variability.

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

Coefficients

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	3.4720	0.4900	7.086	7.64e-12 ***
Log (RMS)	1.1271	0.1224	9.209	< 2e-16 ***
Log (Pioneer + 1)	0.1717	0.0698	2.460	0.01438 *
Log (Sandy + 1)	0.2129	0.0641	3.322	0.00099 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 1.295 on 350 degrees of freedom
Multiple R-squared: 0.3648, Adjusted R-squared: 0.3594
F-statistic: 63 on 3 and 350 DF, p-value: < 2.2e-16

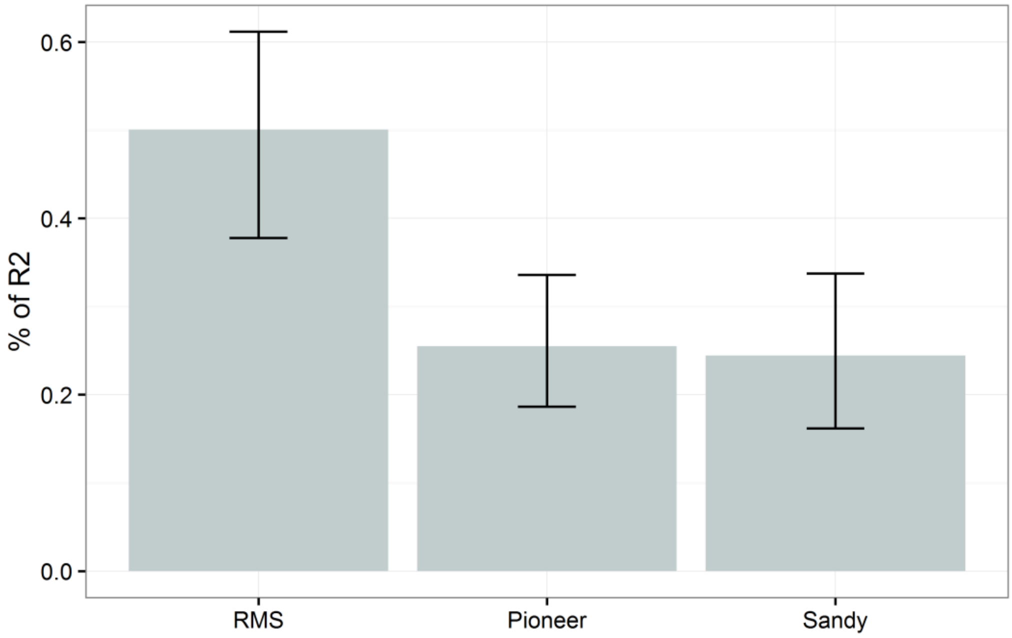


Figure 3.62 Slade Islet bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall R^2 = 0.36

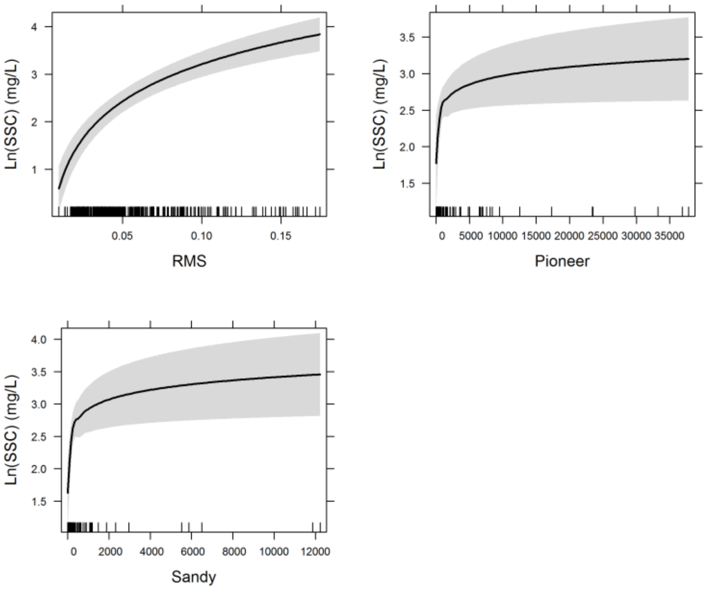


Figure 3.63 Partial effect plots for Slade Islet parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

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, both the wind components and tide amplitude together explained about 61% 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 28% of the SSC variability at Victor Islet (Box 6). The remaining variables combined explained around 33% of SSC variability (Figure 3.64). Results of the partial effects plots (Figure 3.65) 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. Similar patterns were observed at the Freshwater Point site (i.e. the stronger the winds coming from the east, positive values for wind_NESW and negative values for wind_NWSE) the higher the SSC readings recorded.

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

Coefficients

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	3.870109	0.540494	7.160	6.87e-12 ***
Log (RMS)	1.346074	0.140538	9.578	< 2e-16 ***
Log (Sandy + 1)	0.237722	0.030163	7.881	6.91e-14 ***
wind_NESW	0.057217	0.008874	6.447	4.85e-10 ***
wind_NWSE	-0.024910	0.008108	-3.072	0.00233 **
Amplitude	0.242637	0.049128	4.939	1.34e-06 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.8543 on 285 degrees of freedom
Multiple R-squared: 0.6136, Adjusted R-squared: 0.6069
F-statistic: 90.53 on 5 and 285 DF, p-value: < 2.2e-16

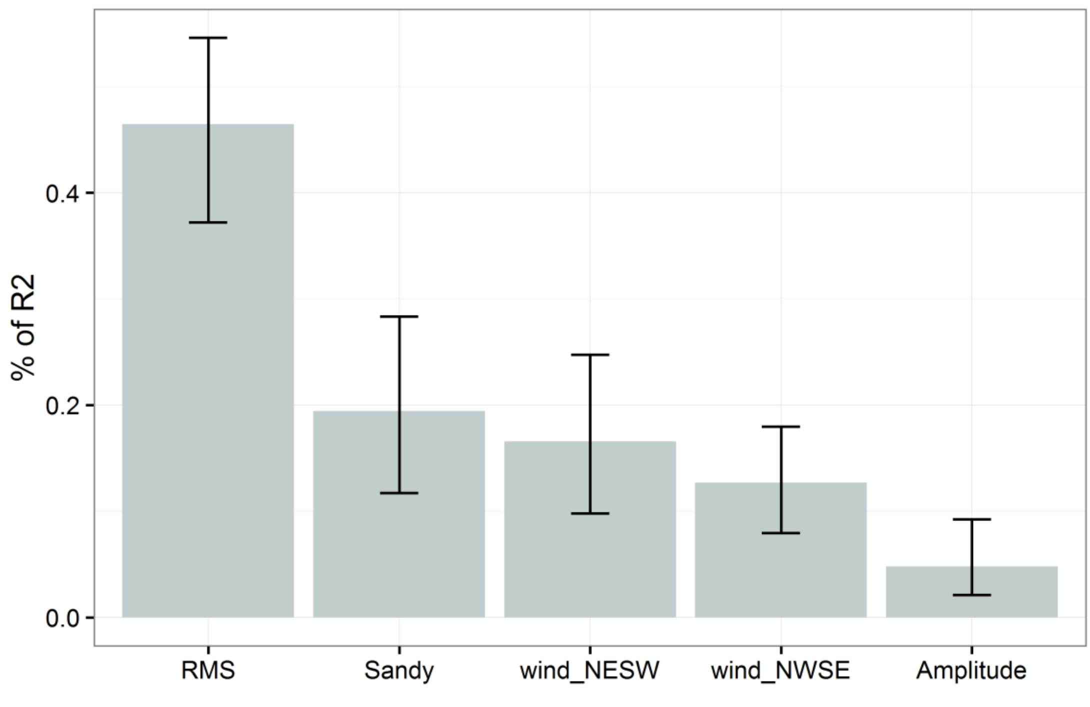


Figure 3.64 Victor Islet (AMB 10) bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall R^2 = 0.61

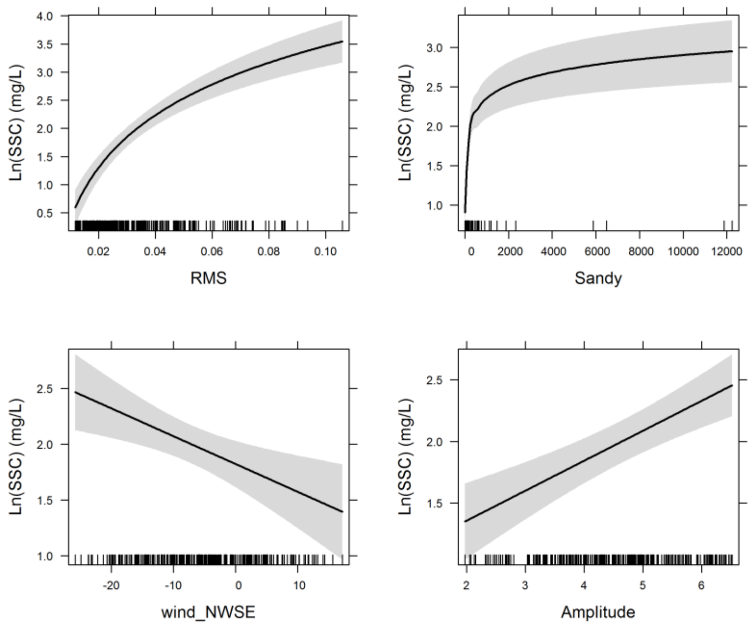


Figure 3.65 Partial effect plots for Victor Islet parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

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, Sandy River discharge, the NESW wind component and tide amplitude together explained about 47% of the SSC variability (Box 7). The relative importance analysis suggested that RMS of water depth was by far the most influential parameter on SSC, explaining about 33% of the SSC variability at Relocation ground (Box 7). The remaining variables combined explained around 14% of SSC variability (Figure 3.66). Results of the partial effects plots (Figure 3.67) 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 Sandy River discharge exhibiting the widest confidence intervals. Overall, an increase in SSC was observed with increases in the environmental predictors. Similar patterns were observed at the Freshwater Point site, i.e. the stronger the winds coming from the east (i.e. positive values for wind_NESW) the higher the SSC readings recorded.

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

Coefficients

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	3.603980	0.349216	10.320	< 2e-16 ***
Log (RMS)	1.226286	0.085731	14.304	< 2e-16 ***
Log (Sandy + 1)	0.152680	0.027708	5.510	7.08e-08 ***
wind_NESW	0.029869	0.006194	4.823	2.14e-06 ***
Amplitude	0.242849	0.045479	5.340	1.71e-07 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.8556 on 340 degrees of freedom
Multiple R-squared: 0.4729, Adjusted R-squared: 0.4667
F-statistic: 76.25 on 4 and 340 DF, p-value: < 2.2e-16

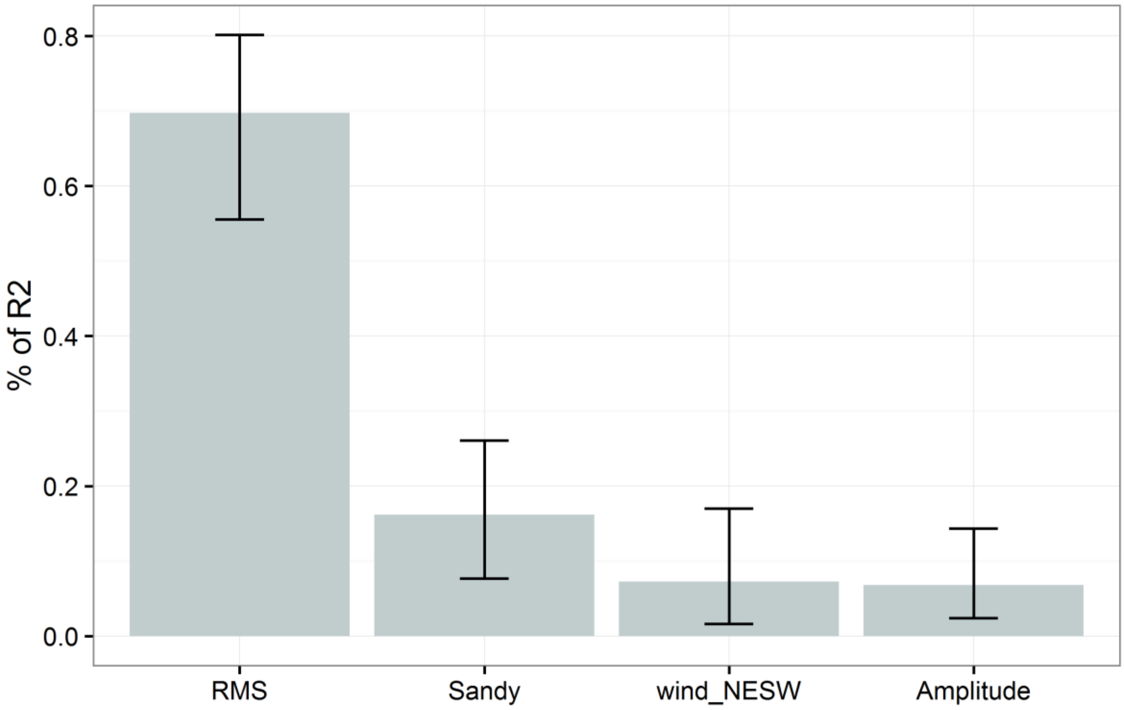


Figure 3.66 Relocation ground (AMB 8) bootstrapping relative importance analysis following a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r squared values are normalized to sum 100%. Overall R^2 = 0.47

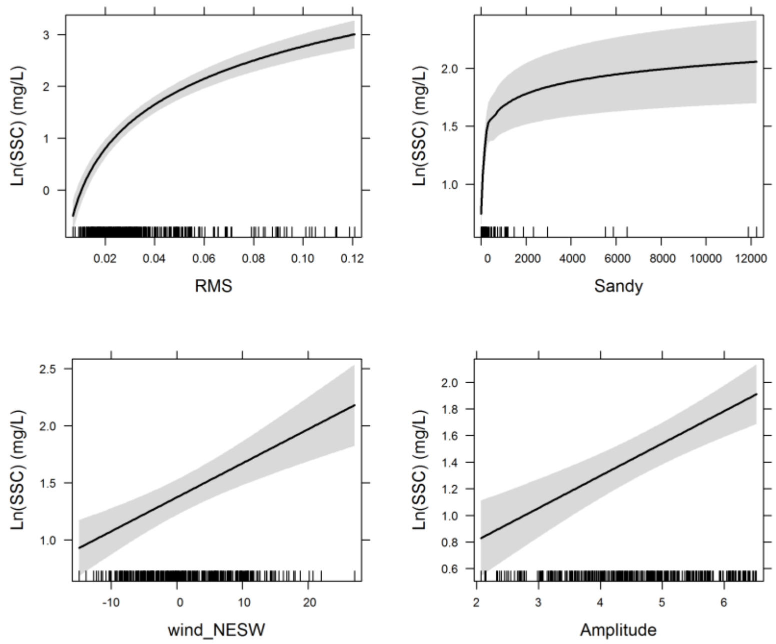


Figure 3.67 Partial effect plots for the Relocation grounds parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

3.5.2 MODIS turbidity proxy

The MODIS turbidity proxy was extracted from the MODIS imagery at all logging sites (except Mackay Marina (AMB 11); and Keswick Island (AMB 12)). The median MODIS turbidity proxy ranged from minimums of 1.11×10^{-3} sr^{-1} at the North of Mackay Relocation ground site (AMB 8) and 1.33×10^{-3} sr^{-1} at Round Top Island (AMB 3), to the highest medians of 5.12×10^{-3} at Freshwater Point (AMB 1) and 9.77×10^{-3} sr^{-1} at Dudgeon reef (AMB 6) (Table 3.10). The 75th percentile numbers recorded south of the Sandy River mouth at Dudgeon Reef, Freshwater Point, Hay Point and Victor Islet were notably higher (upper quartile < 5 $\times10^{-3}$ sr^{-1}) than those at recorded Round Top Island and at the Relocation ground sites (upper quartile < 2.5 $\times10^{-3}$ sr^{-1}).

Table 3.10 Summary statistics for the MODIS turbidity proxy (Rrs(645) ×10^3) at sites from south to north for the period July 2015 to July 2016

Amb. #	1	10	2	6	8	3	*4*	5	*9*	*7*
Name	*Fresh Pt*	*Vict. Is*	*Hay Point*	*Dud. reef*	*N of HP*	*Round Top Is*	*Flat Top Is*	*Slade Is*	*N of Mky*	*Slade Point*
N	170	168	163	174	161	164	*163*	142	*158*	*168*
Min	0.44	0.01	0.83	0.68	0.13	0.01	*0.03*	0.22	*0.06*	*0.08*
Max	34.26	32.77	21.65	33.92	27.57	21.49	*51.65*	44.82	*38.94*	*35.30*
Mean	6.37	4.29	4.96	10.54	2.00	2.11	*4.35*	3.31	*1.84*	*4.35*
SE	0.37	0.36	0.27	0.46	0.20	0.24	*0.42*	0.43	*0.28*	*0.38*
Var	0.02	0.02	0.01	0.04	0.01	0.01	*0.03*	0.03	*0.01*	*0.02*
SD	4.85	4.71	3.39	6.02	2.52	3.10	*5.33*	5.13	*3.49*	*4.89*
Median	5.12	2.86	4.33	9.77	1.48	1.33	*2.88*	1.60	*1.11*	*2.63*
25th %ile	3.54	1.96	2.88	5.47	1.10	0.68	*1.83*	1.08	*0.63*	*1.75*
75th %ile	7.39	4.95	5.69	14.97	2.14	2.24	*5.37*	3.14	*1.91*	*4.91*

The MODIS turbidity proxy time series data at each site followed a similar pattern to that of the *in-situ* SSC (Figure 3.68 and Figure 3.69), with low background values and recurring peak events; except at Dudgeon reef site (AMB 6) where the proxy values were noisy and didn't show any specific trend. One of most prominent peaks in the MODIS turbidity proxy, detected at all sites, occurred in November 2015 (Figure 3.68 and Figure 3.69, orange area). This peak was 3 and 5 times the mean recorded at both site with the highest means (10.54 ×10^{-3} sr^{-1} at Dudgeon reef (AMB 6) and 6.37×10^{-3} sr^{-1} at Freshwater Point; AMB 1). Two other prominent peaks were recorded in February (Figure 3.68 and Figure 3.69, red dot "a") and March 2016 in response to higher river flow conditions of the Pioneer and Sandy Rivers (Figure 3.68 and Figure 3.69, orange areas). The MODIS turbidity proxy was effective in mapping increased turbidity associated with smaller river discharge rates, for example to that recorded in April 2016 (Figure 3.68 and Figure 3.69, blue area and red dot "c").

MODIS true colour images (250 m resolution) assisted in distinguishing the local turbid water boundaries from river plumes and sediment resuspension (Figure 3.70 – Figure 3.73) with finer details on the small-scale transport processes obtained using higher resolutions Landsat 30m image (Figure 3.74).

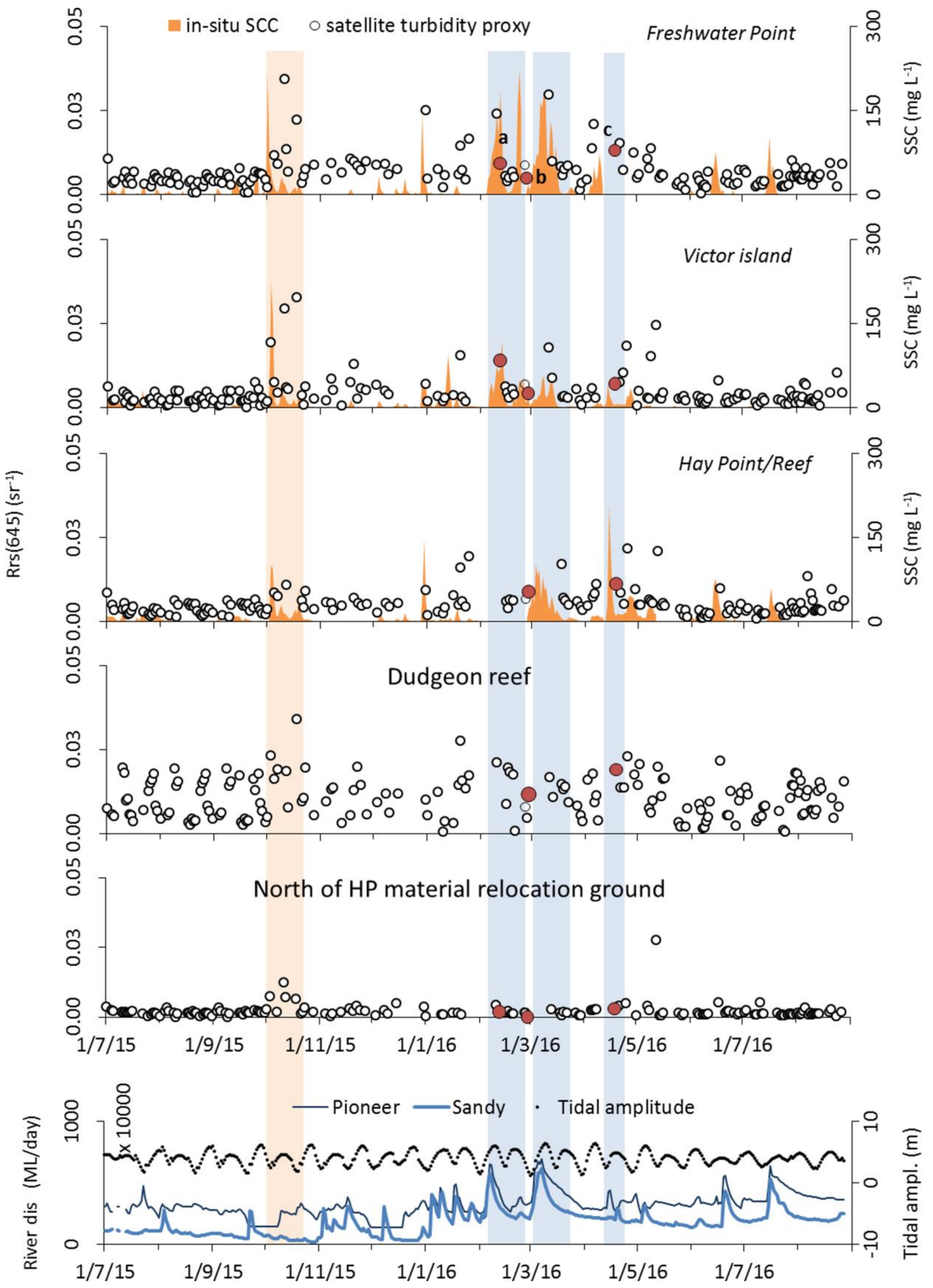


Figure 3.68 MODIS turbidity proxy values measured between July 2015 and August 2016 at the following ambient sites locations (from South to North) and *in-situ* SSC from the loggers (mean values calculated for daily period between 11am and 3pm). Bottom plot shows the Sandy and Pioneer river discharges and the tidal amplitude at Hay Point. The orange area underline the most prominent peaks in the MODIS turbidity proxy (November 2015) and the blue areas peaks following higher river flow conditions in February, March and April 2016. Examples of plumes maps for the 12 and 28 February and the 18 April 2016 (red dots a, b and c, respectively) are given in Figure 3.71 - Figure 3.73

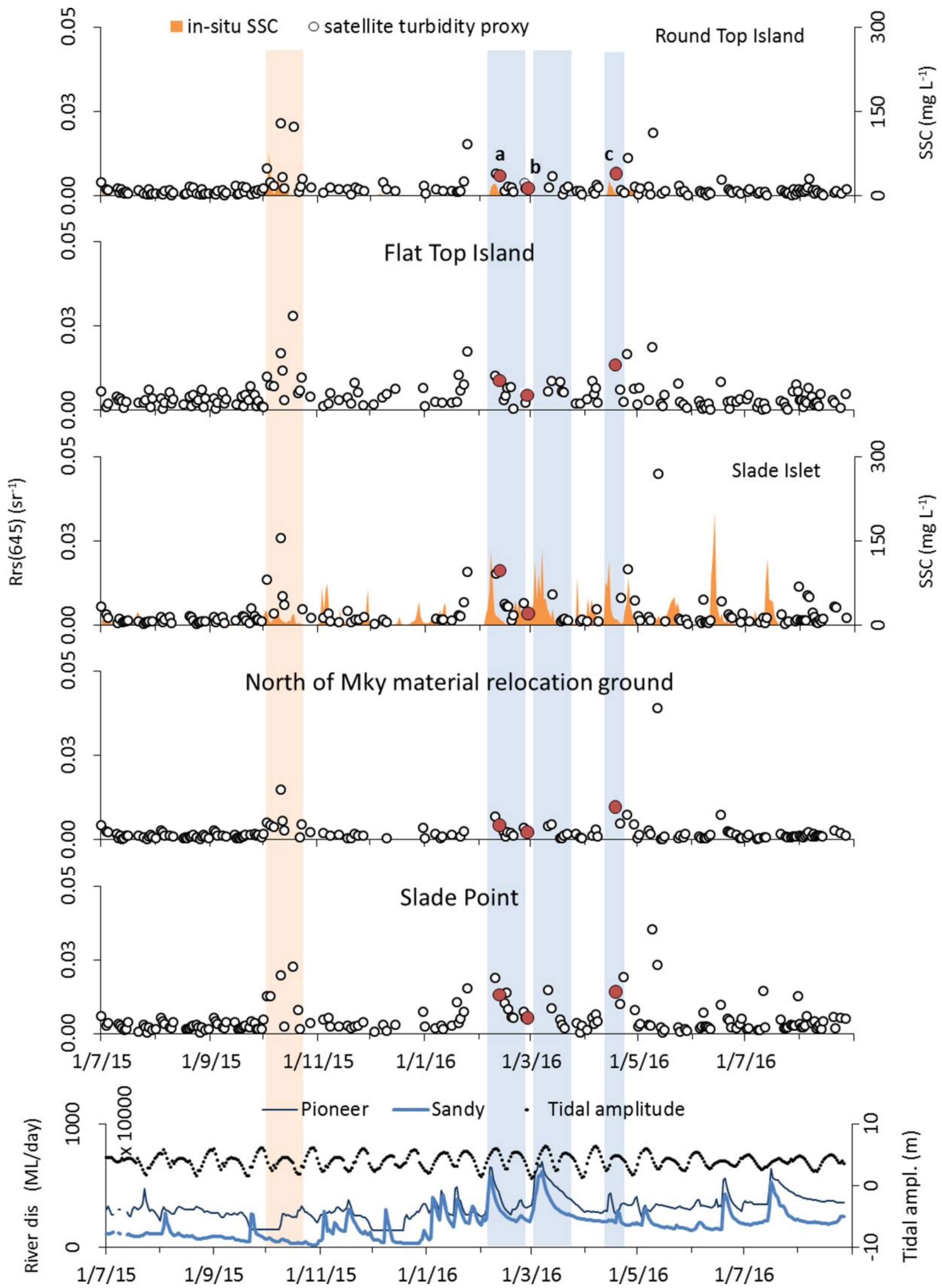


Figure 3.69 MODIS turbidity proxy values measured between July 2015 and August 2016 at the following ambient sites locations (from South to North), and *in-situ* SSC from the loggers (mean values calculated for daily period between 11am and 3pm). Bottom plot shows the Sandy and Pioneer river discharges and the tidal amplitude at Hay Point. The orange area underline the most prominent peaks in the MODIS turbidity proxy (November 2015) and the blue areas peaks following higher river flow conditions in February, March and April 2016. Examples of plumes maps for the 12 and 28 February and the 18 April 2016 (red dots a, b and c, respectively) are given in Figure 3.71 - Figure 3.73

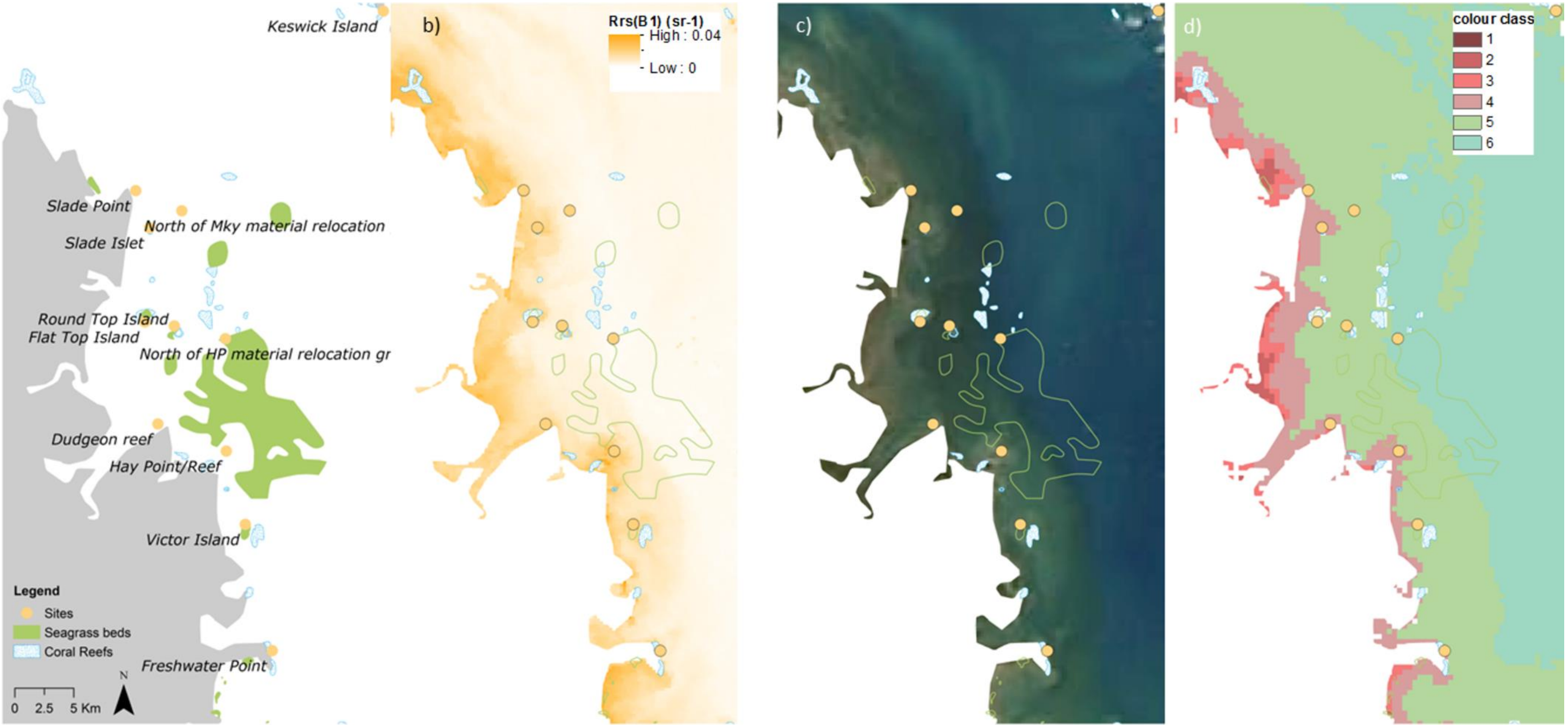


Figure 3.70 a) ambient sites locations and river mouths of the Pioneer and Sandy Rivers (P., and S.); b) MODIS turbidity proxy (MODIS Rrs(645), 250 m resolution) and corresponding; c) MODIS true colour image (250 m resolution) and; d) plume water maps measured the 12 February 2016. The different water types (colour classes 1 to 6) inside the river plumes are mapped using a supervised classification of daily MODIS true colour following the method of Alvarez-Romero et al. (2013)

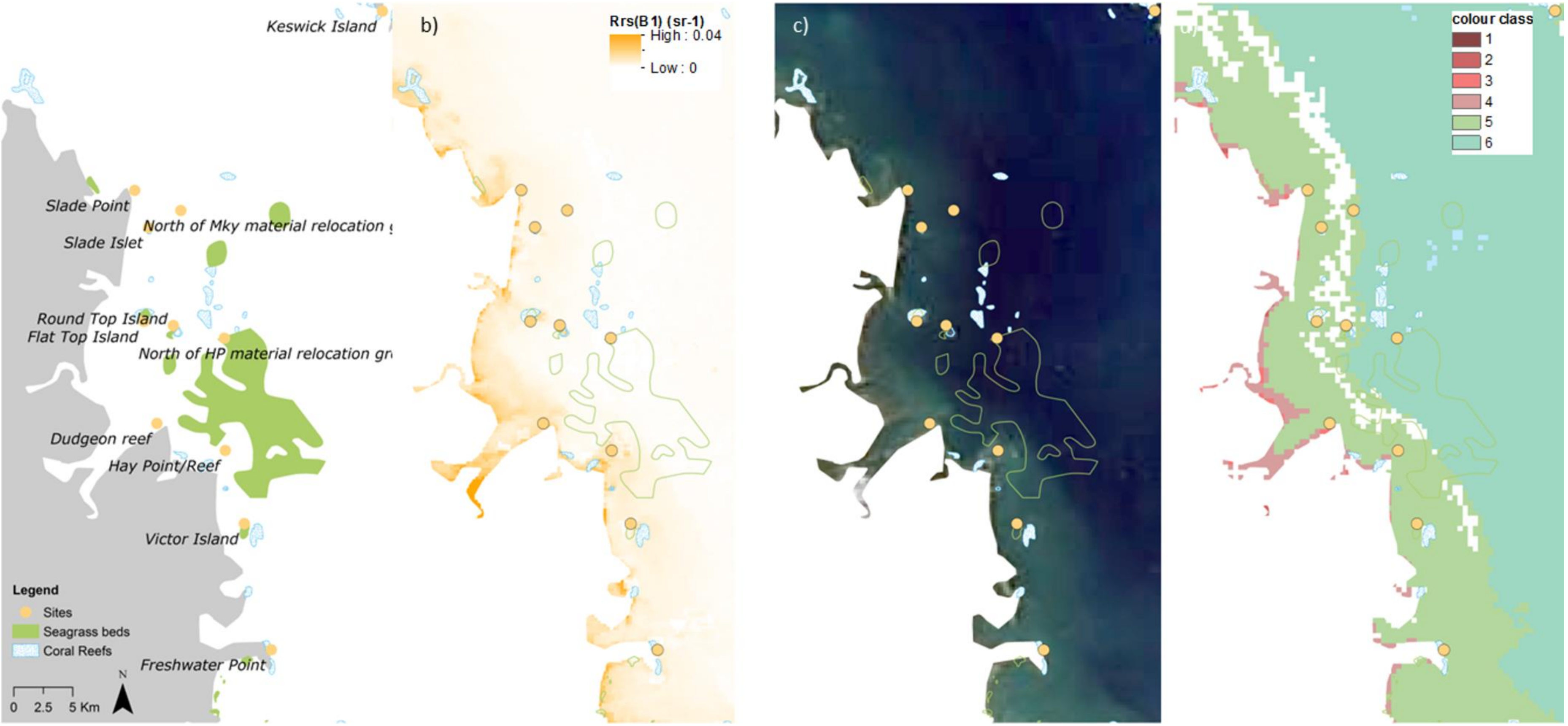


Figure 3.71 a) ambient sites locations and river mouths of the Pioneer and Sandy Rivers (P., and S.); b) MODIS turbidity proxy (MODIS Rrs(645), 250 m resolution) and corresponding; and c) MODIS true colour image (250 m resolution) and d) plume water maps measured the 28 February 2016. The different water types (colour classes 1 to 6) inside the river plumes are mapped using a supervised classification of daily MODIS true colour following the method of Alvarez-Romero et al. (2013)

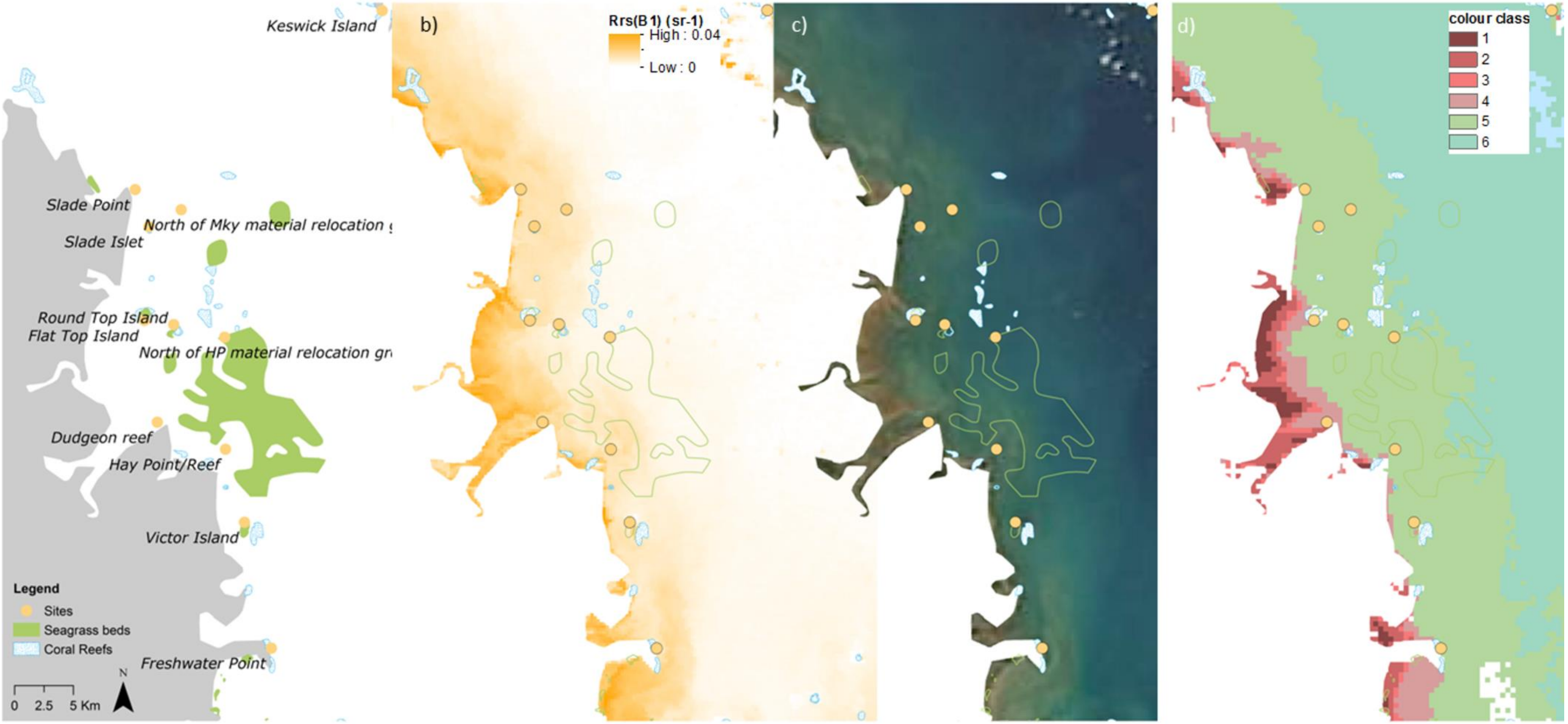


Figure 3.72 a) ambient sites locations and river mouths of the Pioneer and Sandy Rivers (P., and S.); b) MODIS turbidity proxy (MODIS Rrs(645), 250 m resolution) and corresponding; c) MODIS true colour image (250 m resolution) and; d) plume water maps measured the 16 April 2016. The different water types (colour classes 1 to 6) inside the river plumes are mapped using a supervised classification of daily MODIS true colour following the method of Alvarez-Romero et al., (2013)

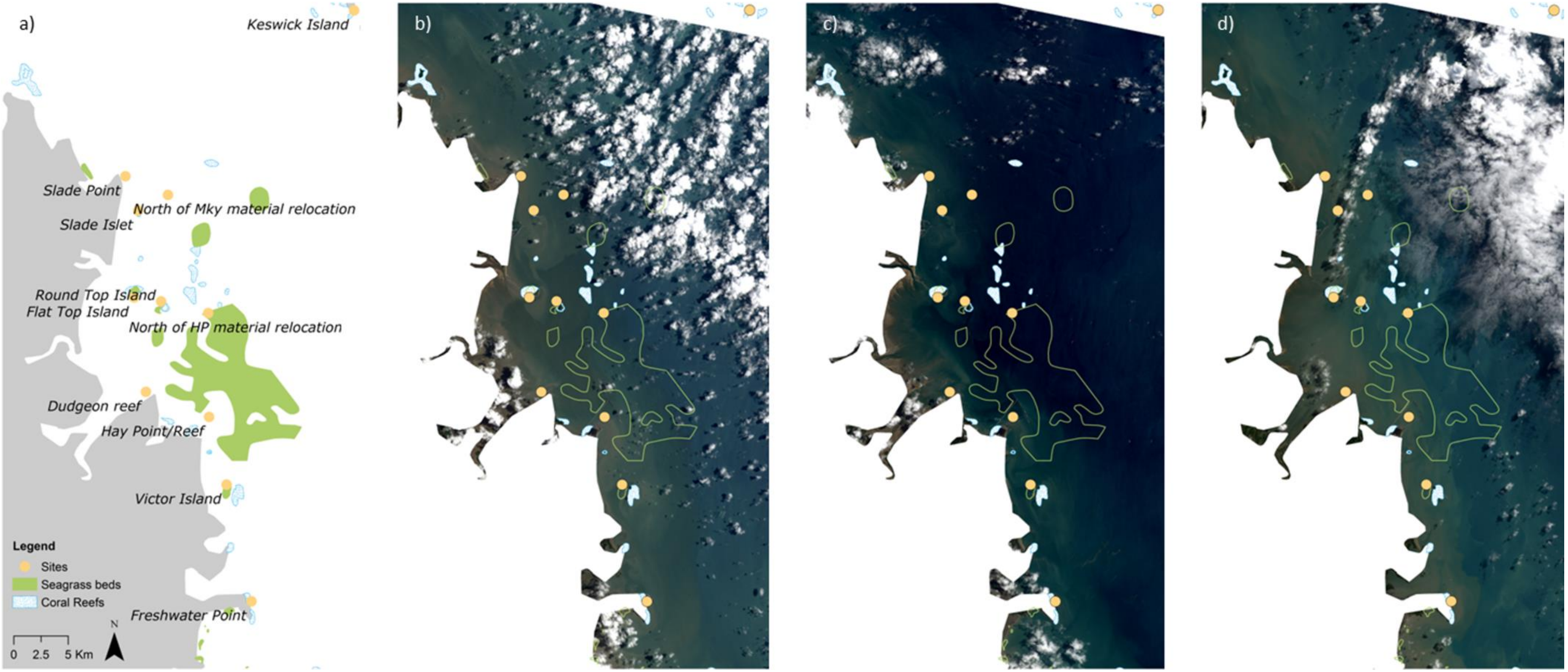


Figure 3.73 Landsat true color images (30 m resolution) for the: a) 12 February; b) 28 February; and c) 16 April 2016

3.5.3 Linear correlation analysis

The result of the linear correlation analysis revealed globally weak relationships for the six monitored sites (Freshwater Point (AMB 1), Hay Point Reef (AMB 2), Round Top Island (AMB 3), Slade Islet (AMB 5) and Victor Islet (AMB 10)), with R^2 ranging between 0.0 and 0.3 (Table 3.11) and a mean R^2 of 0.15, similar to next year results (R^2 = 0.11). The stronger correlations were observed at the Round Top Island and Hay Point reef monitoring sites (R^2 = 0.33 and R^2 = 0.26, respectively). A R^2 of 0.08 was calculated at Freshwater point and was weaker compared to last year statistic for this monitoring site. However, without considering four *in-situ* SSC measurements > 100 mg/L (Figure 3.74, orange dots), the R^2 increased to 0.31. The correlation at Victor Islet was lightly stronger than last year (R^2 =0.15 vs. 0.04), but globally this year's results confirmed a poor performance of the MODIS turbidity proxy for the shallowest sites analysed (Slade Islet and Victor Islet Island). These 2 sites are probably affected by bottom perturbations which may contribute to some noise on the satellite signal and may explain the lowest correlations observed.

Correlations were generated using the mean weekly data to smooth measurement error of daily Rrs(645) (Figure 3.76). These correlations revealed stronger relationships (Table 3.11), up to 0.43 measured at Round Top Island (AMB 3). Freshwater Point (AMB 1) was R^2 = 0.21, but increased to R^2 = 0.44 when the four daily *in-situ* SSC measurements > 100 $mg.l^{-1}$ (Figure 3.75, orange dots) where not included in the calculation of the mean weekly values. Using the mean weekly data didn't increase the R^2 value at Hay Point Reef (R^2 = 0.27). At the freshwater Point (AMB 1) and Round Top Island (AMB 3) sites, the MODIS turbidity proxy showed similar trends as the mean weekly SSC data (Figure 3.76). Despite a lower correlation coefficient at Hay Point Reef (AMB 2), trends between the mean weekly MODIS turbidity proxy and *in-situ* SSC data were similar.

Table 3.11 Correlation statistics calculated between the MODIS turbidity proxy and *in-situ* SSC values (mean daily value calculated between 11am and 3pm are in parentheses). Site water depth is also indicated

Site (Amb. #)	Daily			Weekly	
	Depth (m)	**r-squared**	**p-value**	**r-squared**	**p-value**
Freshwater Point (1)	10.3	0.08/*0.31 (0.22)*	<0.01	0.21/0.44 *(0.55)*	<0.01
Hay Point Reef (2)	11.0	0.26 *(0.26)*	<0.01	0.27 *(0.69)*	<0.01
Round Top Is (3)	9.5	0.33 *(0.08)*	<0.01	0.43 *(0.24)*	<0.01
Slade Is (5)	4.4	0.02 *(0.03)*	Ns.	0.05 *(0.08)*	Ns.
Victor Is (10)	4.3	0.15 *(0.04)*	<0.01	0.18 *(0.16)*	<0.01
Keswick Is (12)	5.2	*(0.04)*	Ns.	*(0.01)*	Ns.
Mean		*0.15 (0.11)*		*0.29 (0.29)*	

Uncertainties of current data that could explain the mismatch between satellite proxy and *in-situ* data and especially at the shallower monitoring sites (Slade Island (AMB 5), Victor Islet (AMB 10), Keswick Island (AMB 12)) may be a result of a single or combination factors, including:

- Optical complexity of the Hay point coastal water zone;
- Bottom perturbations and atmospheric perturbations due to the relatively low SSC concentrations associated with the low rainfall rates of the studied period; and

- Loggers record bottom turbidity while MODIS record surface turbidity and disparities between the satellite and *in-situ* data are thus expected.

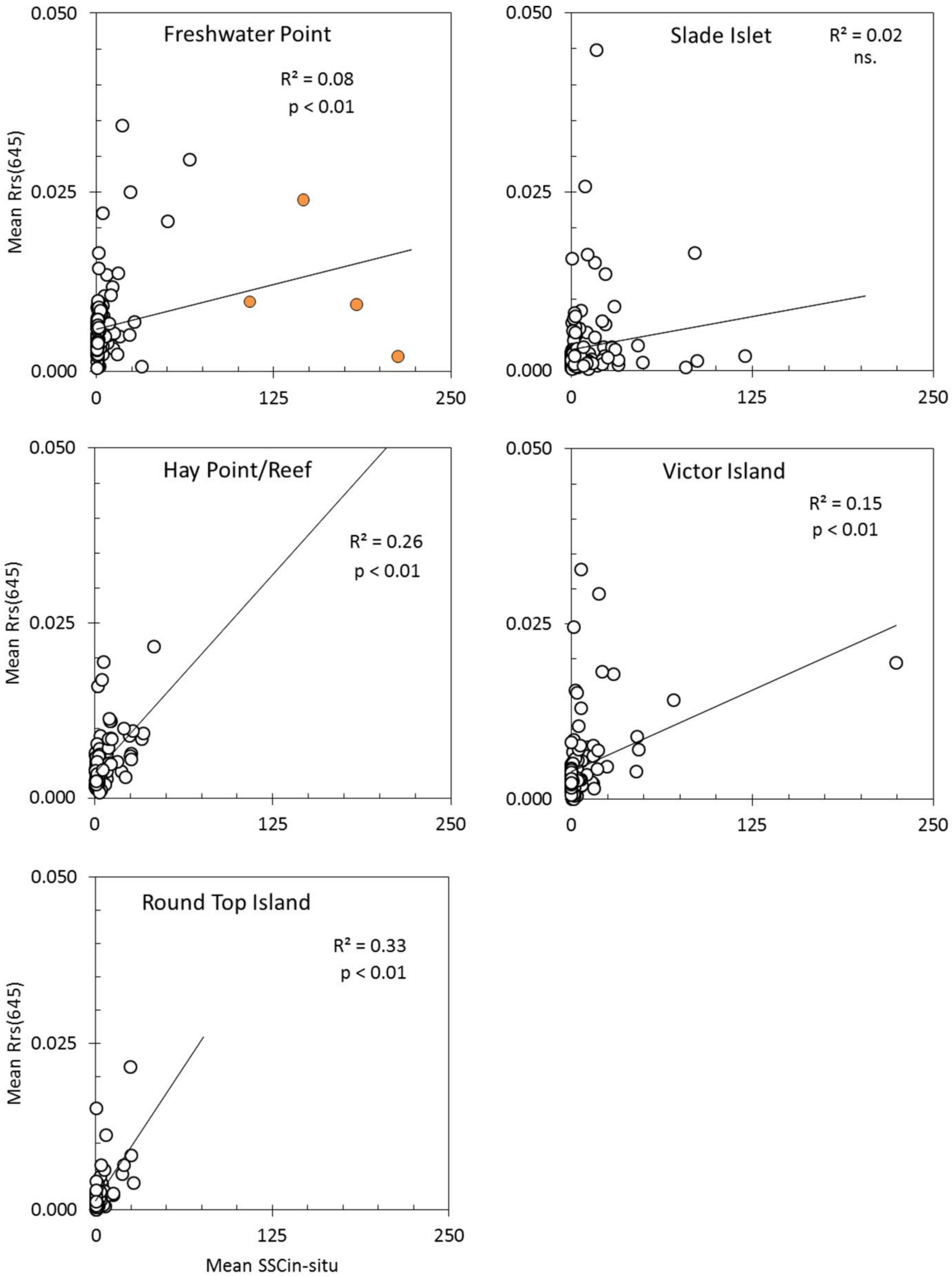


Figure 3.74 Correlations between the daily mean Rrs(645) (satellite proxy for turbidity) and mean SSC (between 11 am and 3 pm) at the six monitored sites (Freshwater Point, Hay Point Reef, Keswick Island, Round Top Island, Slade Islet and Victor Islet)

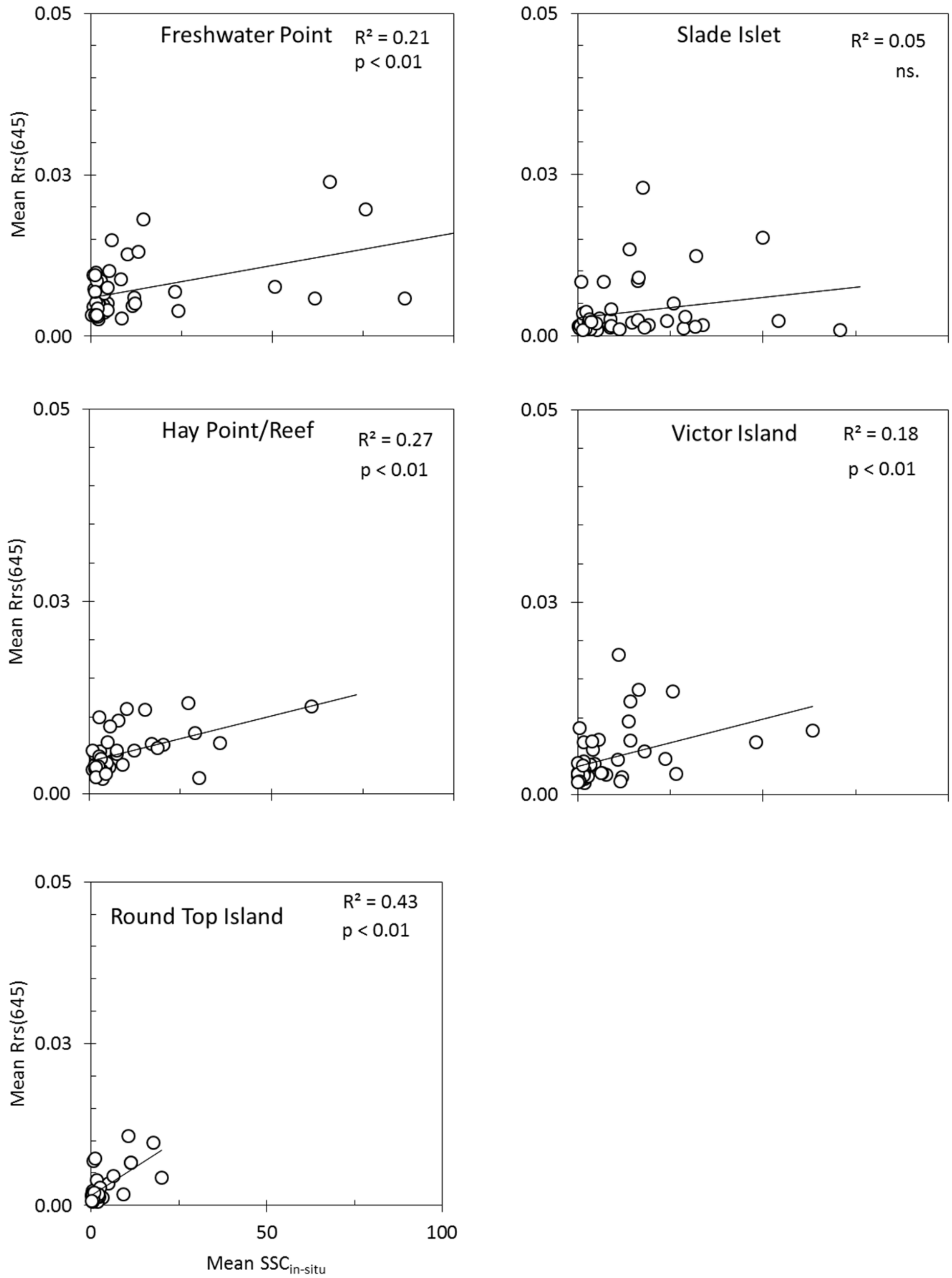


Figure 3.75 Correlations between the mean weekly Rrs(645) (satellite proxy for turbidity) and mean weekly SSC (between 11 am and 3 pm) at the six monitored sites (Freshwater Point, Hay Point Reef, Keswick Island, Round Top Island, Slade Islet and Victor Islet)

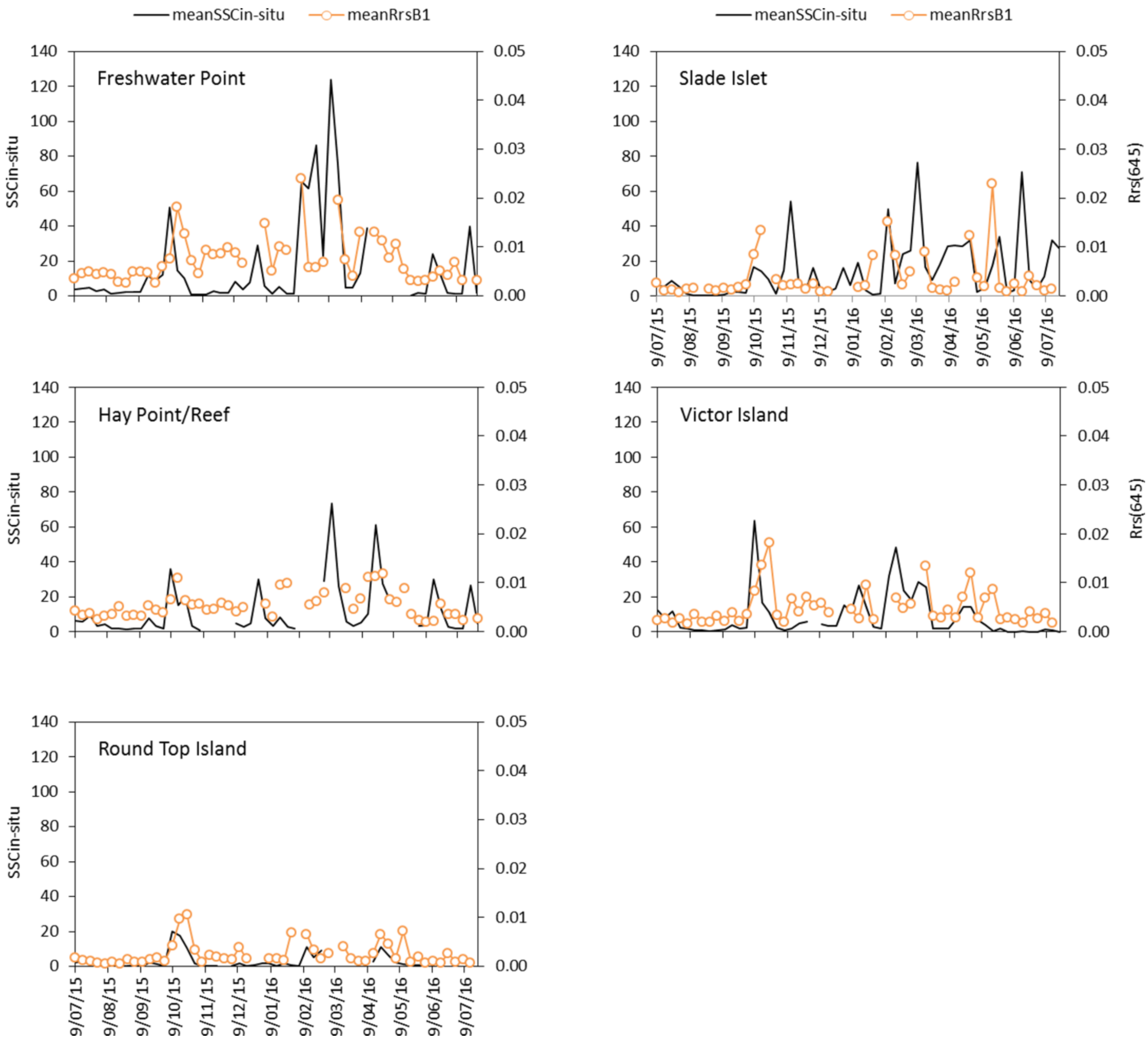


Figure 3.76 Comparisons between the mean weekly Rrs(645) (satellite proxy for turbidity) and mean weekly SSC (between 11 am and 3 pm) at the monitored sites

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 2015/16 wet season was in the order of the 50th %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 higher. In fact, the 2010/11 wet season was in the upper 95 percentile of the distribution of rainfall over the past 115 years. This high inter-annual variability limits the ability to adequately characterise ambient water quality conditions over a one year period. This shows that 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.
- While rainfall and river flow continues to be low, the first 24 months of monitoring continues to provide an opportunity to capture data during low rainfall years. Such opportunities are rare, and the monitoring to date has provided valuable insight into water quality characteristics driven by factors other than rainfall runoff and catchment plumes. Specifically, the low rainfall period continues to provide the opportunity to examine wave energy conditions and the relationships with water quality conditions.
- 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. It shows that there is a regular south-easterly wind experienced in the region, with more than 35% of the days reaching more than 24km/hr. This regular localised weather pattern is probably an important factor requiring consideration in similar water quality campaigns for the region.

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^{o}C, with typically less than 2^{o}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 (in November 2015 probably 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 where highest in coastal sites, including Dudgeon Reef (AMB 6), and in the Mackay Marina (AMB 11), presumably influenced by local land uses.
- This year two plankton surveys were completed (dry and wet season). Interestingly the plankton assemblage (consisting of phytoplankton and zooplankton) where more similar among sites during the dry season survey (November 2015), compared to the wet season (April 2016) survey where sites were more spread in the ordination. There is evidence of seasonal differences in the plankton assemblage in the region, though these results are preliminary, and should be further investigated in the future.
- Trace heavy metals and herbicides/pesticides were non-detectable across the monitoring period this year. These result seems to reflect low rainfall and therefore contribution of contaminants from wider diffusive land use sources, such as heavy industry, urban stormwater and wastewater. Unlike in the first 12mths of monitoring, elevated filterable copper and lead recorded at the Mackay marina site (AMB11), where not detected during this years' monitoring.
- 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). These data have been also useful to assist in generation of 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 phorphorus).
- 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.
- 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 the previous year (2014/2015), 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. 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. Although a wet season with higher levels of precipitation was originally expected this year, the Bureau of Meteorology reports the El Niño–Southern Oscillation in the tropical Pacific Ocean remains neutral. Importantly, the continuation of the program may detect the influence of future rainfall events, thus enabling a more complete characterisation of PAR patterns in the region.
- 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). Patterns of light were similar among all the coastal sites, although similarities are less marked than was observed in the previous year (2014/2015). 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, which was also reported in the previous year. Overall patterns in PAR display greatest dissimilarity to other sites. 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.

4.1.5 River plumes

- The time series of MODIS turbidity proxy at each site followed a similar pattern to that of the in-situ SSC, with low background values and recurring peak events; except at Dudgeon reef site where the proxy values were noisy and didn't show any specific trend.
- The most prominent peaks in the MODIS turbidity proxy occurred in November 2015. Two other peaks were recorded in February and March 2016 and followed two flood events of the Pioneer and Sandy rivers. The use of MODIS imagery of the local coastal environment was effective in mapping increased level of turbidity associated with smaller river discharge rates, such as that experienced during April 2016.
- Correlations between the daily MODIS turbidity proxy and the mean in-situ SSC (between 11 am and 3 pm) were weak for the six monitored sites, with R^2 ranging between 0.0 and 0.3, with a mean R^2 of 0.15, similar to the results from last year (R^2 = 0.11). The results this year confirmed a poor performance of the MODIS turbidity proxy for those shallow sites (Slade Islet and Victor Islet), but also during periods when water column turbidity is high. Strong correlations were observed at Freshwater Point (R^2 = 0.44) and Round Top Island monitoring sites (R^2 = 0.43). Slade Islet and Victor Islet sites are probably affected by bottom perturbation, which may contribute to some noise on the satellite signal and may explain the low correlations observed. Correlations improved when applying the mean weekly data, because it provides a smoothing

function to the data, reducing noise in the MODIS turbidity proxy, up to R^2= 0.43 measured at Round Top Island.

- The use of remote sensing can be problematic in the nearshore coastal environment due to the influence of shallow, optically complex waters and the reduction in the number of images retrieved that are possible due to cloud cover. Another important factor to consider in interpreting the satellite data is that the relatively dry wet season limited the turbidity of the water and, thus, the ability of the satellite data to characterise turbidity levels due to increased atmospheric and bottom perturbations. Furthermore, loggers record bottom turbidity while MODIS record surface turbidity and disparities between the satellite and *in-situ* data are thus expected. These were likely to be important contributing factors to the low average predictability during the 2014/15 and 2015/16 periods.
- The use of MODIS true colour images and higher resolution satellite images (Landsat, 30 m resolution) of the coastal environment allowed distinguishing the boundaries of coastal turbid waters (river plumes and resuspension), with finer details on the small-scale transport processes obtained using higher resolutions images.
- Whilst there are limitations, the satellite images still provides a useful tool for monitoring increased turbidity conditions around the coastal sites and, thus important information that can be used in conjunction with high frequency in-situ data to monitor potential impacts associated with port development.

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 for the 2016/17 program, 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 was put forward as the region continues to experience below average rainfall conditions. It will be important to ensure that the site network is ready to capture a full wet season, in order to characterise the upper water quality conditions for the region.

4.2.3 River plumes

The river plume modelling using MODIS has continued to produce weak relationships, and this continues to be largely associated with continuing below rainfall in the region. It is recommended that the river plume modelling be placed on hold during the 2016/17 ambient marine water quality monitoring period, until a typical wet season is experienced. Given the nature of this methodology, river plume modelling can be completed retrospectively, as necessary in the future.

4.2.4 Data base repository

An electronic version of the ambient marine water quality database has been prepared as an annexure to this report. 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 2016. This data base continues to be maintained by TropWATER personal, with back up copy archived on the James Cook University network with restricted access.

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