PORT OF MACKAY AND HAY POINT AMBIENT MARINE WATER QUALITY MONITORING PROGRAM (JULY 2014 TO JULY 2015)

November 2015

Nathan Waltham, Skye McKenna, Paul York, Michelle Devlin, Sean Campbell, Michael Rasheed, Eduardo Da Silva, Caroline Petus, Peter Ridd

Report No. 15/16

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A Report for North Queensland Bulk Ports Corporation

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Information should be cited as:

Waltham, N., McKenna, S., York, P., Devlin, M., Campbell, S., Rasheed, M., Da Silva, E., Petus, C., Ridd, P., 2015, 'Port of Mackay and Hay Point Ambient Marine Water Quality Monitoring Program (July 2014 to July 2015), Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 15/16, James Cook University, Townsville, 96 pp.

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This publication has been compiled by the Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University.

SUMMARY POINTS

Background

1. North Queensland Bulk Ports commissioned an ambient marine water quality monitoring program for the region surrounding the Ports of Mackay and Hay Point. The primary objective of this program has been to develop a long term understanding of the marine water quality characteristics for the region.
2. This program has included a combination of spot field measurements and high frequency continuous data loggers, laboratory analysis for nutrient, herbicides and heavy metals, and satellite image to examine the influence of river plumes on regional water quality.
3. Thirteen sites make up this program, extending approximately 60km along the Mackay coastline from Slade Point to Freshwater Point, and offshore to Keswick Island. Sites in the network align with either key sensitive receptor habitats (e.g., corals or seagrass), or with key features in the study region (e.g., river flow points).
4. The program commenced July 2014, and this report presents the first 12 months of monitoring.

Climatic conditions

1. The total 2014/15 wet season rainfall across the study was, within the 10th percentile of the distribution of total annual wet season rainfall recorded in the region (1910 to 2015). For the entire ambient marine monitoring period, the total rainfall at Plane Creek Sugar Mill (17 km linear from Hay Point) was 785.8 mm, with 51 % recorded during January 2015. This rainfall was not sufficient to create notable discharge to the marine environment. This contrasts with the 2013/14 wet season where rainfall was within the 95th percentile of historical records.
2. The low rainfall total across the 2014/15 wet season has considerably reduced the ability 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 below average rainfall wet season provided the opportunity to collect continuous water quality data for the region under a period of minimal catchment flow.
4. Tropical Cyclone Marcia crossed the coast to the south of the study area in February 2015, and contributed to a small amount of catchment runoff to the coast, still well below average yearly flow rates.
5. During the reporting period, the daily average wind in the Mackay region was from the south east, with more than 50% of days reaching more than 24km/hr during this monitoring period.

Water chemistry

1. Field water quality conditions were measured at all sites for water temperature, electrical conductivity, pH, dissolved oxygen, and secchi disk depth on four occasions (July 2014, November 2014, March 2015 and August 2015) from 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 summer months.
3. Water column was well mixed during each quarterly survey, with little difference among the three horizons for the parameters measured. The exception was turbidity which

remained higher at the bottom horizon, probably due to remobilisation of the sea floor sediments.

4. The most noteworthy result were elevated nutrient concentrations. Nutrients concentrations, particularly total and dissolved nitrogen, were detected above the relevant guidelines for the region. The contributing factors to these data might include localised signal associated with runoff from land use activities such as farming and urban runoff from centres along the Mackay coastline. The elevated supply of dissolved nutrients is a concern for the region and requires further investigation and management response.
5. Trace heavy metals and TBT were non-detectable across the monitoring period, a factor probably reflecting the low rainfall. The exception was Mackay marina, where copper and lead were detected above the limit of reporting (ultra-trace), while for copper the concentrations were above the guideline during survey 1 (July 2014) and survey 3 (March 2015). This detection in the marina seems to be localised given that each was not detected at the next closest monitoring sites (AMB 5; Slade Islet, or AMB 9B; East cardinal navigation marker).
6. 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 across sites. The only herbicide detected was Diuron, which was detected during both surveys and at most sites.

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 this has been 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. By presenting NTUe/SSC with respect to RMS water depth using box plot distributions, it is shown that as RMS water depth increases, along with 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.
4. Wavelet and Fourier analyses was used to examine periodicity in NTUe/SSC for each site. These analyses revealed important trends in turbidity, with peaks occurring at most sites at periods of approximately 6 and 12 hours, and every 7 and 29 days. These peaks seem to be the result of local synoptic weather patterns, for example, semi diurnal, diurnal and longer period tidal constituents.
5. As part of this monitoring program, a multivariate predictive NTUe/SSC model was developed at sites AMB 1, AMB 2, AMB 3, AMB 5, 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 predictive capacity of the model improved across the logging period, and will increase in accuracy following the 2015/16 logging period.

6. This turbidity model provides management with a powerful tool for use, for example, as the differentiation between natural turbidity and anthropogenic related turbidity may be monitored. For example, this means that during a dredging campaign, that the difference in the measured turbidity compared to the predicted using this model, represents the contribution associated with the activity.

Light attenuation (Photosynthetically active radiation; PAR)

1. High frequency continuous PAR logging data revealed fine-scale patterns of PAR are primarily 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 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 dredge activity 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, the correlation between the concentrations of suspended solids in the water column, was found to explain less than half of the variation in PAR measured at the same time. 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, PAR should be retained in the suite of water quality variables when capturing local baseline conditions of ambient water quality.

River plumes

1. On average, the proposed models to relate 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). RMS of water depth was the main driver of SSC in the water column, and accounted for 63 % of the explained variability by the fitted models. Except for Victor Islet, the river discharge importance to the SSC variability was low, and on average 3 % for the Pioneer River and 7 % for the Sandy River. The low river influence on SSC is probably, once again, the result of the dry period experienced in the 2014/15 wet season.
2. Match-ups analyses of MODIS and *in-situ* SSC data from the ambient marine monitoring program were undertaken to test agreements between the satellite and *in-situ* water turbidity measurements on seafloor. Correlations between the daily satellite images and

the mean SSC (between 11 am and 3 pm) were generally weak (average R^2 of 0.11) at the six monitored sites.

3. 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: $R^2 < 0.1$). The stronger correlations were observed at the Freshwater Point ($R^2 = 0.69$) and Hay Point reef monitoring sites ($R^2 = 0.59$).
4. 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. These were likely to be important contributing factors to the low predictability in application during the 2014/2015 period.
5. Another important factor to consider in interpreting the satellite data is that the 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. The satellite data were, however, able to reproduce the increase in SSC observed around late February 2015 at Hay Point Reef, Round Top Island and Freshwater Point. This evidence supports the ability of this monitoring tool during average or above average rainfall years.
6. During this period of monitoring, there was no river flow which prevented our ability to identify and map local sediment plumes. It would be expected that the mapping of true colour in the nearshore shallow environment, on cloud-free days, would still allow the edge of the plumes to be distinguished. Under a scenario of tracking the plume associated with a dredging campaign, would be improved with using a higher resolution satellite images.
7. Whilst there are limitations in the small areas associated with the nearshore coastal zone, the ability to retrieve remote sensed data is improved as the mapping moves further away from the complex nearshore environment. Thus, in combination with a monitoring program targeting high frequency sampling in the near shore environment through appropriate loggers and *in-situ* sampling for the validation of the RS data, the extraction of data from large spatial images still provides a useful tool for characterising the water quality around the coastal sites.

Recommendations

1. In reviewing of the data following the first 12 months of monitoring, we have identified opportunities to refine and improve the efficacy of the program. The most apparent has been a reduction in the number of sites with continuous loggers, with the program conceivably reducing to 7 sites (with an additional site with a PAR logger only).
2. While the number of logging sites has been refined, we recommend increasing the frequency of maintenance in response to managing potential data redundancy. By increasing the logger maintenance program, provides the opportunity to collect more frequent spot water quality data, to more explicitly examine nutrient dynamics, and also to assist the satellite modelling component of this program.

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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. The Port of Mackay is located approximately four kilometres north of the Pioneer River, and is enclosed by large break walls that allow 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 these operating port facilities.

In both port areas, NQBP have undertaken numerous environmental monitoring programs, spanning over many years. Typically, monitoring in the marine environment has been associated with development work and projects occurring at the Port, such as construction, expansion, capital and maintenance dredging and sediment relocation actives. Historically, extensive monitoring has been implemented around these development and project works, and stopped soon after when a project impact has been completed and compliance monitoring no longer needed.

Many of NQBP's environmental monitoring programs are transitioning to a more long-term and ongoing design, which allows environmental changes in and around the port area to not only be identified, but to also be examined in the context of natural changes occurring in the region.

1.2 Program outline

NQBP's ambient marine water quality monitoring program aims to monitor a strategic locations within the Port area to capture changes that may relate to activities occurring at either the Port of Mackay of the Port of Hay Point. Importantly, the project spans a considerable distance along the Mackay coastline with key monitoring sites aiming to detect natural cyclic changes, quantify river discharges and explore changes in water quality from other human activities in the area (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 provide a greater understanding of the natural variability in key water quality parameters, including those experienced at the nearest sensitive receiving habitats for both Ports.

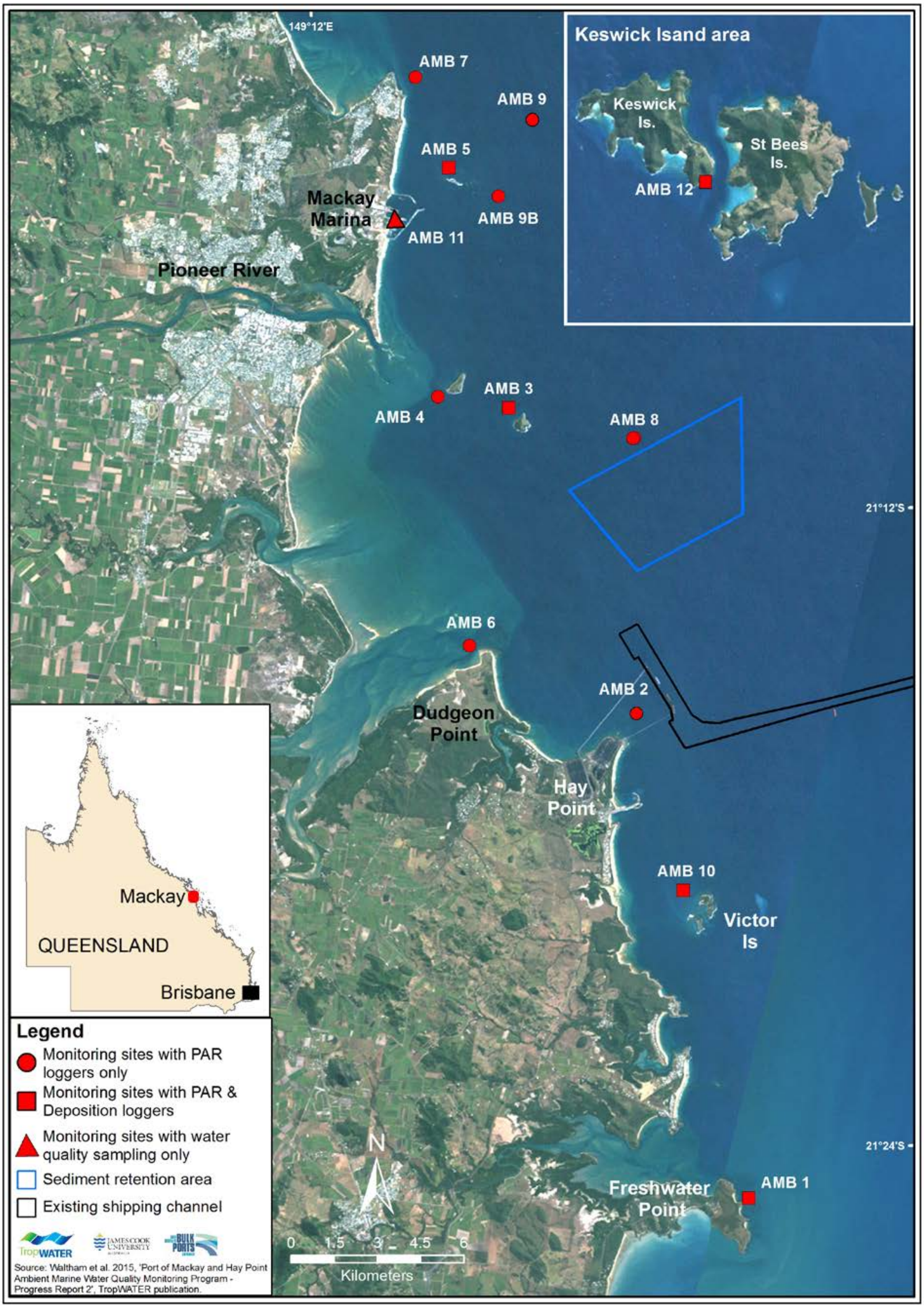


Figure 1.1 Locations of the marine water quality monitoring program sites and parameters monitored at each site

Table 1.1 Locations of the marine water quality monitoring program sites. (*) logger discontinued from station and relocated to East Cardinal Marker (AMB 9B)

Location	AMB site no.	Lat.	Long.	Water quality	Deposition logger	PAR logger
Freshwater Point	1	-21.42	149.34	Yes	Yes	Yes
Hay Point/Reef	2	-21.26	149.30	Yes	Yes	Yes
Round Top Island	3	-21.17	149.26	Yes	Yes	Yes
Flat Top Island	4	-21.17	149.24	Yes	-	Yes
Slade Islet	5	-21.09	149.24	Yes	Yes	Yes
Dudgeon reef	6	-21.24	149.25	Yes	-	Yes
Slade Point	7	-21.07	149.23	Yes	-	Yes
North of HP material relocation ground	8	-21.18	149.30	Yes	-	Yes
North of Mky material relocation ground	9	-21.08	149.27	Yes	-	*
East Cardinal marker	9B	-21.10	149.26	Yes	-	Yes
Victor Islet	10	-21.32	149.32	Yes	Yes	Yes
Mackay Harbour	11	-21.11	149.22	Yes	-	-
Keswick Island	12	-20.93	149.42	Yes	Yes	Yes

1.3 Rainfall and river flows

The total wet season rainfall across the study was low for the first 13 months of the program, within the 10th percentile of the distribution of total annual wet season rainfall recorded in the region (Figure 1.2). For the entire ambient marine monitoring period the total rainfall at Plane Creek Sugar Mill (17 km linear from Hay Point) is 785.8 mm, with 51 % of the total rainfall recorded during January 2015. The rainfall events that have occurred in the region have not been sufficient to contribute to flow pulses, and therefore the low rainfall is generally considered to be a failed wet season, for example, certainly compared to the flow experienced in previous wet seasons (e.g., 2013/14). The low rainfall total across the 2014/15 wet seasons has reduced considerably our ability to characterise the upper range in marine water quality conditions within the study region. The data therefore in this report needs to be considered in this context.

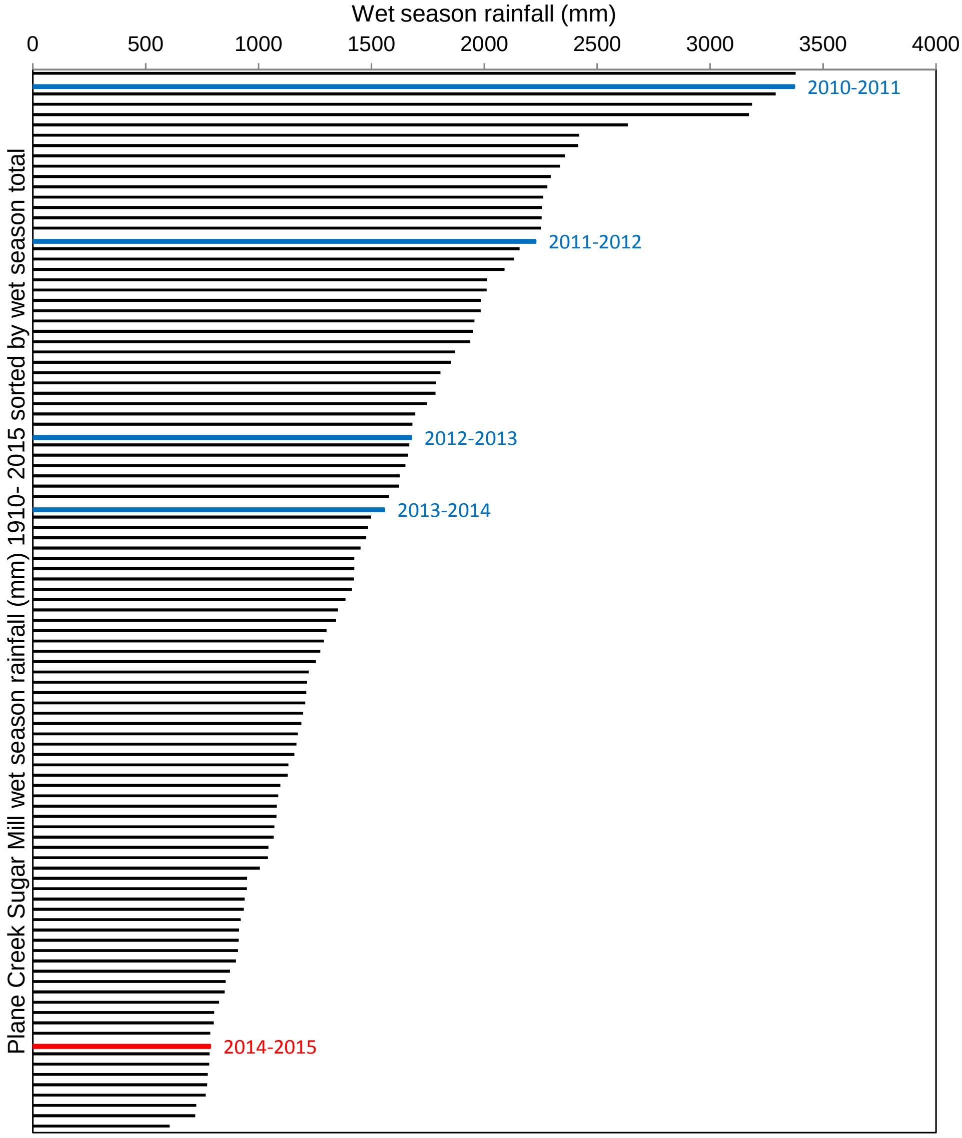


Figure 1.2 BOM wet season (November – February) rainfall data for Plane Creek Sugar Mill (station number: 33059) for years 1910 to 2015 ranked in order of decreasing total rainfall (mm). Blue bars show total rainfall over the past few years, red bar represents the 2014/15 ambient marine water quality monitoring period

Low rainfall during the monitoring period contributed to a relatively short hydrograph 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 January 2015, with the tail of the hydrograph returning to pre-flow levels again within a week. This was followed by a much larger flow event, approximately around the time that Tropical Cyclone Marcia crossed the coast to the south of Sarina. Overall, these short flow events seem to have contributed to only a small amount of catchment runoff to the coast, certainly well below average yearly flow rates.

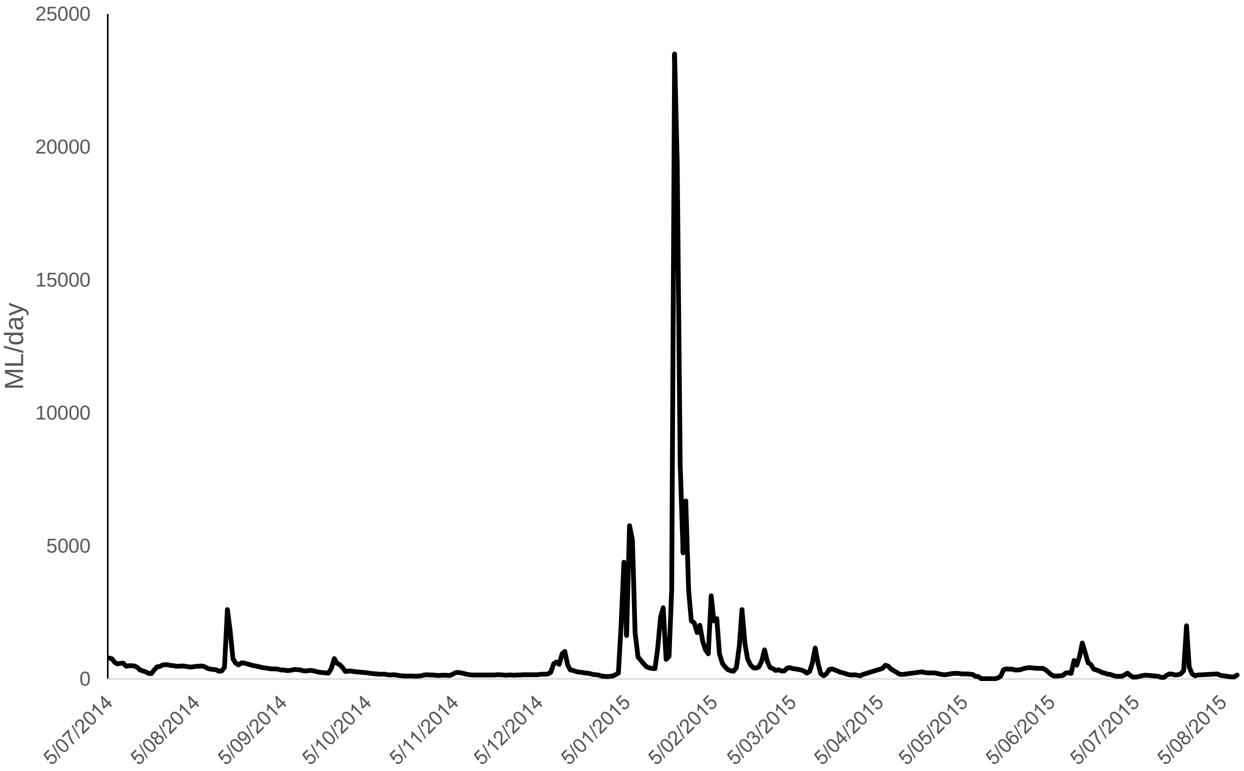


Figure 1.3 Flow recorded for Pioneer River across the monitoring period

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 50% 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.

A tropical cyclone (Cyclone Marcia; Figure 1.5) travelled close to the study area, crossing the coast to the south of Sarina in February 2015. While it contributed some rainfall and flow in the Mackay region, it was minor compared to the conditions experienced to the south.

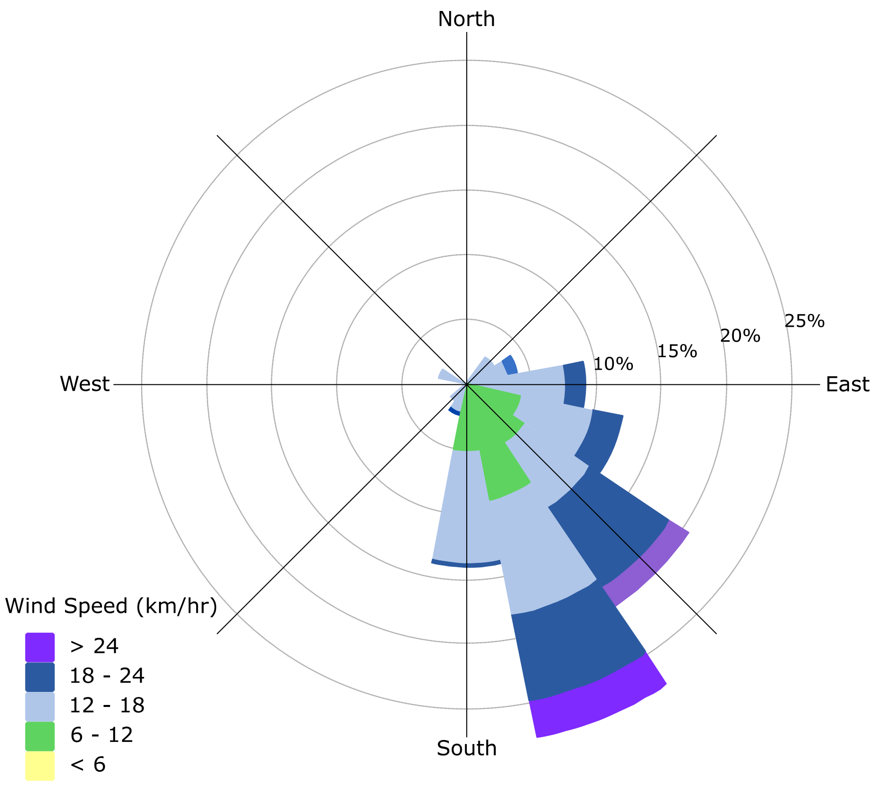


Figure 1.4 Daily average wind direction and strength recorded in Mackay airport for the survey period

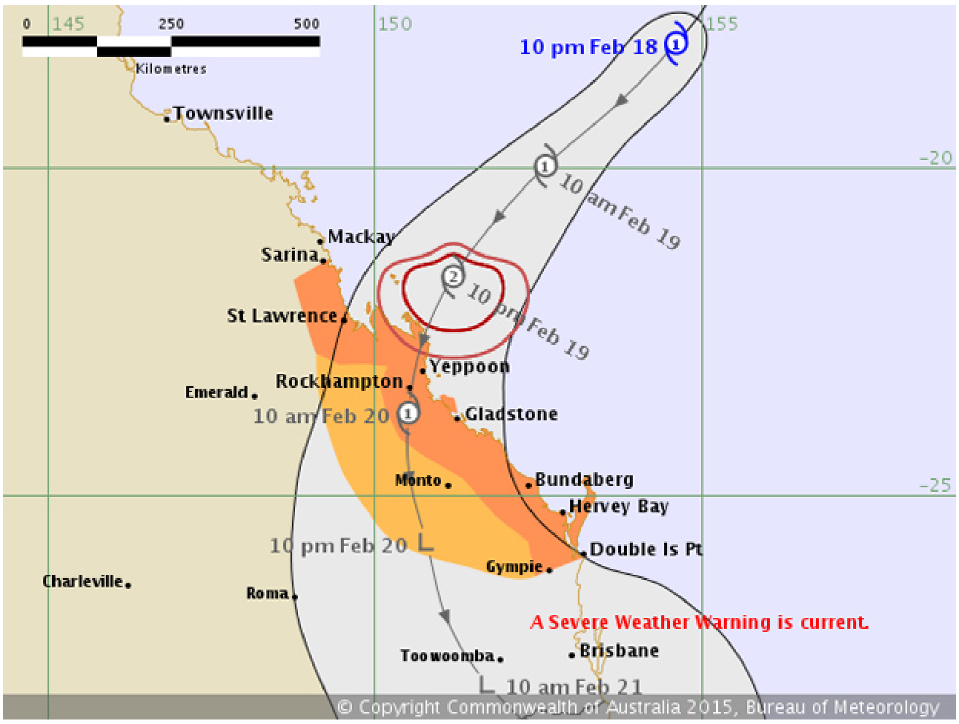


Figure 1.5 Tropical Cyclone Marcia that crossed the coast in February 2015, to the south of the study area (source: Commonwealth of Australia, Bureau of Meteorology)

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 undertake an ambient marine water quality monitoring program, in order to characterise conditions in the region (Figure 1.1).

The scope of works includes the fabrication, deployment and servicing of logger equipment, and the downloading, processing and provision of data, in addition to laboratory and ambient monitoring of water quality collected at sites across the Mackay and Hay Point region.

2 METHODOLOGY

2.1 Ambient water quality

Spot water quality samples were collected at all sites (AMB 1 – 12) on a quarterly basis (Table 2.1) over the 12 month project from a research vessel for water temperature, electrical conductivity, dissolved oxygen (%), pH, turbidity, and light attenuation (Figure 2.1). In addition to these spot measurements, secchi disk depth was also recorded, as a measure of the optical clarity of the water column, along with light attenuation using a LiCor meter. The 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.

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 (Silver (Ag), Arsenic (As), Cadmium (Cd), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), Zinc (Zn)), and Tributyltin (TBT);
- Nutrients (total nitrogen/phosphorus, ammonia, nitrite, nitrate, total dissolved nitrogen/phosphorus);
- Total Suspended Solids (TSS);
- 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 2014) and a wet (March 2015) season was deemed reasonable.

Figure 2.1 TropWATER staff conducting field water quality sampling

Table 2.1 Water chemistry surveys completed between July 2014 and July 2015

Survey	Date
Survey 1	July 2014
Survey 2	November 2014
Survey 3	March 2014
Survey 4	August 2015

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 1-L 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 for TSS was passed through a pre-weighted 0.45 µm Millipore filter. After collection of suspended material, filters were rinsed with MilliQ water to remove salt before being dried to a constant weight. The concentration of TSS was then determined by gravimetric method as presented in 'Standard Methods for the Examination of Water and Wastewater, 2540 D. Total Suspended Solids Dried at 103–105 °C'.

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, TBT, and pesticides 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		
Reduction Potential		
Light Attenuation		
Pesticides/herbicides		
Organophosphate pesticides Chlorpyrifos, Malathion, Diazinon,Primiphos-methyl	In house LC/MS method: EP234A	0.0002-0.001 µg/L
Thiocarbamates and Carbamates Thiobencarb	In house LC/MS method: EP234B	0.0002 µg/L
Dinitroanilines Pendimethalin	In house LC/MS method: EP234C	0.001 µg/L
Triazinone Herbicides Hexazinone	In house LC/MS method: EP234D	0.0002 µg/L
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 Diuron, Ametryn, Atrazine, Cyanazine, Prometryn, Propazine, Simazine, Terbuthylazine, Terbutryn	In house LC/MS method: EP234F	0.0002 µg/L
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, Tributyltin	3125B ORC/ICP/MS	0.05 to 100 µg/L

2.2 Multiparameter water quality logger

Sediment deposition, turbidity, water depth, Root Mean Squared (RMS) water depth and water temperature were measured at six sites (AMB 1, AMB 2, AMB 3, AMB 5, 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.

2.2.1 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 thus enable for the accurate comparison between 90 degree backscatter and 180 degree backscatter measurements.

2.2.2 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.

2.2.3 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 can be used for the analysis of the effect of tide and water depth on turbidity, deposition and light levels. The RMS water height shows short term variation in water depth and is therefore an indication of wave action. 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.

2.2.4 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)

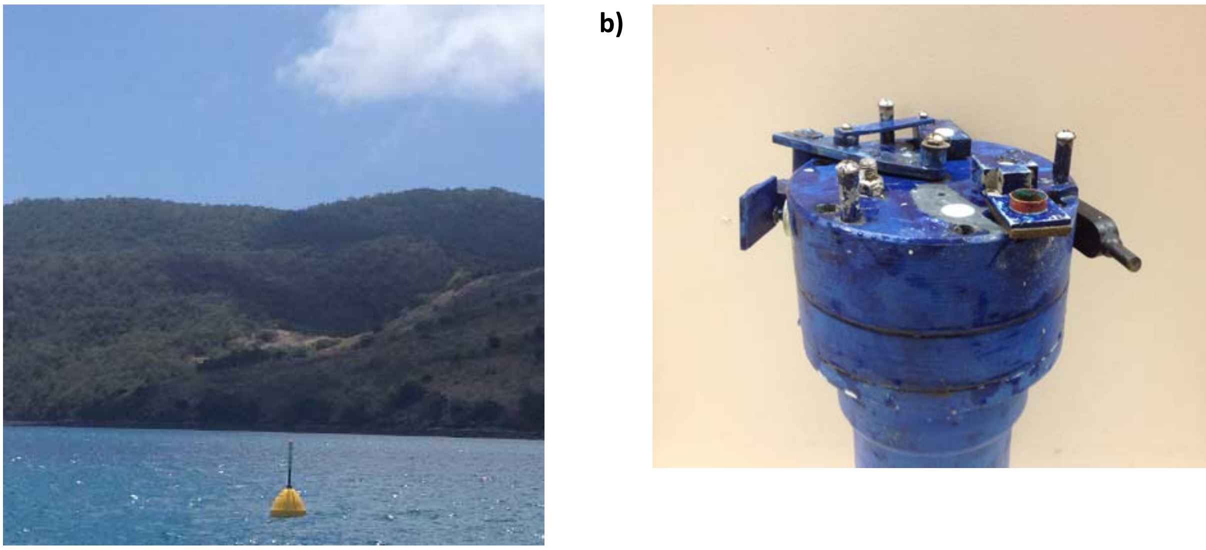


Figure 2.2 Example coastal multiparameter water quality instrument: a) site navigation beacon for safety and instrument retrieval; b) instrument showing sensors and wiping mechanisms

2.3 Photosynthetically active radiation (PAR)

Light loggers (submersible Odyssey™ photosynthetic irradiance autonomous continuous loggers (light loggers)) were deployed at eleven locations identified by NQBP around Mackay and Hay Point to assess Photosynthetically Active Radiation PAR (Figure 2.3). At each of the eleven sites PAR was continuously recorded and downloaded quarterly as part of the laboratory and physiochemical components of the program.

Automatic wiper brushes installed on each logger cleaned the optical surface of the sensor every 15 minutes to prevent marine organisms fouling the sensors (Figure 2.3). At each location, two independent PAR loggers and wiper units were deployed at the seabed approximately 5 to 10 m apart and independently connected to a surface float. PAR loggers were replaced and downloaded every three months. The presence of dual loggers provided the advantage of a reduction in the risk of loss of data through unit malfunction, fouling or disturbance during the three months between equipment exchange and download. The units were constructed by TropWATER and are widely used in coastal monitoring, including in the Mackay region and Gladstone harbour.

Odyssey PAR loggers log a cumulative reading at programmed intervals. To determine total daily PAR (mol photons m^2/day) at each site these cumulative readings are summed for each day. A calibration factor was calculated for each logger using a solar simulator and a LI-COR Underwater Radiation Sensor (LI-192) and LI-250A Light Meter. Two reference light loggers were deployed outdoors at Hay Point and Mackay to measure surface irradiance and trends in ambient PAR and to assist QA/QC procedures.

Loss of PAR data occurred at several sites due to delayed deployment of PAR loggers (July – September 2014 at AMB 1 Freshwater Point and AMB 2 Hay Point), loss of logger equipment due to trawling (July – November 2014 at AMB 9 Mackay material relocation ground which was relocated to AMB 9B East Cardinal marker), and sediment burial and loss of loggers during Cyclone Marcia (October 2014 – February 2015 at AMB 6 Dudgeon Point, and AMB 2 Hay Point).

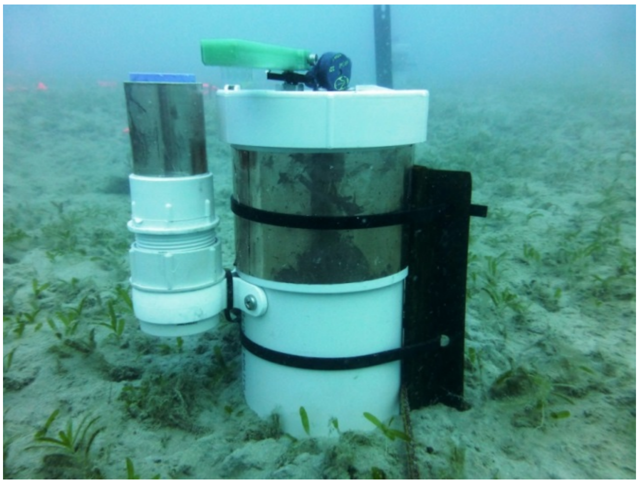


Figure 2.3 Odyssey PAR logger and wiper unit similar to those deployed in Mackay/Hay Point. Two individual loggers and associated wiper units were attached to star pickets at each site

2.3.1 Relationship between turbidity and total daily PAR

Generalised additive mixed models (GAMM) were used to examine the relationship between turbidity (NTU) and photosynthetically active radiation (PAR – mol photons m^2/day) using the “mgcv” package for R (Wood, 2014). The data for daily averages were logged transformed to reduce heterogeneity of variance (Zuur, 2012).

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 analysis, environmental parameters were examined 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 pooled into 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).

Plume maps were used to drive the river selection for the statistical analysis. Plume maps were produced by supervised classification of spectrally enhanced quasi-true colour Moderate Resolution Imaging Spectroradiometer Aqua sensor (MODIS Aqua, http://oceancolor.gsfc.nasa.gov). The classification results in 6 colour classes, describing a gradient from very turbid brown (class 1) to mostly green water masses (class 5) and plume edge (class 6) (Fox and Monett 1992; Álvarez-Romero et al., 2013).

Remote sensing (RS) analyses are conducted as part of the port of Mackay and Hay Point Ambient marine water quality monitoring program. The aim of these RS analyses is to provide historical baseline of the natural variation in water turbidity in the coastal water of the Port of Mackay and Hay points. 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. RS analyses uses Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery to monitor surface turbidity. MODIS imagery is a free 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).

Main objectives of the RS part of the project include:

- Test the potential of MODIS satellite images, in combination with *in-situ* SCC measurements, to provide historical time series of the natural variation in water turbidity in coastal waters of Mackay and Hay Point;
- Analyse temporal patterns of the satellite turbidity measurements in relation to environmental forcing, including the tidal amplitude, river discharges and wind across the study area;
- Analyses have been undertaken (Table 2.3a) to test if variations in historical daily satellite Rrs(645) (proxy for turbidity) could be predicted based on local river discharge, tide and wind. The percentages of variation explained by the selected environmental variables were between 8% and 27% across all sites investigated. These results indicated that more than 70% the temporal variability observed in the remotely-sensed turbidity (determined as Rrs(645) readings) was not explained by the selected environmental variables.

In achieving this outcome, it was suggested to:

- 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 (Table 2.3b).
- To 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 (Table 2.3c).

2.4.1 Environmental and remote sensing data

The environmental database has been updated to present, and contains historical (January 2009 to August 2015) environmental variables that potentially affect water turbidity in the study area, including daily River discharges (ML/day), tide (m), and wind intensity ($wind_i$ in km/hr) and direction ($wind_d$ in degree) data (Table 2.4).

Table 2.3 Analyses of the historical and ambient satellite and environmental datasets

Dataset name	Dates	Analyses	Objective
A) Historical	January 2009 to June 2014	statistical analyses of MODIS and environmental data	Test if we can predict variations in daily Rrs(645) (proxy for turbidity) 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.
B) Ambient (*in-situ*) *(this report)*	July 2014 to July 2015	statistical analyses of MODIS and environmental data	Test if we can predict variations in mean daily SSC 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
C) Ambient (sat) *(this report)*	July 2014 to July 2015	Match-ups analyses of MODIS and *in-situ* turbidity data from the ambient marine monitoring program	Test the capability of MODIS Rrs(645) data as a proxy for turbidity levels in the coastal waters of Mackay and Hay Point

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
Environmental	January 2009 to August 2015	Daily River discharges (ML day^{-1}) for the O'Connell, Pioneer, Sandy, Rocky, Carmilla, Waterpark and Fitzroy 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 Mackay tide gauge station	Bureau of Meteorology of the Australian Government.	tidal current velocities
		Wind intensity ($wind_i$ in km h^{-1}) and direction ($wind_d$ in degree) measured at 12 am at the Mackay radar station	Bureau of Meteorology of the Australian Government.	wave-induced sediment resuspension.

The MODIS satellite database was updated to August 2015, and contains daily 250 m MODIS Band-1 (λ : 645 nm) and Band-2 (λ : 858 nm) remote sensing reflectance (Rrs(λ)) data derived from the MODIS 250-m surface reflectance land product (MYD09GQ) from January 2009 to end of August 2015 (Table 2.4). Rrs(645) and Rrs(858) were extracted from each daily 250-m MODIS Band-1 and Band-2 imagery at 11 ambient sites locations (Figure 3.30) using ArcMap

Spatial Analyst (ESRI, 2010). A 1 km buffer was created around each *in-situ* monitoring site and the ArcMap Zonal Statistic tool was used to extract Rrs(645) and Rrs(858) values for each pixel in the buffered area. Each *in-situ* ambient site was thus assigned daily maximum, mean and standard deviation Rrs(645) and Rrs(858) values, all calculated from the buffered Rrs(645) and Rrs(858) values extracted.

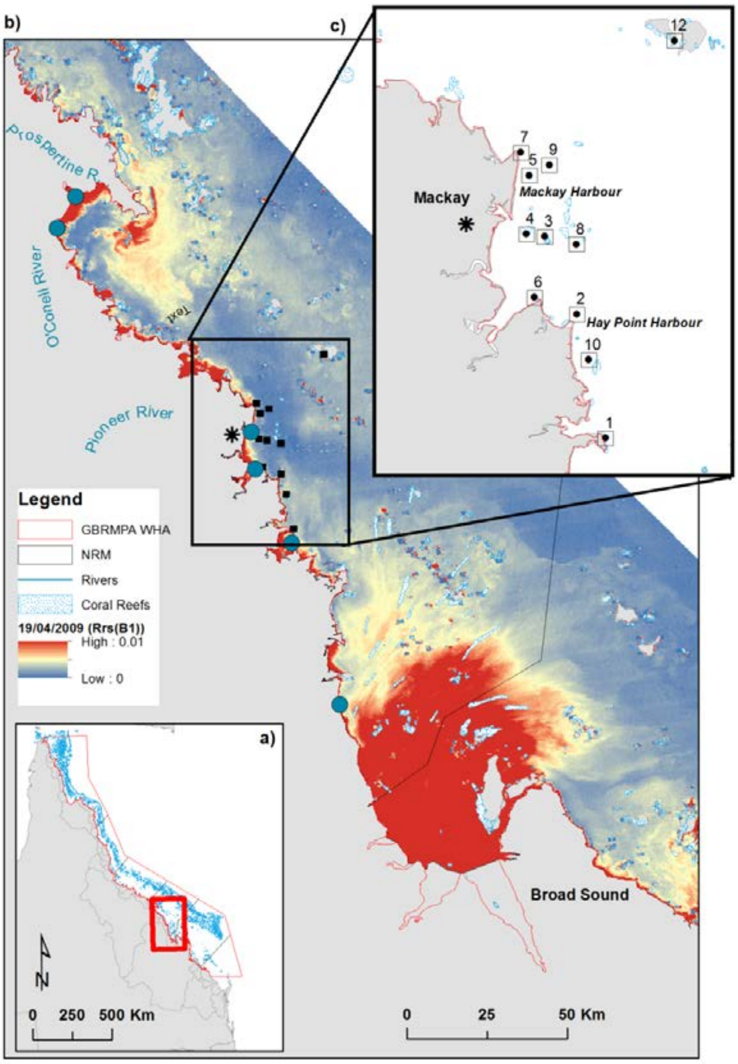


Figure 2.4 a) study area, b) example of MODIS data: Rrs(645) measured the 19 April 2009, and c) locations of ambient *in-situ* monitoring sites

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 with at least 7 of the 11 ambient sites (i.e., more than 50%) non-affected by clouds.

2.4.2 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 2014 and July 2015 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

Water temperature ranged between 19 and 31^{o}C over the past 12 months and showed a strong seasonal effect 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 two and three but little variation between sites (Figure 3.1). There are no guidelines for water temperature, however, temperature is an essential interpretative aid for ecological assessment in environments. For example, species such as fish and other animals have thermal stress effect temperature points, which causes discomfort and could be misconstrued as being a toxicological impact. There were no observed or known impacts on species in the region during this monitoring period.

Electrical conductivity (EC) was stable across all sites, with the exception of survey one (July 2014) which had lower values presumably following some rainfall runoff in the region (Figure 3.1). Following the first survey (July 2014), EC returned to conditions more similar to oceanic waters, and remained at those values for the remainder of the period. There was no difference in EC with water depth at all sites, supporting the point that the water column was well mixed during this monitoring period.

Dissolved oxygen saturation levels ranged between 70 to 105% (Figure 3.1). There was some local variability among sites, with the lowest levels recorded at AMB 11 (Mackay Marina), particularly 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. For all other sites, the water column was well mixed with dissolved oxygen levels similar along the depth profile.

Field pH measurements were stable across sites and depths with the exception of one sample from survey three (March 2015) at Dudgeon Point (AMB 6), which was markedly lower than others and is probably an error in the transcription from the field unit to the datasheet (7.17 value recorded); in any case it is an outlier in the dataset and it has been removed (Figure 3.2). Both lab and field measurements of pH were taken during surveys for QA/QC purposes. Lab and field pH values were reasonably consistent for survey two, but greater discrepancies were apparent for surveys 3 (March 2015) and 4 (August 2015) where lab values were higher. Field pH showed a trend of decreasing pH across the four survey periods, however, the laboratory surface pH samples, did not support this trend (see Appendix). Rather, laboratory measured pH was consistent across all sites and a slight seasonal effect was apparent with the highest values recorded during surveys 2 (November 2014) and 3 (March 2015). The reason for this difference between field and laboratory measured pH in water samples is due to equilibration of samples that occurs during transport time between field and laboratory analysis. Field and laboratory measurements for pH is recommended in the future sampling, to demonstrate the water samples during transport remain stable.

Field turbidity measurements ranged between <1 to 150 NTU (Figure 3.2). There was an apparent pattern of increased turbidity with depth, with highest values occurring during survey 2 (November 2014). Laboratory turbidity measures also displayed higher concentrations than their field equivalents, which is probably related to slight differences in accuracy between field and laboratory equipment. Highest turbidity values were recorded at AMB 11 (Mackay Marina), particularly at the bottom horizon. 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 2 and 17m (Figure 3.3). 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.

Table 3.1 Summary statistics for physico-chemical data recorded at sites during the program. Values are mean across four surveys, with range in parentheses

Site	Depth (m)	Water Temp (°C)	EC (mS/cm)	Dissolved Oxygen (mg/L)	DO %	pH	Turbidity (ntu)	Secchi depth (m)
AMB 1	6.5	23.74	52.81	6.11	89.46	8.03	25.95	3.49
	(4-8.2)	(19-29.64)	(41.4-57.1)	(5.31-6.99)	(82.3-96.6)	(7.79-8.25)	(0-114)	(2.03-5.6)
AMB 2	11.1	23.85	52.59	6.27	92.31	8.06	16.56	6.65
	(8-13.5)	(19.12-29.79)	(41-57.1)	(5.52-7.51)	(84.7-99.5)	(7.81-8.27)	(0-47.3)	(2.03-14.5)
AMB 3	10.33	23.69	52.37	6.33	93.29	8.06	30.97	7.33
	(8.8-12.2)	(19.44-29.36)	(40.5-56.9)	(5.79-7.13)	(85.9-98.9)	(7.8-8.25)	(0-161.1)	(3.25-11)
AMB 4	6.68	23.86	52.45	6.32	91.02	8.06	23.50	3.88
	(6-8.4)	(19.34-29.57)	(40.7-56.8)	(5.7-7.14)	(71.4-101.3)	(7.8-8.26)	(0-79.5)	(3.1-7.17)
AMB 5	8.7	23.77	52.44	6.42	94.10	8.06	6.00	6.89
	(6.2-11.1)	(19.41-29.17)	(40.7-56.8)	(5.84-7.38)	(84.8-99.1)	(7.88-8.26)	(0-24.6)	(4.73-10)
AMB 6	3.85	23.68	52.84	6.31	92.91	8.08	13.05	4.15
	(2.3-4.8)	(18.19-30.03)	(41.9-57)	(5.55-7.07)	(85.2-102.7)	(7.79-8.24)	(0-50.9)	(2.55-6.3)
AMB 7	8.95	23.83	52.53	6.51	92.07	8.05	7.19	6.73
	(7-10.1)	(19-29.22)	(40.8-56.8)	(5.68-8.53)	(84.7-99.1)	(7.67-8.27)	(1-23.7)	(2.55-11)
AMB 8	15.5	23.63	52.35	6.46	92.76	8.06	23.62	9.45
	(15-16.2)	(19.51-29.26)	(40.8-56.8)	(5.9-7.55)	(84.7-99.8)	(7.82-8.25)	(0-137.1)	(3.45-16)
AMB 9	15.78	23.69	52.33	6.49	94.28	8.08	6.94	8.45
	(12.2-19)	(19.47-29.08)	(40.6-56.8)	(5.71-7.74)	(84.6-103.4)	(7.91-8.25)	(0-23.4)	(2.95-16)
AMB 9B	12.73	25.35	56.34	6.40	96.70	8.05	26.67	6.95
	(11.4-14.6)	(19.93-29.43)	(56-56.8)	(5.86-7.29)	(91.9-99.7)	(7.95-8.21)	(0-67.5)	(2.14-8.9)
AMB 10	7.23	23.86	52.69	6.50	92.18	8.07	14.83	3.81
	(5.6-8.2)	(19.31-29.8)	(41.1-57.1)	(5.53-8.93)	(85.2-98.2)	(7.81-8.27)	(0-62)	(2.14-7.4)
AMB 11	6.38	24.24	51.96	6.06	87.36	8.07	31.60	4.26
	(5.2-9.0)	(19.57-30.23)	(39.2-56.7)	(5.1-7.03)	(80.5-95.2)	(7.82-8.25)	(0-177)	(2.14-6.5)
AMB 12	6.98	23.98	51.66	6.26	91.75	8.07	5.59	5.35
	(5-8.1)	(20.84-28.94)	(39.3-56.4)	(5.68-7.85)	(84.3-102.9)	(7.83-8.28)	(0-21.6)	(2.81-7.17)

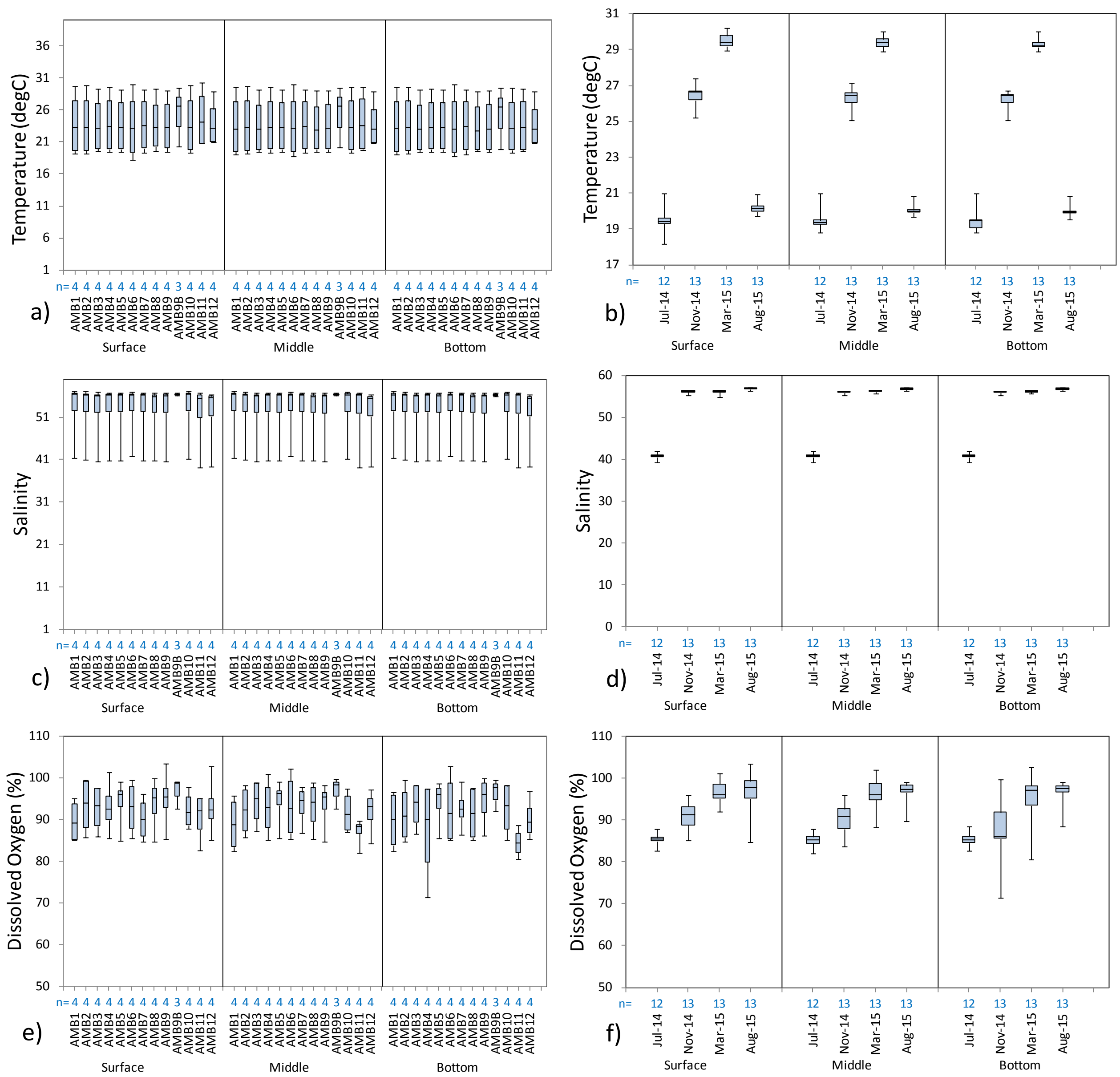


Figure 3.1 Box plots of physico-chemical parameters recorded at sites for the three depth horizons

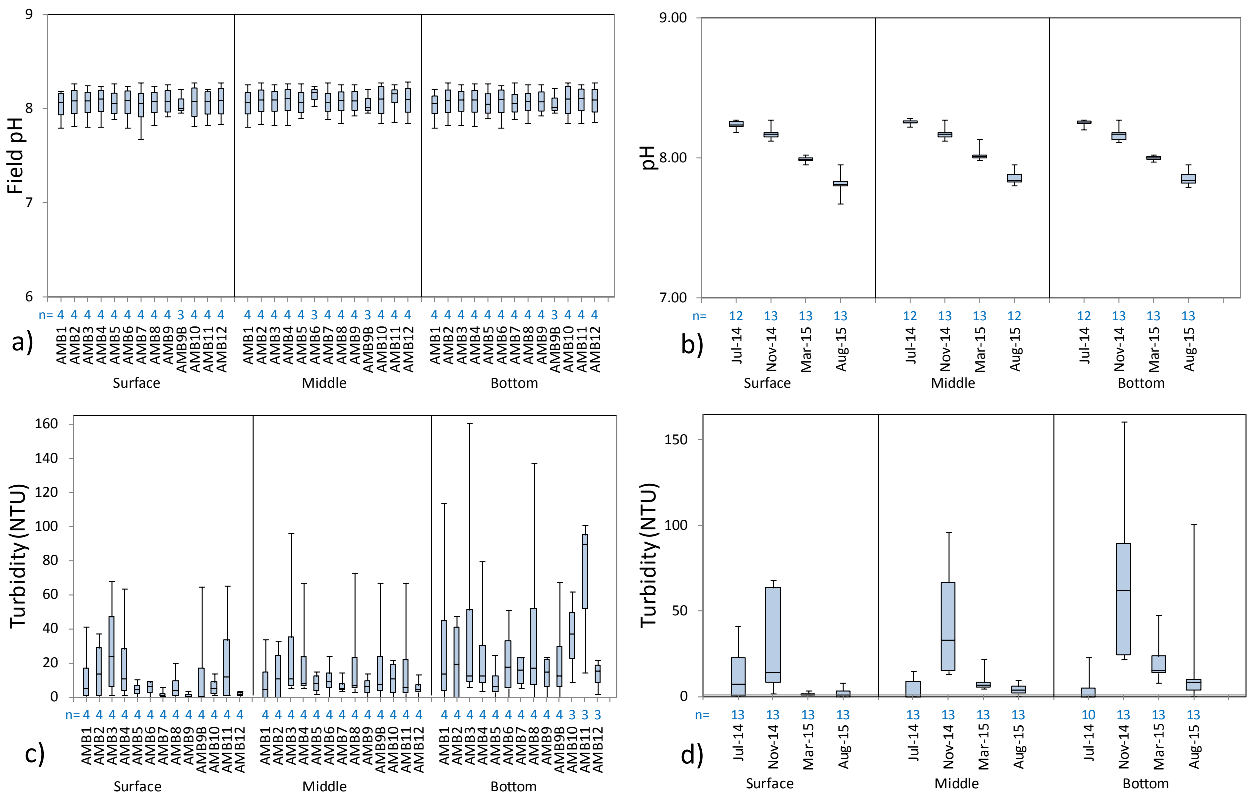


Figure 3.2 Box plots of physico-chemical parameters recorded during each survey for the three depth horizons

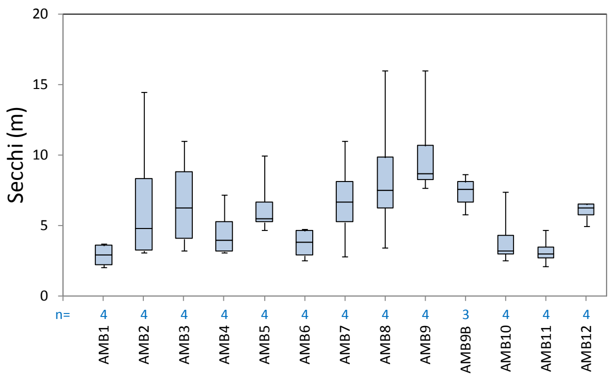


Figure 3.3 Box plot of secchi depth recorded at sites

3.1.2 Nutrients and chlorophyll-*a*

Nutrient concentrations were compared, where possible, with 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). Concentrations exceeding the guidelines were observed for total nitrogen, ammonia and NOx across all sites (Figure 3.5). These high concentrations might be associated with contribution from local land use, whereby despite low rainfall, there would be still some base flow from rivers and local rainfall that is known to contribute to nutrient loadings to coastal regions (see 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 surveys 2 and 4 (early and late summer). This algal bloom may also be contributing to the variation among sites in secchi disk depths and ephotic depth calculations (Table 3.1). Additional investigation into the phytoplankton community and processes are recommended for the region.

The highest total nitrogen and total dissolved nitrogen values occurred during survey 4 (August 2015) particularly, for sites East Cardinal marker near the Mackay sediment relocation areas (AMB 9B), Victor Islet (AMB 10), Mackay Harbour (AMB 11) and Keswick Island (AMB 12). Nitrite was only detected three times: during survey 1 (July 2014) at Mackay Harbour (AMB 11) and during survey 2 (November 2014) at sites Hay Reef (AMB 2), and Mackay Dredge Sediment Relocation Areas (AMB 9). Nitrate (above the guidelines) concentrations were also highest for Mackay Harbour (AMB 11). Ammonia concentrations, although demonstrating greater among site variability showed exceedances for all sites except Flat Top (AMB 4) and all surveys except survey three, however, the highest values were again observed for Mackay Harbour and AMB 7 (Slade Point). Similarly, dissolved inorganic nitrogen, although still showing local site variability was consistently above QWQG for all sites at all surveys (Figure 3.5). Oxides of nitrogen and particulate nitrogen also demonstrated a number of exceedances with a high level of variability (Figure 3.5). These exceedances reflect the increasing trend of nutrient levels presented in the Reef Water Quality Protection Plan report cards for the Mackay-Whitsunday Area (2009 to 2014), and probably reflect a broader catchment scale water quality challenge for the region.

In contrast to total nitrogen, total phosphorous concentrations were consistently below QWQG at all sites and for all surveys (Figure 3.6). Filterable reactive phosphorous concentrations and particulate phosphorous concentrations were generally within the QWQG (2010), but in exceedance of the Mackay-Whitsunday water quality objective values (Folker et al., 2014). Filterable reactive phosphorous concentrations above the guidelines were highest for Dudgeon Point (AMB 6), East Cardinal marker near the Mackay spoil grounds (AMB 9B) and Mackay Harbour (AMB 11) and during survey 4 (August 2015; Figure 3.6). Particulate phosphorous concentrations were higher at Freshwater Point (AMB 1), Hay Reef (AMB 2) and Victor Island (AMB 10) and during survey 1 (July 2014, Figure 3.6). Chlorophyll-*a* were generally low, exceedances were observed to have a seasonal contribution. Surveys 1 (July 2014) and 4 (August 2015) were below the guidelines, whereas, surveys 2 (November 2014) and 3 (March 2015) exceeded the guidelines (Figure 3.7); highest chlorophyll-*a* concentrations were measured at Slade Point (AMB 7) and Mackay Harbour (AMB 11). Total suspended sediments were low, with the only elevated concentration of 24 mg/L, which was recorded at Keswick Island (AMB 12). This erroneous result is considered to be an analytical error given all other water samples collected on the same day were very low. The possible reason for this error is due to contamination of some particles that accumulated on the filter paper during filtering, which has contributed to the measurement. This data point has been removed from the data plots. Additional laboratory steps have been since implemented to mitigate this error.

Table 3.2 Summary statistics for nutrients and chlorophyll-*a* recorded at each site during the program. Values in blue indicate concentrations exceeding the QWQG (2009) and the GBRMPA guidelines (2010). Blank cells have no guideline limit set

		Total Suspended Solids	Total Nitrogen	Particulate N	Total Dissolved Nitrogen	Ammonia	Nitrite	Nitrate	Dissolved Inorganic Nitrogen	NOx	Dissolved Organic Nitrogen	Total Phosphorus	Particulate P	Total Dissolved Phosphorus	Filterable Reactive Phosphorus	Dissolved Organic Phosphorus	Chlorophyll-*a*	Phaeophytin-*a*
	Unit	**mg/L**	**µg N/L**	**µg N/L**	**µg N/L**	**µg N/L**	**µg N/L**	**µg N/L**	**µg N/L**	**µg N/L**	**µg N/L**	**µg P/L**	**µg P/L**	**µg P/L**	**µg P/L**	**µg P/L**	**µg/L**	**µg/L**
	LOR	**0.1**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**0.2**	**0.2**
	GBRMPA 2010	**2**		**20**									**2.8**				**0.45**	
	QWQG 2009	**2**	**140**	**20**		**4**				**3**		**20**	**2.8**		**6**		**0.45**	
Survey 1	Mean	1.68	165.17	29.33	135.83	5.58	0.17	5.42	11.17	5.58	124.67	8.67	1.58	7.08	5.58	1.50	0.39	<0.2
Jul-14	Min	0.90	151.00	5.00	114.00	3.00	<1	1.00	5.00	1.00	97.00	7.00	0.00	4.00	3.00	0.00	0.23	<0.2
	Max	3.70	179.00	55.00	153.00	9.00	2.00	19.00	28.00	19.00	143.00	11.00	4.00	10.00	9.00	4.00	0.63	<0.2
Survey 2	Mean	3.34	134.50	16.58	117.92	7.17	2.00	3.40	10.33	3.80	107.58	10.50	2.58	7.92	2.92	5.00	0.80	0.25
Nov-14	Min	2.10	100.00	1.00	99.00	3.00	2.00	1.00	3.00	2.00	89.00	8.00	0.00	7.00	2.00	3.00	0.26	0.20
	Max	5.10	164.00	48.00	136.00	11.00	2.00	6.00	15.00	7.00	123.00	14.00	6.00	10.00	4.00	7.00	2.64	0.33
Survey 3	Mean	2.47	164.23	23.54	140.69	3.54	<1	7.33	9.92	6.38	130.77	8.92	1.38	7.54	3.77	3.77	0.90	0.25
Mar-15	Min	1.10	142.00	1.00	123.00	3.00	<1	4.00	5.00	2.00	111.00	7.00	0.00	6.00	2.00	0.00	0.33	0.2
	Max	5.30	199.00	52.00	164.00	4.00	<1	9.00	14.00	10.00	155.00	12.00	3.00	9.00	6.00	5.00	2.74	0.31
Survey 4	Mean	2.35	249.77	79.69	170.08	4.62	<1	4.40	7.38	3.09	162.69	11.38	2.54	8.85	7.08	1.77	0.45	0.25
Aug-15	Min	1.60	177.00	3.00	144.00	4.00	<1	1.00	5.00	1.00	139.00	7.00	0.00	6.00	5.00	0	0.23	0.23
	Max	3.70	414.00	241.00	186.00	6.00	<1	10.00	17.00	11.00	176.00	16.00	7.00	11.00	10.00	5	1.6	0.28
Overall	Mean	2.44	179.56	37.86	141.70	5.18	0.43	5.19	9.66	4.83	132.04	9.88	2.02	7.86	4.86	3.00	0.67	0.25
	Min	0.90	100.00	1.00	99.00	3.00	<1	1.00	3.00	1.00	89.00	7.00	0.00	4.00	2.00	0.00	0.23	0.2
	Max	5.30	414.00	241.00	186.00	11.00	2.00	19.00	28.00	19.00	176.00	16.00	7.00	11.00	10.00	7.00	2.74	0.33

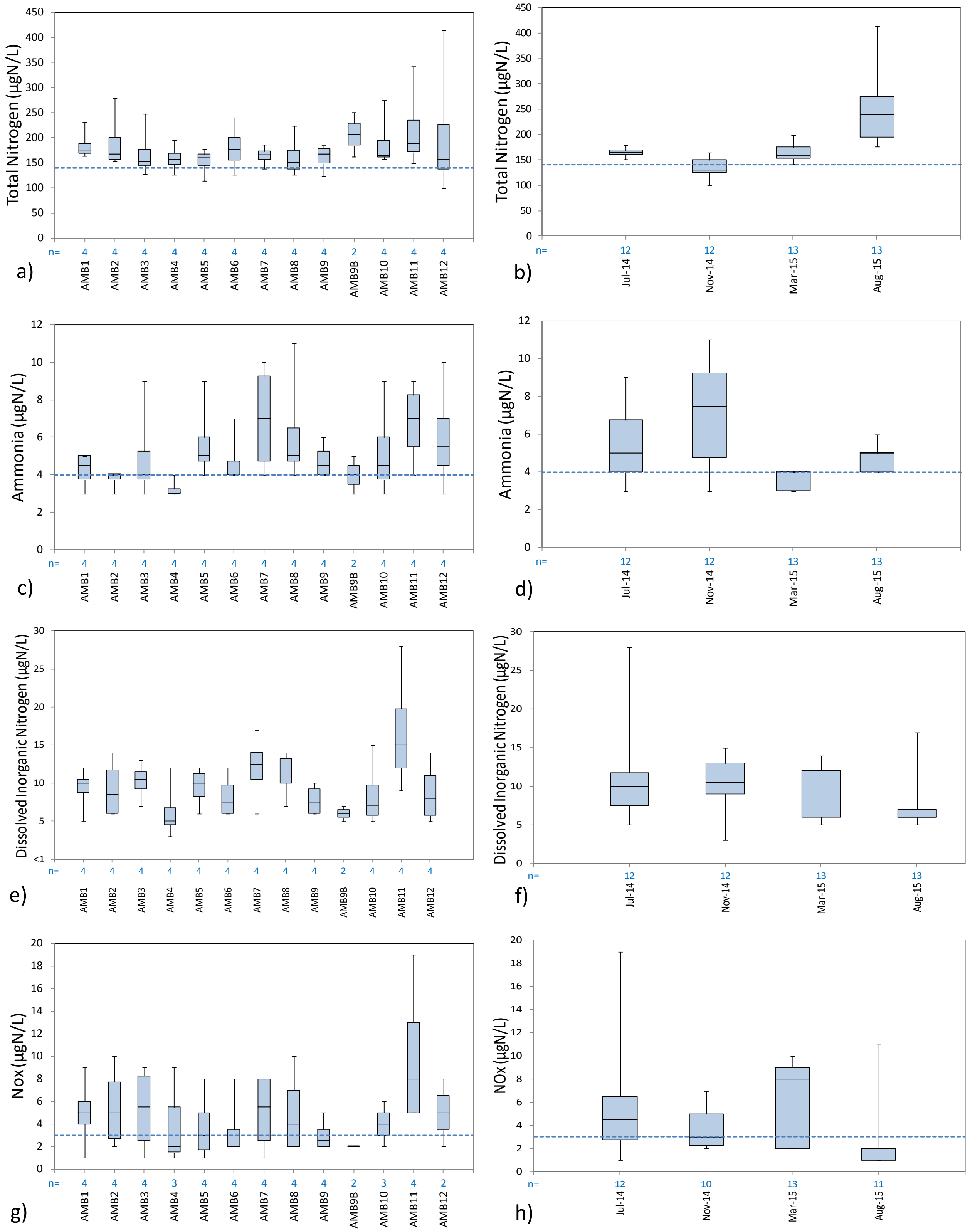


Figure 3.5 Box plots of nutrient parameters recorded at each site and during each survey (cont.). Blue lines indicate the relevant water quality guidelines (GBRMPA, 2010; QWQG, 2009)

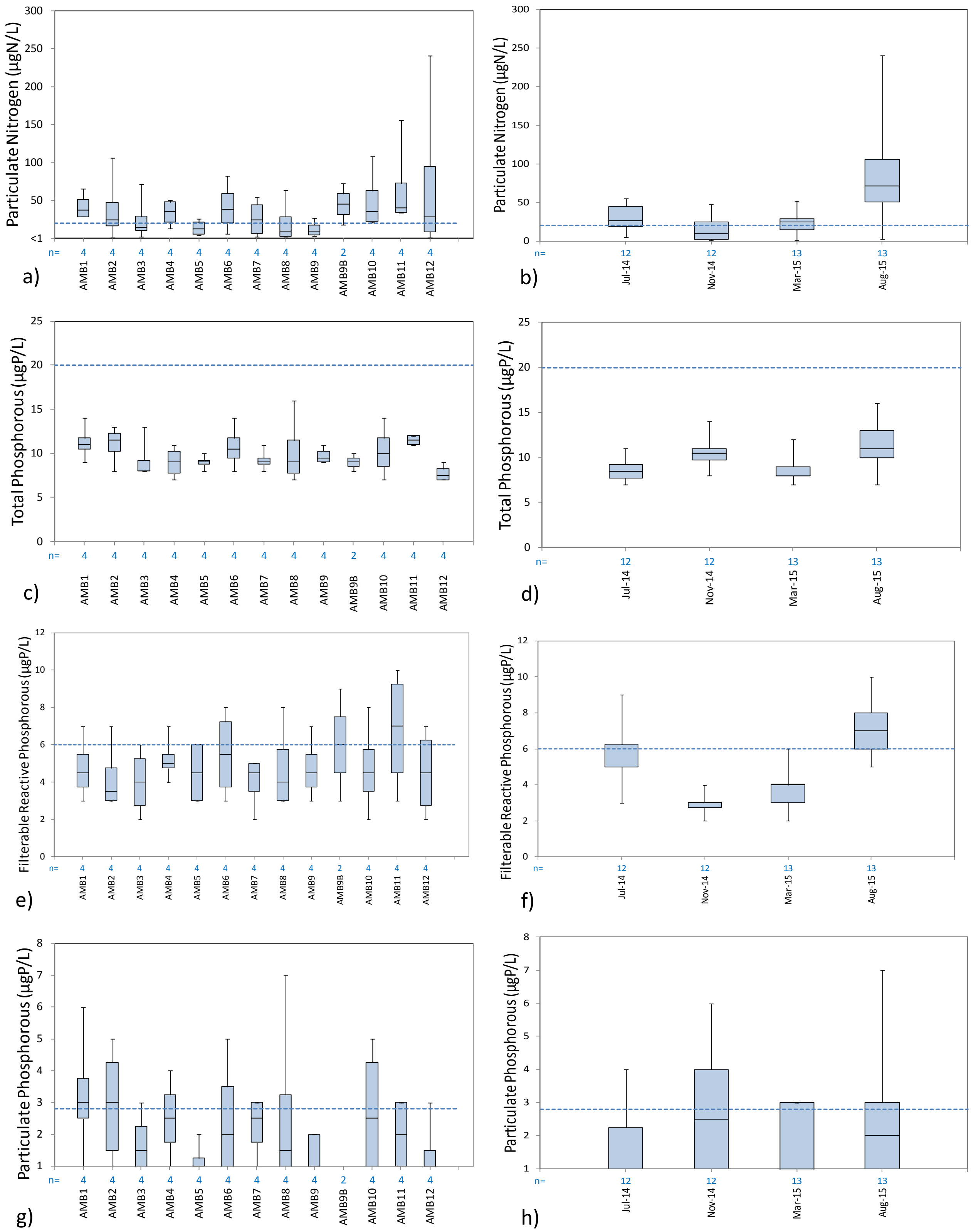


Figure 3.6 Box plots of nutrient parameters recorded at each site and during each survey (cont.). Blue lines indicate the relevant water quality guidelines (GBRMPA, 2010; QWQG, 2009)

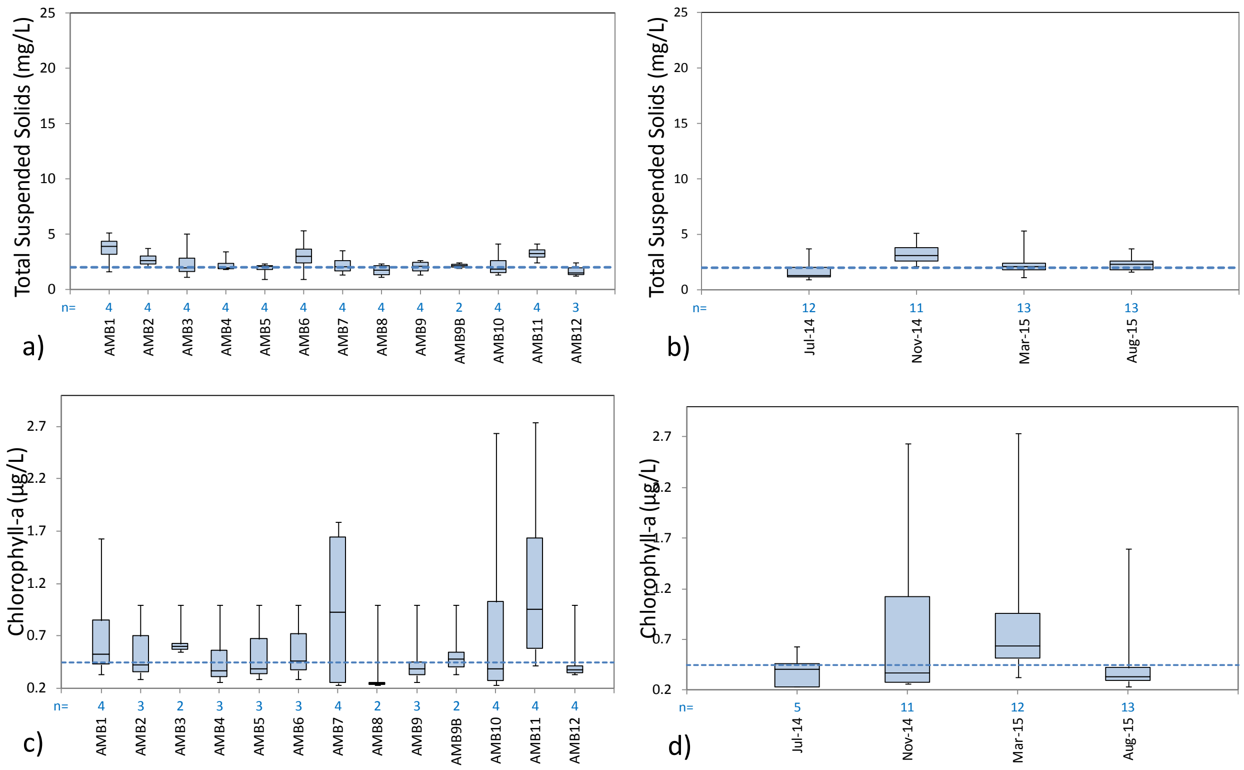


Figure 3.7 Box plots of nutrient parameters recorded at each site and during each survey (cont.). Blue lines indicate the relevant water quality guidelines (GBRMPA, 2010; QWQG, 2009)

3.1.3 Water heavy metals and TBT

Where possible, heavy metal concentrations were compared to the ANZECC and ARMCANZ 2000 water quality guidelines (ANZECC, 2000). Most filterable metals examined were not detected above the limit of reporting, the exception to this was arsenic. No ANZECC guideline exists for arsenic, however, all detected arsenic concentrations were well below the low reliability guidelines for both As(III) and As(V) (2.3 and 4.5 µg/L respectively). In addition, copper was detected in every survey at the Mackay Harbour site (AMB 11) in exceedance of the ANZECC 95% protection limits. Lead was detected once (survey 1; July 2014) at Slade Point (AMB 7), but was below the 95% protection value. Tributyltin was not detected above the limit of reporting (no samples were collected during the first survey, however, it is expected that tributyltin would not have been detected).

Table 3.3 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 red represent exceedances

		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**	**ng Sn/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**
Survey 1	Mean	1.45	<0.2	<1	0.25	<0.5	<0.1	<5	<0.0001	-
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	-
Survey 2	Mean	1.28	<0.2	<1	<0.2	<0.5	<0.1	<5	<0.0001	<2
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
Survey 3	Mean	1.68	<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
Survey 4	Mean	1.22	<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
Overall	Mean	1.41	<0.2	1.5	0.25	<0.5	<0.1	<5	<0.0001	<2
	Min	0.8	<0.2	<1	0.2	<0.5	<0.1	<5	<0.0001	<2
	Max	1.9	<0.2	2	0.3	<0.5	<0.1	<5	<0.0001	<2

3.1.4 Water pesticides and herbicides

The majority of pesticide and herbicide concentrations were not detected above the limit of reporting (Table 3.4). 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). In this instance, Diuron concentrations at Flat Top (AMB 4; survey 1, July 2014), Slade Islet (AMB 5; survey 1, July 2014), while Mackay Harbour (AMB 11; survey 1 and 3, July 2014 and March 2015 respectively) were found in exceedance of this objective. It should be noted that although all detected pesticide levels were below 95% protection guidelines, and the period of study did not experience a typical dry and wet season, therefore runoff was minimal. The detection of Diuron in March 2015 at the AMB 11 might be a consequence of a local source. Overall, these values do not fully characterise concentrations that might be recorded during average or even more wet rainfall years.

Table 3.4 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 this reporting period

		LOR	Guidelines (GBRMPA)	WQO's (WQIP, 2014)	Survey 1			Survey 3			Overall 2014-2015		
					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	0.0000	0.0000
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
Diazinon	**µg/L**	**0.0002**	0.01	0.01	0.0027	0.0006	0.0072	<0.002	<0.002	<0.002	0.0027	0.0006	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
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
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
Hexazinone	**µg/L**	**0.0002**	1.2	0.01	0.0006	0.0004	0.0008	0.0003	0.0003	0.0004	0.0005	0.0003	0.0008
Propiconazole	**µg/L**	**0.0002**		0.01	0.0013	0.0004	0.0048	0.0004	0.0002	0.0006	0.0011	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
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
Tebuconazole	**µg/L**	**0.0002**		0.01	0.0014	0.0014	0.0014	0.0006	0.0006	0.0006	0.0010	0.0006	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
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
Diuron	**µg/L**	**0.0002**	1.6	0.01	0.0070	0.0020	0.0213	0.0045	0.0018	0.0115	0.0062	0.0018	0.0213
Ametryn	**µg/L**	**0.0002**	1.0	0.01	<0.0004	<0.0004	<0.0004	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Atrazine	**µg/L**	**0.0002**	1.4	0.01	0.0006	0.0004	0.0008	0.0004	0.0002	0.0007	0.0004	0.0002	0.0008
Cyanazine	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
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
Propazine	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Simazine	**µg/L**	**0.0002**	3.2	0.01	0.0016	0.0016	0.0016	<0.0002	<0.0002	<0.0002	0.0016	0.0016	0.0016
Terbuthylazine	**µg/L**	**0.0002**		0.01	<0.0004	<0.0004	<0.0004	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Terbutryn	**µg/L**	**0.0002**		0.01	0.0010	0.0009	0.0010	<0.0002	<0.0002	<0.0002	0.0010	0.0009	0.0010

3.1.5 Ordination of data

Exploratory statistical examination of the surface physico-chemical data collected using multidimensional scaling (nMDS) revealed a separation in the water quality conditions among surveys (Figure 3.8). Survey 2 (November 2014) was characterised by relatively higher turbidity, as revealed by the direction of the vector trajectory line, whereas survey four (August 2015) contained relatively higher nutrient levels. These differences were significant and presumably a function of the emerging seasonal trends for the region that relate to water temperature (Table 3.5). Removal of temperature as a variable from the nMDS produced no apparent change to the separation and groupings in the ordination. Continuation of the data collection in 2015/16 will improve the ability to further examine these underlying patterns, and will also allow temporal assessment of water quality conditions between years.

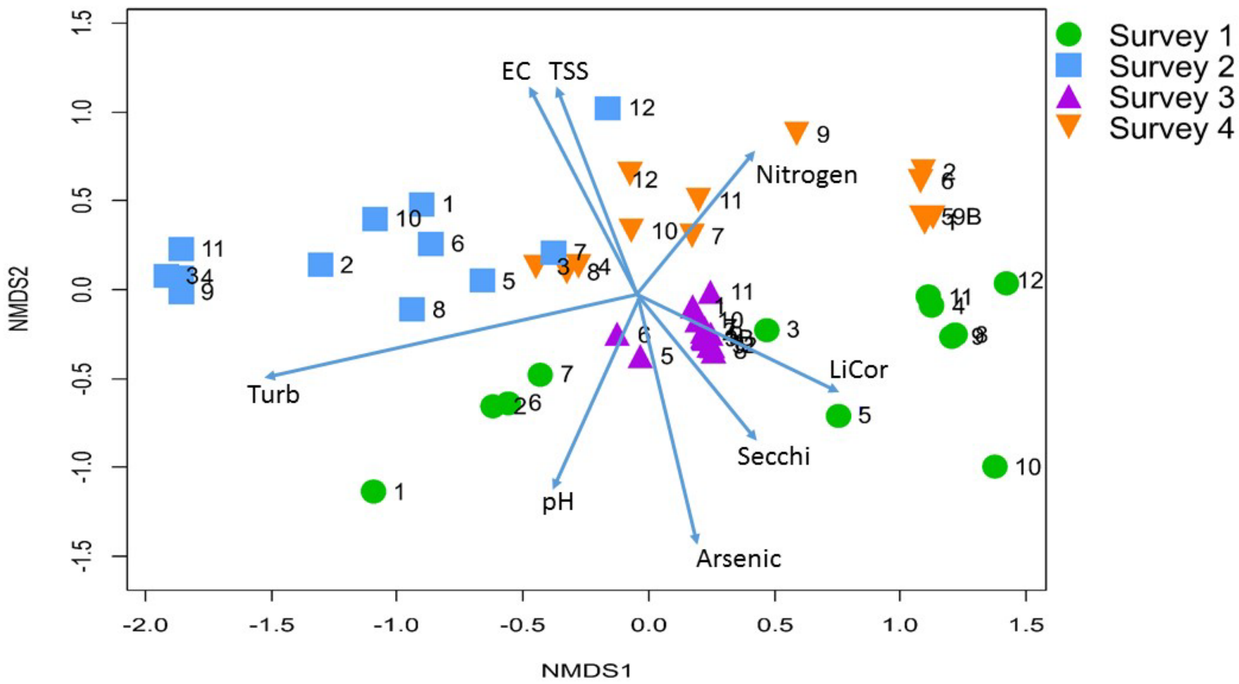


Figure 3.8 Non-dimensional ordination plot using field *in-situ* surface measurements for all surveys. Labels are shortened site names. Stress is 0.09. Data has been 4^{th} root transformed on the Euclidean distance matrix. Survey number correspond with Table 2.1

Table 3.5 PERMANOVA table of results relating to Figure 3.8

Source	df	SS	MS	Pseudo-F	P(Perm)
Survey	3	29.615	9.8717	18.2450	0.001
Temperature	1	2.761	2.7609	3.9417	0.016
Survey*Temp	3	7.348	2.4492	4.5266	0.003
Residual	42	22.725	0.5411		
Total	49	62.449			

Exploratory statistical examination of the physico-chemical data for the three water depth horizons using multidimensional scaling (nMDS) revealed a separation in the water quality conditions among surveys and also for the different profile depths. Of the measured water quality variables, turbidity emerged as the driving factor for the separation of depth horizons (Figure 3.9). This overall pattern was not consistent among surveys (non-significant interaction; Table 3.6). Once again, after removing temperature from the NMDS produced no apparent change to the separation and groupings shown in the nMDS. Continuing the data collection in 2015/16 will increase the ability to further examine these underlying patterns (particularly whether turbidity continues to contribute to separation of water depth horizons), and also allow for assessment between years.

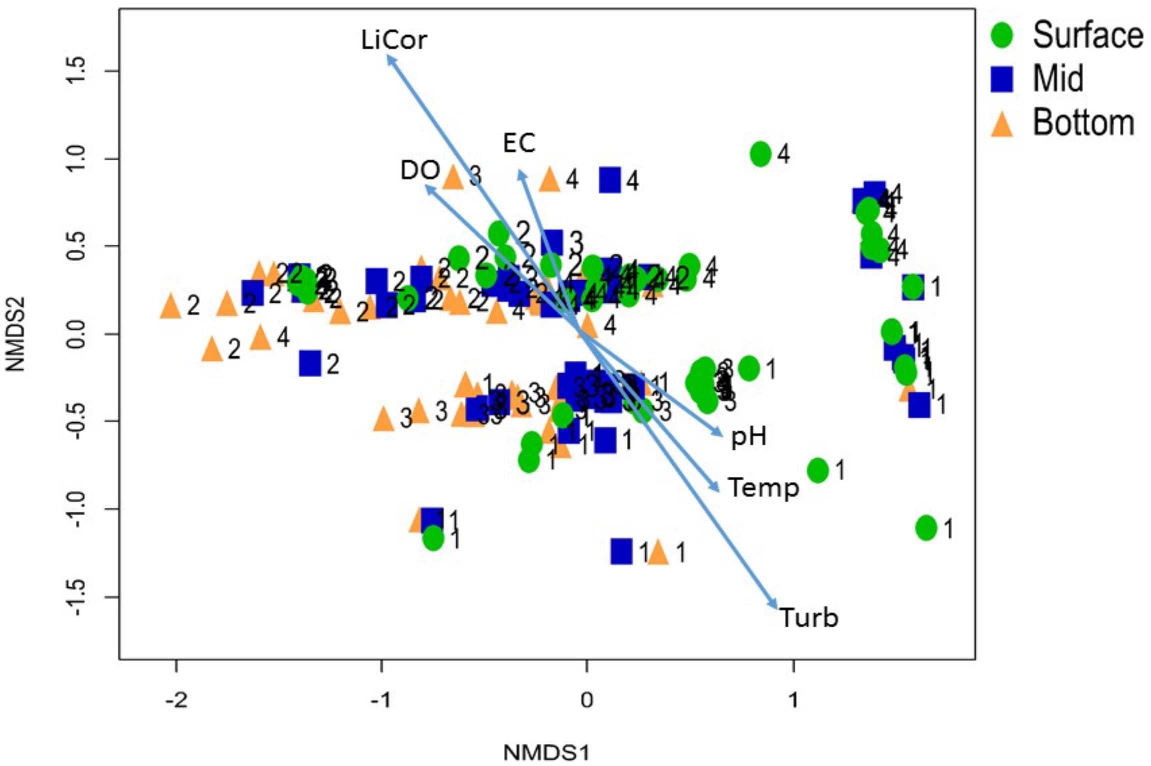


Figure 3.9 Non-dimensional ordination plot using field *in-situ* surface measurements for all surveys and depths. Stress is 0.06. Data has been 4th root transformed on the Euclidean distance matrix. Survey number correspond with Table 2.1

Table 3.6 PERMANOVA table of results relating to Figure 3.9

Source	Df	SumsOfSqs	MeanSqs	F.Model	R2	Pr(>F)
Survey	3	79.657	26.5522	45.096	0.44574	0.001
Depth	2	14.121	7.0606	11.992	0.07902	0.001
Survey:Depth	6	1.909	0.3182	0.540	0.01068	0.879
Residuals	141	83.021	0.5888		0.46456	
Total	152	178.708			1	

3.2 Multiparameter water quality logger

Instruments were deployed at six sites, AMB 1, 2, 3, 5, 10 and 12, from 7 July 2014 to 7 July 2015 (see Table 1.1). Using basic statistics, and wavelet and Fourier analysis of parameters we describe observed trends, differences between sites and discuss driving forces in these environments. Expanding on this we provide polynomial models of SSC relative to RMS water depth and multiparameter predictive numerical modelling of NTUe/SSC.

Data is presented throughout the text, (in addition to a companion appendices report), in a time series format, monthly and yearly statistical summaries and using wavelet and Fourier analysis techniques for future comparison. The box plots provide a visual representation of the descriptive statistics for suspended sediment concentration (SSC), deposition rate (mg/cm^2/day), temperature and RMS water height. 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.

Data is further analysed using wavelet and Fourier analysis. The basic function of wavelet and Fourier analysis is to transform data from its original form into a form that enables the identification of frequencies at which signals exist. An introduction to wavelet analysis can be found in Torrence and Compo (1998). For this specific application, MATLAB was used and small alterations to the code provided by Torrence and Compo (1998) were made for specific parameters and to reduce bias towards low frequencies (Liu et al., 2006).

Fourier analysis is conducted over a specified data 'window', which for this study was the whole data set collected to date. Fourier analysis provides information on how much of a signal exists at each frequency in the original data, but it does not provide information on the time at which the signal occurs. This means that if there is a periodic signal that does not occur consistently over the entire data set the results won't indicate the times at which it occurred, but will produce an averaged value.

Wavelet analysis is able to examine time-varying data as it transforms a time series into time-frequency space (Torrence and Compo 1998). This enables identification of frequencies to be made at any specific point in time. Both methods have strengths and weaknesses, and presenting the results of both techniques, provides a better understanding of the frequencies at which signals are present in the data may be obtained.

In Figure 3.11, wavelet and Fourier analysis of the RMS water height data at AMB 3 Round Top Island provides a good example of how both methods aid in understanding the frequencies at which signals are present in the original data. The processed results show the wavelet analysis results in the coloured picture, the Fourier analysis results are presented vertically on the right and the raw data on the bottom of the figure. The wavelet analysis is presented with the period of the signal on the y-axis and time on the x-axis. The colour scale used shows the strength of the signal with blue showing low strength, yellow showing moderate strength and red showing high strength. The Fourier results have the period on the vertical axis and the horizontal axis is of the total frequency strength in relative units. The original data is presented with time on the x-axis and RMS water height on the y-axis.

In the Fourier results (Figure 3.11) the obvious features are the peaks at approximately 3 hour, 12 hour, 24 hour and between 7 to 30 days. These results are useful in showing clear frequencies at which signals are present throughout the entire data set and the relative amplitude of each signal.

Unfortunately they do not provide the detail on when signals were prominent in time. As a result, this can lead to important signals that were present for a short period of time being overlooked due to the averaging function of Fourier analysis. For this reason, the Fourier analysis is best used only for the identification of recurring frequency signals.

The wavelet analysis is not quite as easy to interpret as the Fourier results but does have the advantage of presenting the results in the frequency-time domain. This allows the time varying data to be analysed at any point throughout the data set. For example, Figure 3.11 shows the approximate periods of 12 and 24 hours to have high strength signals at disjointed intervals along the time axis. These time periods are associated with tidal signals, which suggests that there is a relationship between tides and RMS water height, but only at certain times in the data set. This information aids in understanding the patterns that exist in the parameters of the natural environment and encourage confidence that natural events can be distinguished from those resulting from human influence.

Applying wavelet and Fourier analysis to physical marine parameters during ambient, active and post dredging campaigns is a method that enables long term changes to be identified. By determining the natural periodic signals in parameters such as turbidity, light, deposition, temperature, water height and RMS water height from an ambient study, we can analyse data collected during and after the project for changes from the ambient monitoring period. For example, using wavelet and Fourier analysis on turbidity data may identify the introduction of a new periodic signal or an increased signal at the 12 and 24 hour tidal period during the dredging campaign that, following the end of the dredging campaign, returns to the same signal observed in the ambient monitoring period. This longer term analysis is a powerful means to demonstrate whether long term impacts are observed in the environment rather than predominantly focusing on short term changes.

3.2.1 RMS water height

RMS water height can vary between sites as a result of water depth and a sites exposure. AMB 12 had the lowest median RMS water height (0.008) and lowest variance (10^{th} percentile = 0.003, 90^{th} percentile = 0.032). It is positioned in the lee of Keswick and St Bees Islands which shelter it from the prevailing wind and waves. The more exposed sites (along the coastline) had a higher median RMS water height value and greater variance. For example, AMB 5 had a median RMS water height of 0.037 and the 10^{th} percentile was equal to 0.014 while the 90^{th} percentile was equal to 0.110.

Running wavelet and Fourier analysis on the RMS water height data highlights recurring periods over which variations in RMS water height are identified across the year. Figure 3.11 shows recurring high RMS water height values at approximately 12 and 24 hours, and 7, 14 and 30 day periods. Synoptic weather systems that cross the coastline at periods of approximately 14 and 30 days are likely the largest driving parameter accounting for peaks in RMS water height. Changes in water depth due to the tide are also likely to account for the 12 and 24 hour period signal (Figure 3.11) in RMS water height.

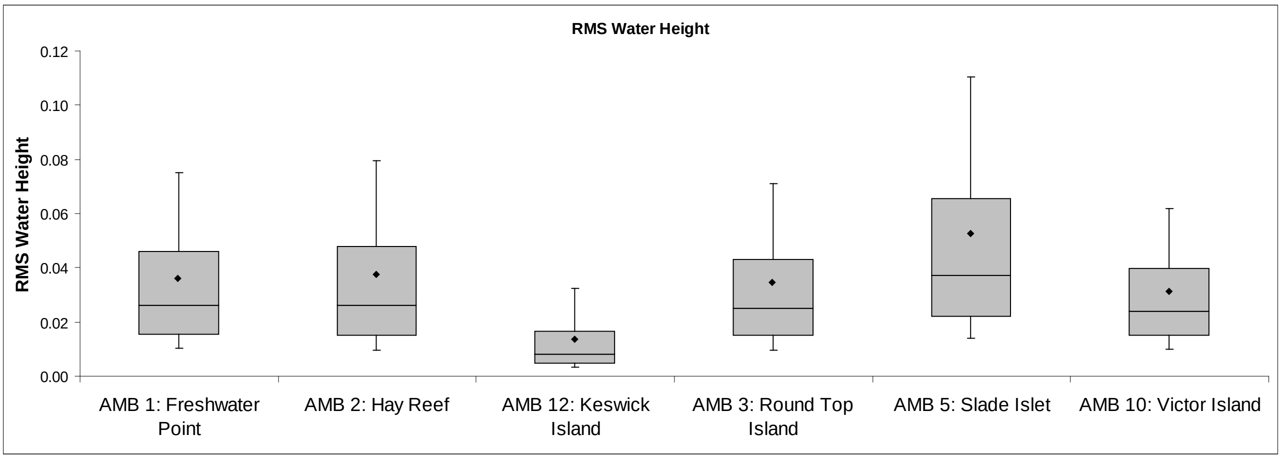


Figure 3.10 Box plot of RMS water depth at 6 sites for the year deployment commencing in July 2014 through to July 2015

Table 3.7 RMS water depth statistics at sites for the monitoring period between July 2014 and July 2015

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
Mean	0.036	0.037	0.014	0.034	0.053	0.031
median	0.026	0.026	0.008	0.025	0.037	0.024
min	0.000	0.000	0.000	0.000	0.000	0.000
lower quartile	0.016	0.015	0.005	0.015	0.022	0.015
upper quartile	0.046	0.048	0.017	0.043	0.066	0.040
max	0.332	0.568	0.197	0.383	0.754	0.444
90th percentile	0.075	0.079	0.032	0.071	0.110	0.062
10th percentile	0.010	0.010	0.003	0.010	0.014	0.010
n	55207	42153	55452	55422	55591	55470
St. Dev	0.031	0.034	0.015	0.030	0.048	0.025
St. Error	0.000	0.000	0.000	0.000	0.000	0.000

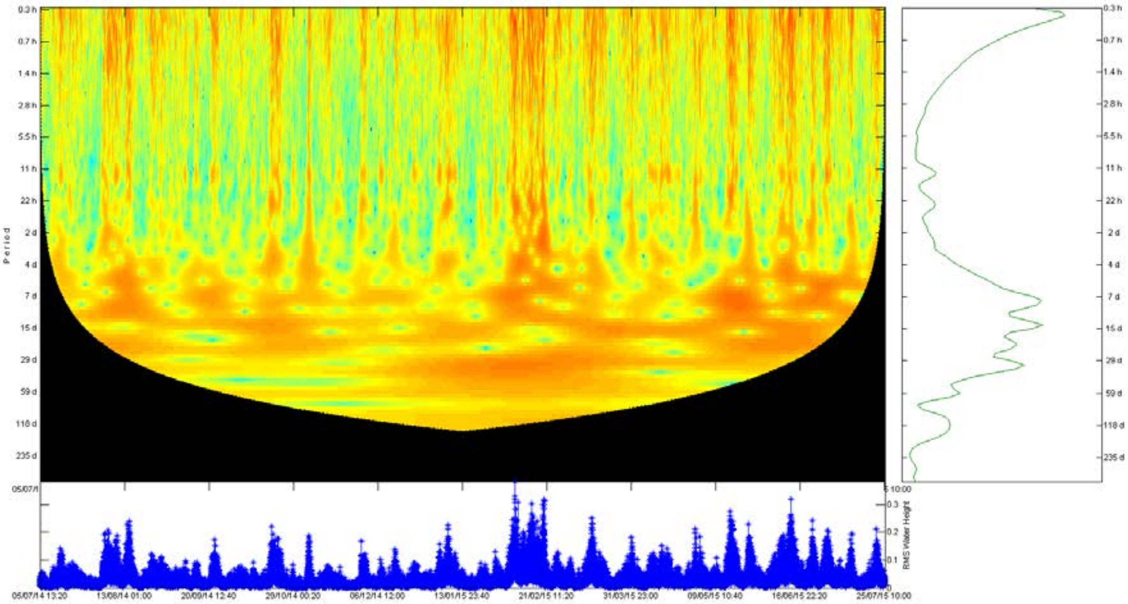


Figure 3.11 Wavelet and Fourier analysis of RMS data at AMB 3, Round Top Island. The main coloured figure shows the wavelet analysis results. Blue indicates a weak signal, yellow a moderate signal and red a strong signal of specific periods (y-axis) at specific points in time (x-axis). The Fourier analysis presented vertically on the right of the figure shows peaks at periods where a periodic signal. The raw data is shown at the bottom of the figure in units of RMS water height (y-axis) and time (x-axis)

3.2.2 NTUe/SSC data

The NTUe/SSC time series data at each site follows a typical pattern of low background values with recurring peak events. This is a typical pattern emerging in similar data collected by the James Cook University Marine Geophysics group (see Ridd et al., 2001). The most prominent peaks in NTUe/SSC, detected at all sites, occurred in February 2015 during the period in which Tropical Cyclone Marcia crossed the coastline several hundred kilometres to the south of Sarina. SSC during February 2015 approached 400 mg/L at all sites except for AMB 12. This peak was 30 times the mean at the site with the highest mean (13 mg/L at AMB 10, Victor Inlet) and approximately 45 times higher than the mean at the reference site (9 mg/L at AMB1, Freshwater Point).

The yearly averaged median SSC values ranged from a minimum of 1.15 mg/L at AMB 12, to the highest median of 5.41 mg/L at AMB 10 (Table 3.7). These values indicate low suspended sediment for most of the year. Investigating the site specific distribution of SSC values show that the sites closer to shore (AMB 1, 2, 5 and 10) had a larger variance of SSC (Figure 3.12) with the 75th and 90th percentile numbers at these sites notably higher than those at AMB 3 (upper quartile = 3.25mg/L, 90th percentile = 9.88 mg/L) and AMB 12 (upper quartile = 1.78 mg/L, 90th percentile = 2.99 mg/L). The results are visually represented as box plots for each site in Figure 3.12. These summary statistics are important in defining possible water quality conditions during low rainfall years, however, these data statistics are likely to be higher during more average rainfall year conditions.

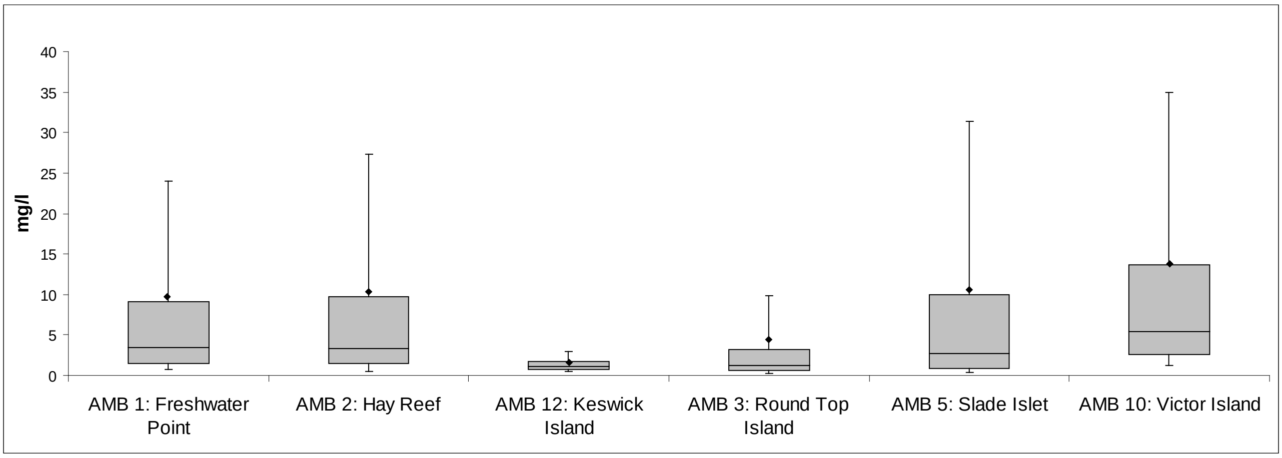


Figure 3.12 Box plot of SSC sites for the period July 2014 to July 2015. Compliance line for coastal waters (2mg/L; GBRMPA, 2010)

Table 3.8 Summary statistics for SSC at sites for the period July 2014 to July 2015

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
Mean	9.77	10.39	1.61	4.39	10.59	13.83
median	3.40	3.29	1.15	1.25	2.72	5.41
min	0.00	0.00	0.00	0.00	0.00	0.00
lower quartile	1.48	1.44	0.73	0.61	0.90	2.64
upper quartile	9.16	9.67	1.78	3.25	10.01	13.72
max	446.26	505.31	44.64	478.73	410.74	609.37
90^{th} percentile	23.95	27.32	2.99	9.88	31.43	34.98
10^{th} percentile	0.75	0.52	0.46	0.30	0.39	1.28
n	50234	38969	39997	54223	45064	51009
St. Dev	20.51	20.93	1.93	12.66	20.15	25.60
St. Error	0.09	0.11	0.01	0.05	0.09	0.11

Site AMB 12, Keswick Island, showed the lowest median NTUe/SSC (1.15 mg/L) and lowest range of NTUe/SSC values (10^{th} percentile = 0.46 mg/L, 90^{th} percentile = 2.99 mg/L). This is likely influenced by the site being sheltered from the trade south east weather systems (see Figure 3.10 RMS water height), which results in less re-suspension of sediments by wave energy. A linear regression analysis of the 90^{th} percentile SSC with respect to the 90^{th} percentile RMS water depth at each site gives R^2 = 0.42. This suggests that the size of peak wave events are a significant driver for peak SSC events during this reporting period (Figure 3.13). This relationship may change as more data is collected during the 2015/2016 period, and particularly if rainfall that generates catchment flow is experienced.

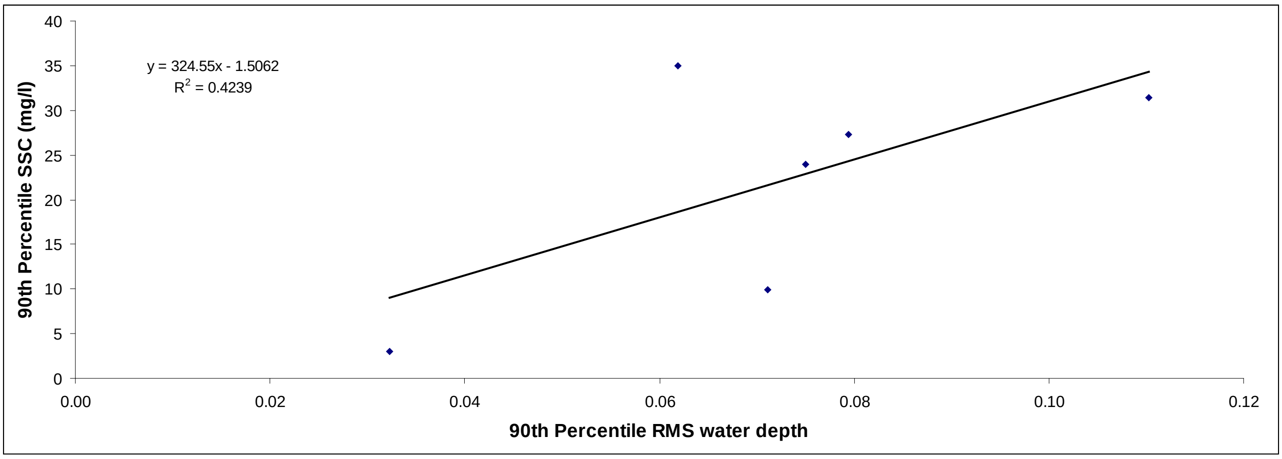


Figure 3.13 Regression plot of the 90th percentile RMS water height and the 90th percentile SSC at each site

Similarly, the data presented in time series format shows 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. This pattern again supports the emerging conclusion that wave stress on the sea floor resulting from weather events is one of the primary drivers of measured NTUe/SSC in the data set. Studying specific events, such as Cyclone Marcia passing across the coastline in February 2015 (shown below Figure 3.14), provides a good example of how closely the patterns in NTUe/SSC match those in RMS water depth (Figure 3.14). This peak in NTUe/SSC has been examined in more detail in the River Plume section.

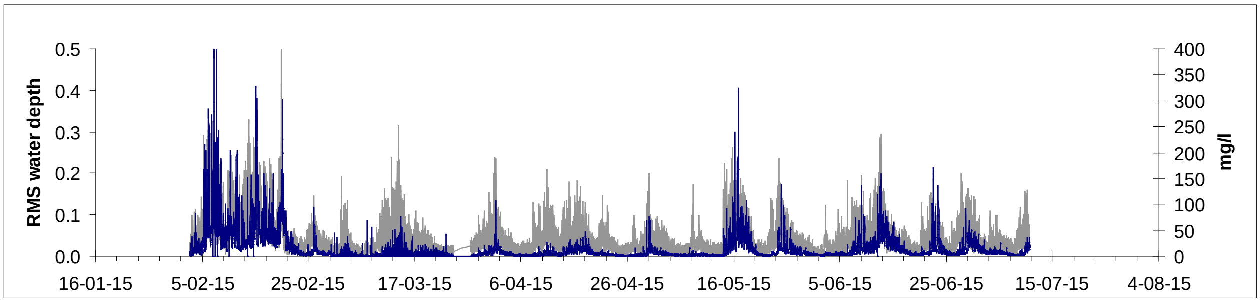


Figure 3.14 Spikes in SSC (blue) and RMS water height (grey) at AMB 2 (Hay Reef)

Wavelet and Fourier analysis highlights periodic high values of NTUe/SSC at each of the sites occurring at periods of approximately 6 and 12 hours and every 7 and 29 days. The wavelet and Fourier analysis of the RMS water depth at each site shows peaks in RMS water depth occurring at periods of approximately 12 and 24 hours and every 7 and 30 days. The similarities in the periodic patterns observed in the NTUe/SSC and RMS water depth wavelet and Fourier analysis further suggests that wave energy may be a key driver of NTUe/SSC in these environments.

As previously discussed, the periodic peaks in RMS water depth are likely the result of synoptic weather systems, semi diurnal, diurnal and longer period tidal constituents. Tide may directly influence NTUe/SSC if tidal current caused the re-suspension of sediment through shear stress on the sea floor. Tide may indirectly influence NTUe/SSC by changing a sites exposure to prevailing weather which in turn influences re-suspension by wave stress on the sea floor. Also bottom stress will be affected by tidal depth variations resulting in a change in the amount of sediment being resuspended.

The wavelet and Fourier analysis of the NTUe/SSC data from site AMB 3 at Round Top Island (Figure 3.15) provides an example of how we are able to identify recurring patterns in the data and use this to describe the environment. In the example shown, the blue line and box highlight peaks at the approximate period of 12 hours. This suggests that the combined influence of RMS water depth and semi-diurnal and diurnal tidal components influence NTUe/SSC at this site. The red lines and box highlight recurring peaks in NTUe/SSC at periods between approximately 7 and 30 days. These peaks are likely the result of longer period tidal constituents and periodic synoptic weather systems. Comparing the Fourier analysis of both parameters shows similarities where wave stress is the predominant factor driving NTUe/SSC and differences where other factors such as advection and current, influence NTUe/SSC.

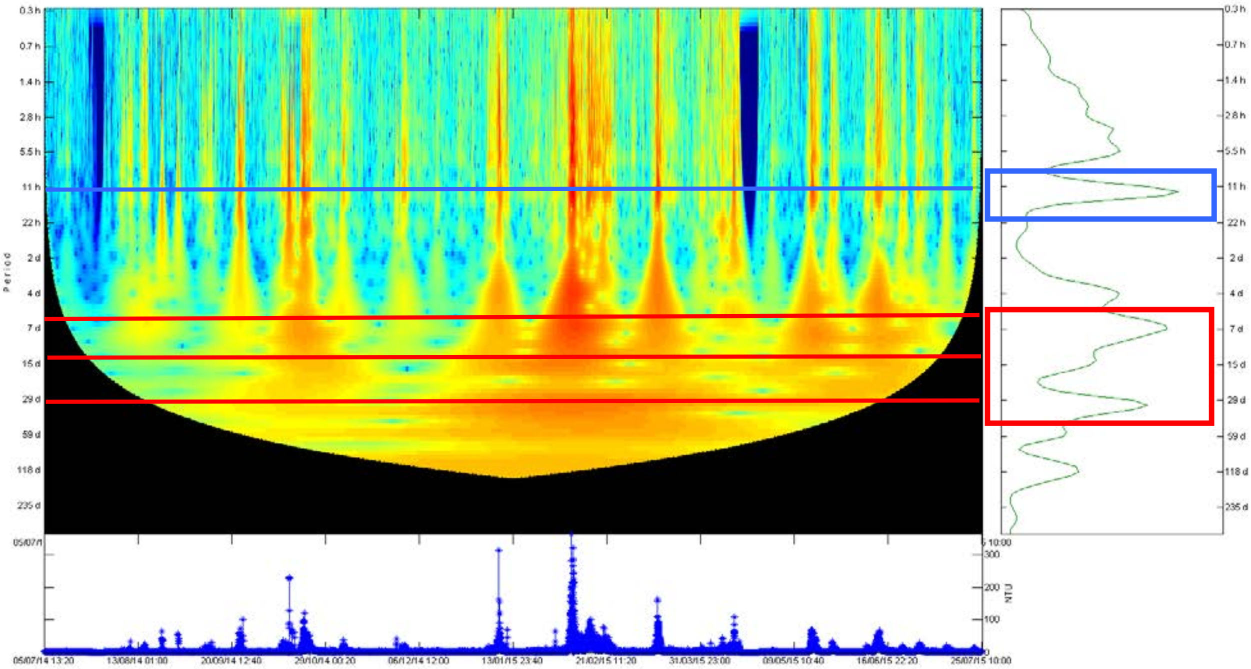


Figure 3.15 Round Top Island wavelet and Fourier analysis of NTUe

By 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 (Figure 3.16). The 2 mg/l compliance line in Figures 3.12 and 3.16 shows that values for all sites regularly exceed the water quality guideline for SSC in coastal waters and suggests that increases in RMS water height alone may lead to these SSC guidelines being exceeded. With increasing RMS water depth, the variation also increases which is likely a function of a more dynamic environment and more wave energy. While the example shown is for AMB 3, the pattern is true for all sites in the study. A polynomial fit of the 75th percentile and 90th percentile values at defined RMS water depth intervals fits the data quite accurately and further describes the general trend of increasing NTUe/SSC with increasing RMS water depth (Figure 3.17).

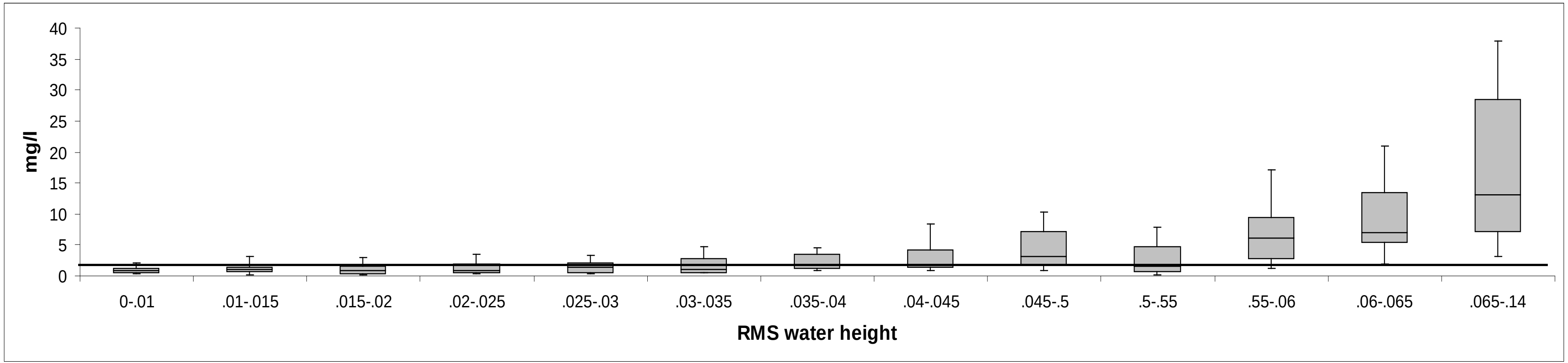


Figure 3.16 Box plot distribution of SSC at RMS water depth intervals using the data from AMB 3. Compliance line included for coastal waters (2mg/L; GBRMPA, 2010)

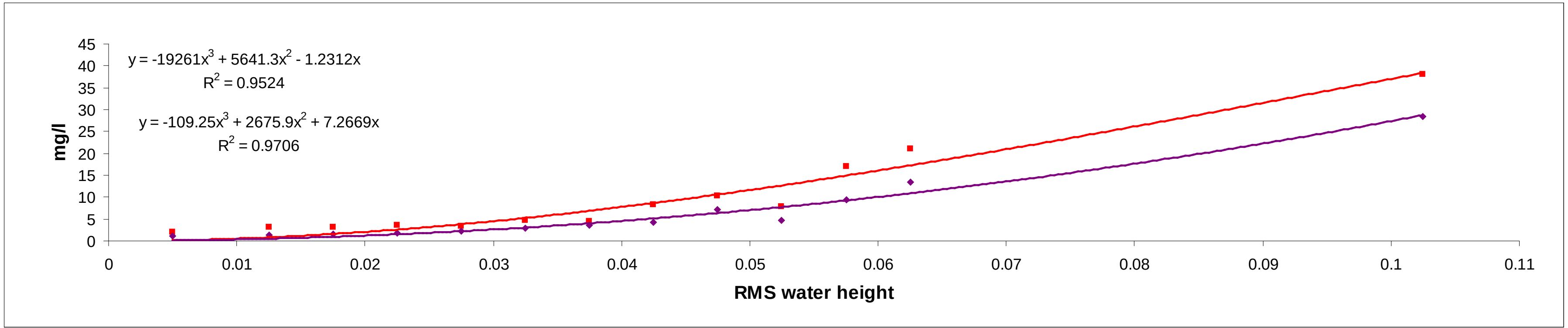


Figure 3.17 SSC (AMB 3 – Round Top Island) 75th (purple) and 90th (red) percentiles from defined increments of RMS water depth and polynomial trend lines used to fit the data. The top equation defines the 90th percentile trend line and the bottom equation the 75th percentile trend line

3.2.3 Deposition

The statistical summary of the daily average deposition rates for each site are presented in Figure 3.18 as box plots and summarised in Table 2.9. The data indicates that AMB 12, Keswick Island, had the greatest deposition with a median daily average deposition rate of 5.77 $mg/cm^2/day$. The median daily average deposition rate ranged from 1.34 – 3.36 $mg/cm^2/day$ at the 5 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.

Comparing the deposition statistics to the RMS water depth and NTUe/SSC statistics shows that while AMB 12 has the highest deposition rate, it also has the lowest NTUe/SSC and RMS water depth values. One possible explanation for this could be that low wave energy (littoral drift) enables sediment transported to the site to be deposited.

In the data collected during the first 12mths, it was interesting that the reference site (AMB2, Freshwater Point) had a mean deposition rate similar to sites close to the port facilities, and near to the entrance of Pioneer River. AMB10, located on the leeward side of Victor Islet, had the second highest mean deposition rate for the region.

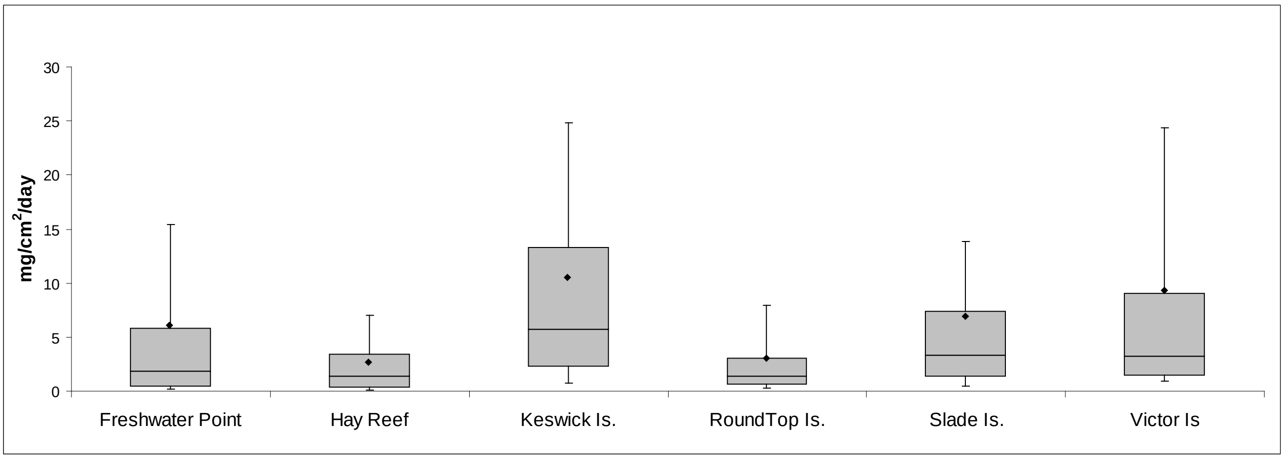


Figure 3.18 Box plot of daily deposition rate at sites for the year deployment commencing in July 2014 through to July 2015

Table 2.9 Daily average deposition rate statistics at 6 sites for the year deployment commencing in July 2014 through to July 2015

Deposition Rate Statistics						
Site	Freshwater Point	Hay Reef	Keswick Is.	RoundTop Is.	Slade Is.	Victor Is
Mean	6.12	2.68	10.56	3.07	6.91	9.34
median	1.82	1.34	5.77	1.37	3.36	3.24
min	0.01	0.01	0.04	0.05	0.08	0.22
lower quartile	0.42	0.35	2.27	0.62	1.39	1.48
upper quartile	5.81	3.42	13.31	3.03	7.36	9.01
max	97.84	26.56	100.95	24.71	154.99	133.22
90th percentile	15.39	7.04	24.82	7.94	13.82	24.38
10th percentile	0.15	0.08	0.71	0.30	0.49	0.89
n	324	294	304	309	336	278
St. Dev	12.09	3.72	14.52	4.52	13.21	17.05
St. Error	0.67	0.22	0.83	0.26	0.72	1.02

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 close to 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. An example of this is presented in Figure 3.19 for AMB 12. The RMS water depth peak starting on the 5 February 2015 and ending on the 21 February 2015 (aligning approximately with Tropical Cyclone Marcia; Figure 1.5) is followed by a very large spike in the daily deposition rate.

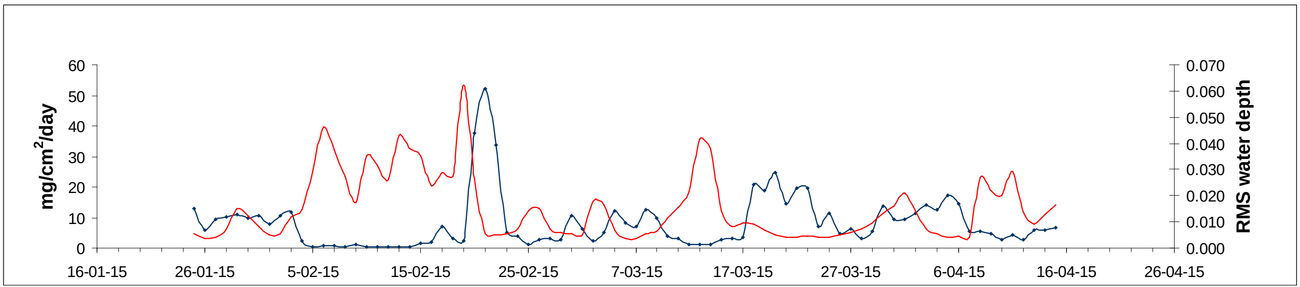


Figure 3.19 AMB 12, Keswick Island, daily deposition rate (blue) and daily average RMS water depth (red)

3.2.4 Water temperature

Water temperature data matched closely among all sites. Seasonal changes in water temperature were apparent, peaking between December and March at approximately 30-31 ^{o}C; a factor that was also observed in the field *in-situ* water temperature surveys. The lowest temperatures were observed in July where temperature dropped to between 18–22.5 ^{o}C. Decreases in temperature over short time periods match with increases in RMS water depth. This is most evident in February 2015 where a drop in temperature coincided with Cyclone Marcia (see Appendix). While water temperature is generally not a compliance condition of approval for operations, the temperature data here has importance in future interpretation of ecological processes in the region, and the GBR more broadly (e.g., Johanson et al., 2015).

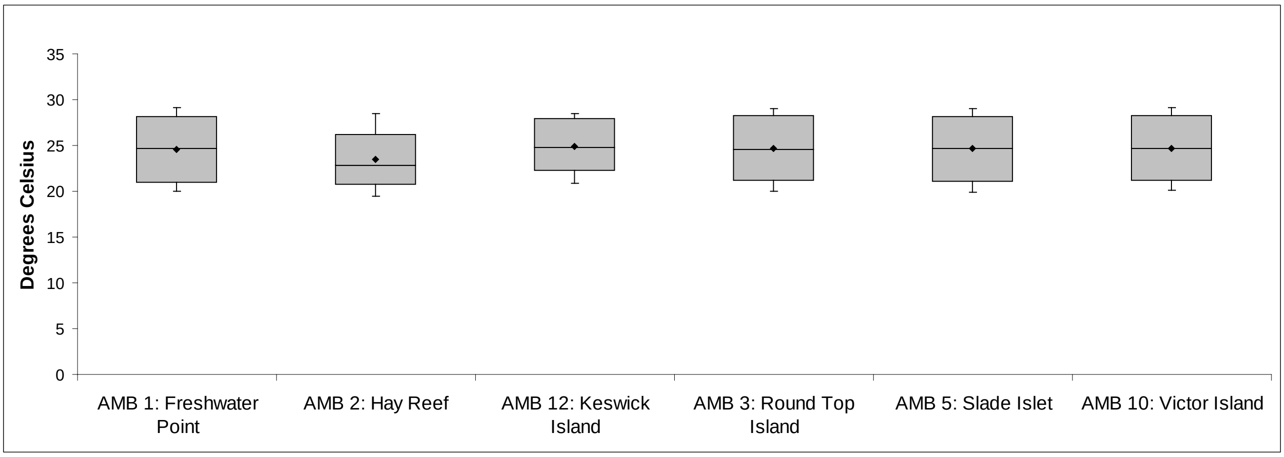


Figure 3.20 Box plot of temperature at sites for the deployment between July 2014 and July 2015

Table 3.10 Daily water temperature statistics at sites for the deployment between July 2014 and July 2015

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
Mean	24.57	23.45	24.86	24.66	24.63	24.70
median	24.63	22.78	24.75	24.57	24.67	24.71
min	17.64	18.26	19.71	18.46	18.35	18.10
lower quartile	20.97	20.76	22.27	21.21	21.10	21.24
upper quartile	28.16	26.19	27.91	28.22	28.18	28.29
max	30.86	30.52	29.92	30.10	30.12	30.60
90^{th} percentile	29.08	28.51	28.49	29.04	29.05	29.14
10^{th} percentile	19.98	19.49	20.89	20.05	19.91	20.06
n	55203	42148	55438	55396	55589	55464
St. Dev	3.64	3.29	2.90	3.54	3.59	3.60
St. Error	0.02	0.02	0.01	0.02	0.02	0.02

3.2.5 Multiparameter predictive NTUe/SSC model

Natural turbidity (NTUe/SSC) is primarily driven by the re-suspension of sediment due to wave and current stress on the sea floor. The natural environment frequently has periods where high turbidity is observed. 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 anthropogenic activities (development, catchment runoff, or dredging). Excess turbidity or overburden (the difference between natural and anthropogenic activity related turbidity) is likely to result in deposition as the re-suspension processes (i.e., the model inputs) are insufficient to keep the sediment in suspension.

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

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. 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 used data from July through to January to fit the parameters and the data from February through to July 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 3.11). These R^2 values show that the models performed quite well when tested and with the continuation of *in-situ* data collection these predictive models will only increase in their predictive accuracy.

Table 3.11 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	Freshwater Point	Keswick Island	Round Top Island	Slade Islet	Victor Island
Fit period (July 2014 to Jan 2015)	0.86	0.76	0.61	0.34	0.07	0.12
Test period (Feb to July 2015)	0.52	0.77	0.57	0.75	0.64	0.62

As an example of the strength of this model, Figure 3.21 presents the predicted (blue) and the measured (red) NTUe values at AMB 2. Also shown is a breakdown of model constituents on a time series scale and the proportion of NTUe/SSC each constituent accounts for. In this example, the RMS water height accounts for the majority of NTUe/SSC predicted, with the RMS water height from the previous day accounting for the next highest proportion. The water depth, tidal current and tidal range account for a very small part of the predicted NTUe/SSC in this model.

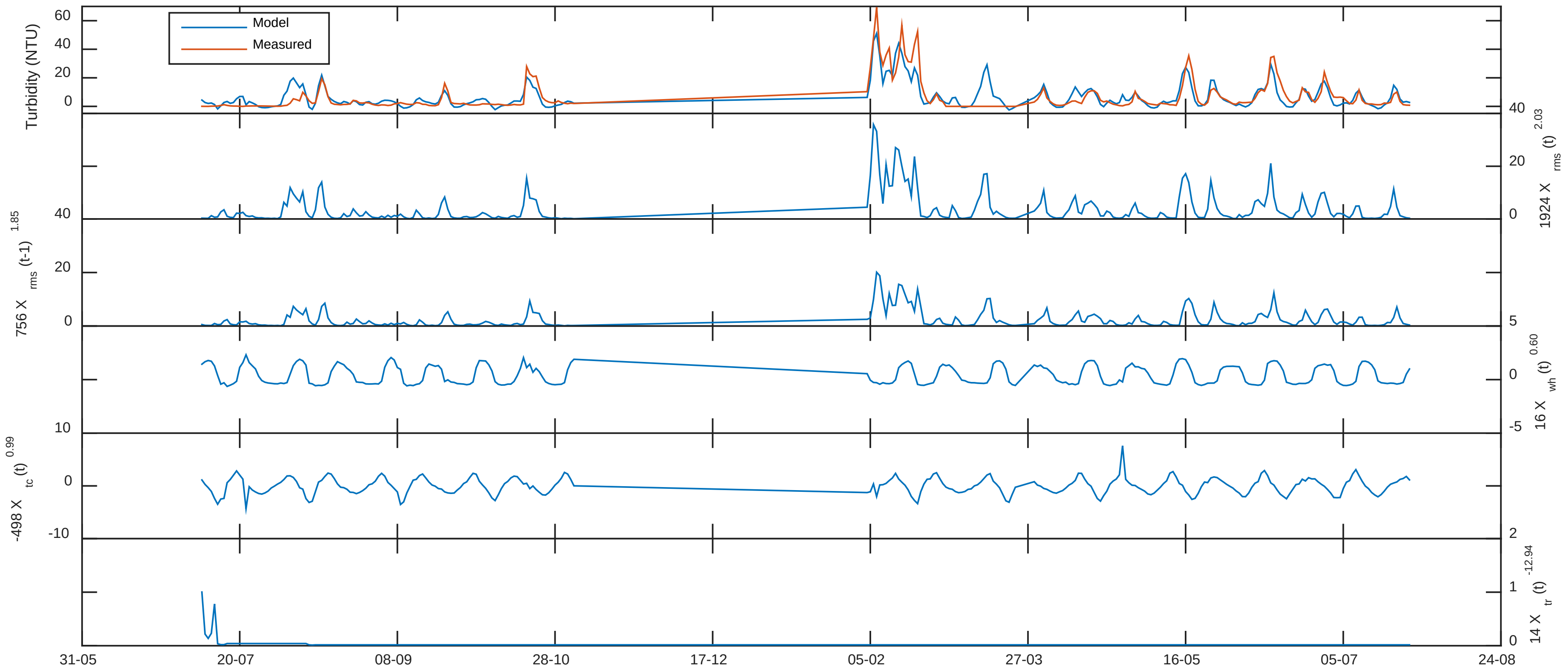


Figure 3.21 AMB 2 (Hay Reef) multiparameter predictive NTUe/SSC model. The model was generated using the first three months of data (July to November 2014) and tested on the remaining data (February to July 2015). The section shows the measured NTUe in red and the predicted NTUe in blue, the below sections show the NTUe values explained by each input constituent in the model. Missing data between November 2014 and February 2015 due to logger and mooring equipment had been completely removed from this site

3.3 Photosynthetically active radiation (PAR) logging

Benthic photosynthetically active radiation (PAR) was monitored over 11 sites between 7 July 2014 and 7 July 2015. Using statistics 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 - Hay Point Material Relocation Ground and AMB 9B – East Cardinal Marker), while higher levels were more regularly measured at shallower sites (e.g., AMB 6 - Dudgeon Point, AMB 5 - Slade Islet and AMB 10 - Victor Islet; Table 3.12).

Table 3.12 Summary statistics for total PAR (mol photons m/day) recorded at sites during the program (10 July 2014 – 24 July 2015)

	Freshwater Point AMB1	Hay Reef AMB2	Round Top Island AMB3	Flat Top Island AMB4	Slade Islet AMB5	Dudgeon Reef AMB6	Slade Point AMB7	Hay Point MRG AMB8	East Cardinal AMB9B	Victor Island AMB10	Keswick Island AMB12	Average Surface Control
Depth (LAT)	3.8	5.9	9.5	5.7	4.4	-0.5	8.3	14.4	11.5	4.3	5.2	Surface
Mean	1.19	0.33	1.57	1.34	2.09	3.34	1.11	0.70	0.66	2.02	3.11	36.30
Median	0.85	0.14	1.42	1.06	1.80	2.81	0.76	0.52	0.44	1.86	2.99	34.36
Minimum	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	4.99
Lower quartile	0.15	0.01	0.50	0.23	0.55	1.57	0.15	0.14	0.06	0.65	2.02	27.42
upper quartile	1.93	0.46	2.43	2.24	3.22	4.55	1.87	1.11	1.05	3.12	4.03	46.67
Maximun	5.48	2.92	4.85	4.97	8.84	10.66	5.30	2.75	3.19	8.10	8.11	56.69
90th percentile	2.86	0.91	3.14	3.10	4.38	6.96	2.74	1.61	1.65	4.21	5.19	53.08
10th percentile	0.01	0.00	0.05	0.02	0.03	0.72	0.00	0.01	0.00	0.09	1.32	22.09
n	255	143	379	380	380	212	381	380	246	382	382	382
St. Deviation	1.22	0.49	1.20	1.22	1.81	2.34	1.11	0.64	0.69	1.57	1.53	11.96
St. Error	0.08	0.04	0.06	0.06	0.09	0.16	0.06	0.03	0.04	0.08	0.08	0.61

Benthic PAR was highly variable within sites throughout the year with peaks and troughs occurring both regularly and intermittently over time (Figure 3.22). 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 coastal sites such as AMB 6 (Dudgeon Point), AMB 5 (Slade Islet) and AMB 10 (Victor Island) displayed much greater variation in daily PAR compared to deeper sites further off shore such as AMB 3 (Round Top Island), AMB 8 (Hay Point material relocation ground) and the AMB 9A (East cardinal marker). 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, there seems to be a general pattern of greater daily PAR levels from July 2014 through to December 2014 at the shallow and deeper coastal sites (e.g., AMB 10, Victor Island and AMB 3, Round Top Island), respectively, in contrast to the period January 2015 through to July 2015 (Figure 3.23 a and b). These two sites show similar patterns in monthly PAR throughout the year with February and July 2015 having the lowest PAR. The offshore Keswick Island site (Figure 3.23c) showed a different pattern with light peaking between November 2014 and March 2015 and lower levels around June 2015. Overall, PAR was lower in June and July 2015 than the previous July period (2014) across all sites. This is due to a large number of cloudy days represented by dramatic troughs in the surface control PAR levels which were accompanied by greater rainfall and catchment flow (Figure 1.3), and associated higher RMS and turbidity during June and July 2015 (see Figure 3.14).

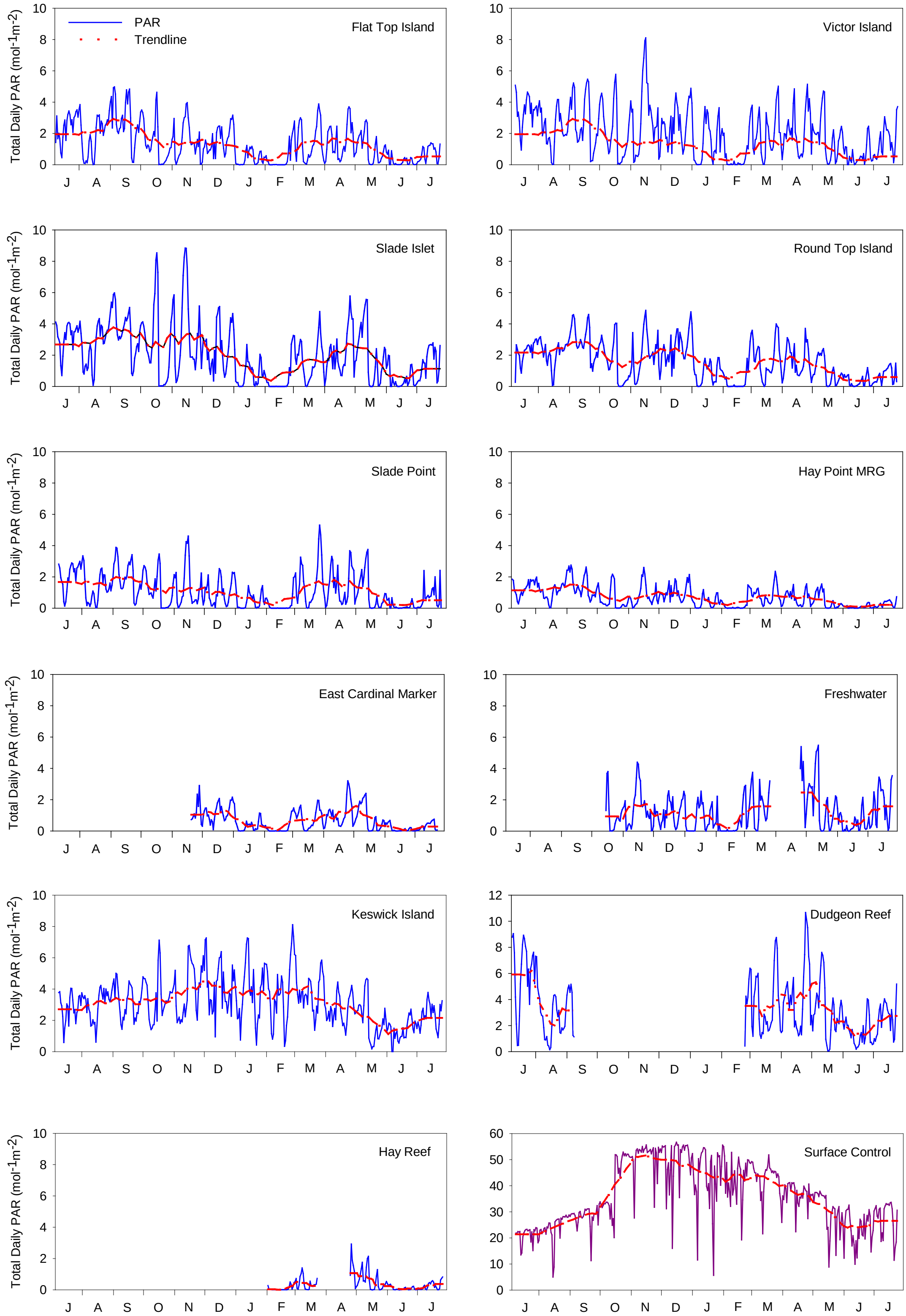


Figure 3.22 Time series of mean total daily photosynthetically active radiation (PAR) (mol photons m²/day) recorded at all sites and the surface control sites during the first year of the program (10 July 2014 and 24 July 2015)

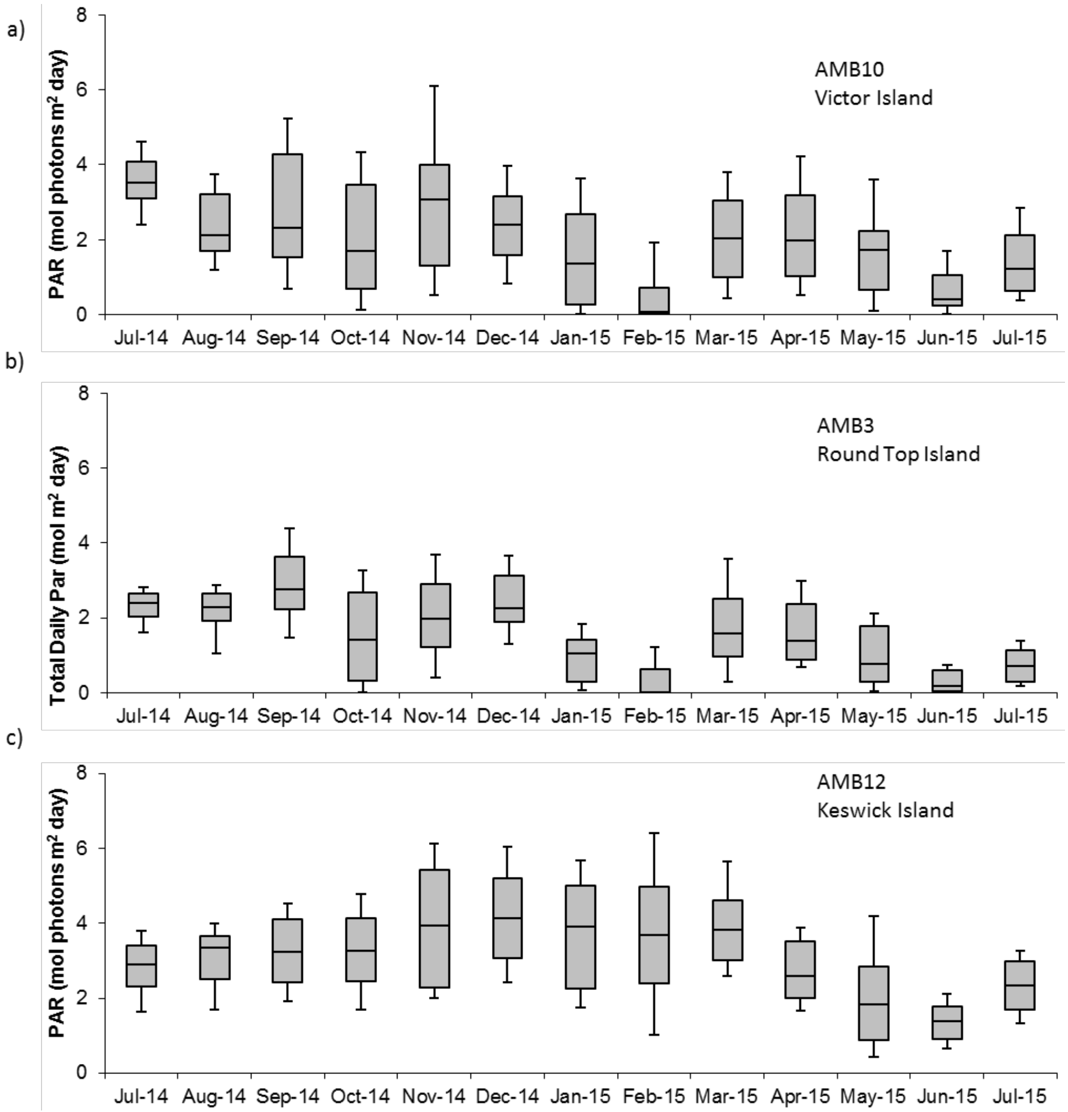


Figure 3.23 Monthly means and variation in total daily photosynthetically active radiation (PAR) (mol photons m^2/day) at a representative inshore site: a) AMB 10, Victor Island; b) representative deeper coastal site (AMB 3, Round Top Island); and c) offshore site (AMB 12, Keswick Island) during the first year of the program

3.3.1 Similarities in patterns of PAR among sites

As sites were located at various depths below the lowest astronomical tide datum (LAT), direct comparisons of PAR among sites is not statistically valid (correlation between water depth and PAR was strong; R^2 = 0.44). Therefore, the similarity in patterns of PAR over time among different sites was compared by plotting total daily PAR for each day to examine the strength of the relationship using pairwise comparisons (Figure 3.24). The strength of the linear relationship between sites was measured using an R^2 value shown on each pairwise scatterplot. There were strong relationships in patterns of benthic PAR among shallow coastal sites with similarities generally strengthening between sites that were situated in closer geographic proximity to each other (e.g., Slade Islet and the East Cardinal marker sites R^2 = 0.84). There were also strong similarities between distant coastal sites that were located in similar environments (e.g., Victor Islet and Slade Islet, R^2 = 0.77, which are both located on the northern sides of islands). Freshwater Point was the exception, with the least similarities among other coastal sites (maybe due to its location on exposed coastline, highlighting the heterogeneity of water quality conditions experienced in the region). Keswick Island also stands out as having very different patterns to all of the 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.

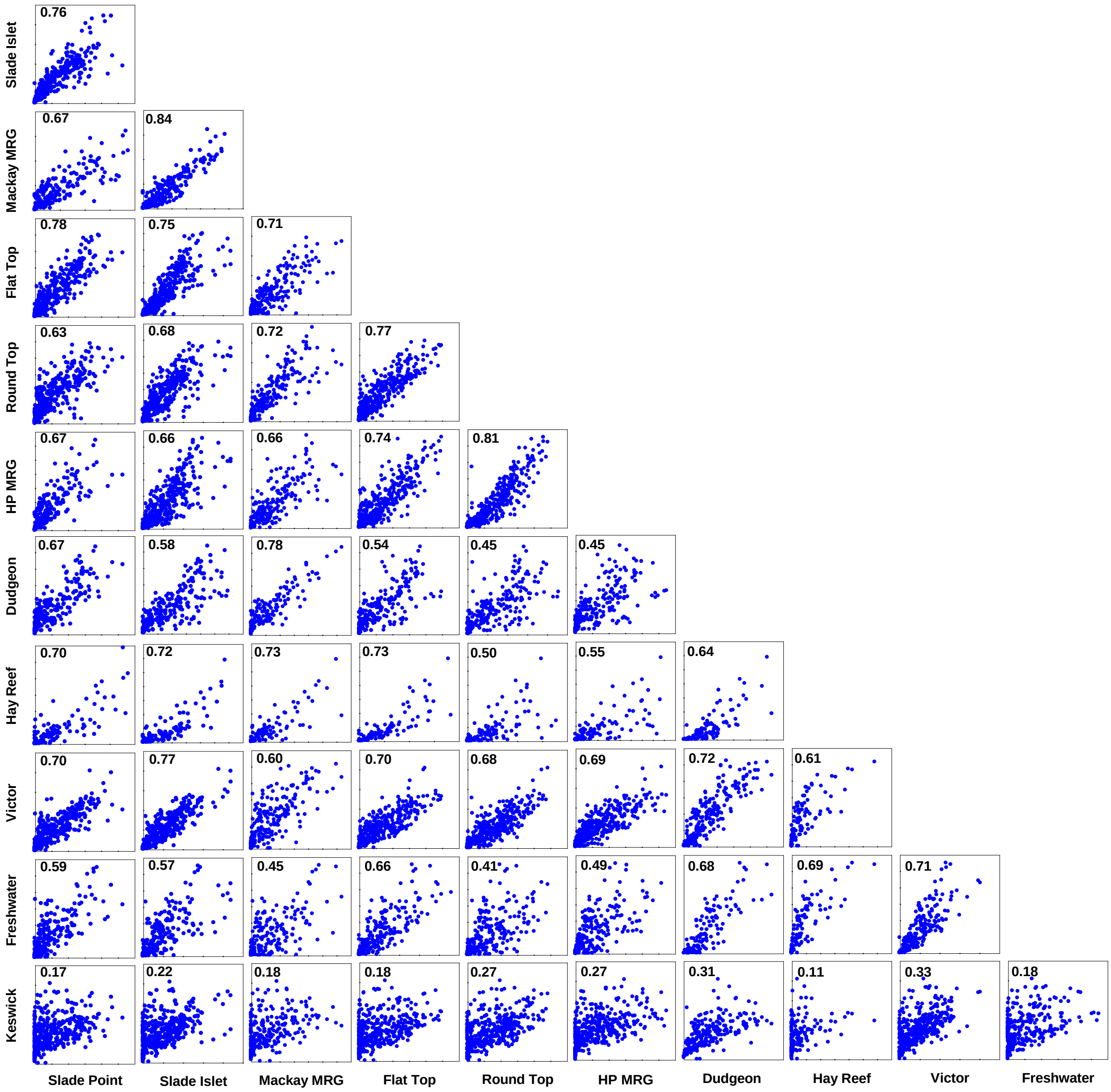
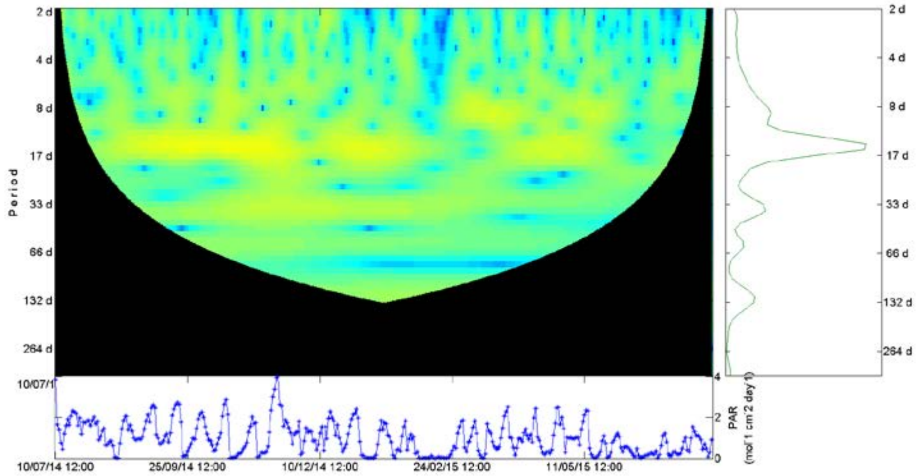


Figure 3.24 Scatterplots of pairwise comparisons among sites indicating the strength of the relationship between patterns of daily PAR (R^2 values are presented for each comparison)

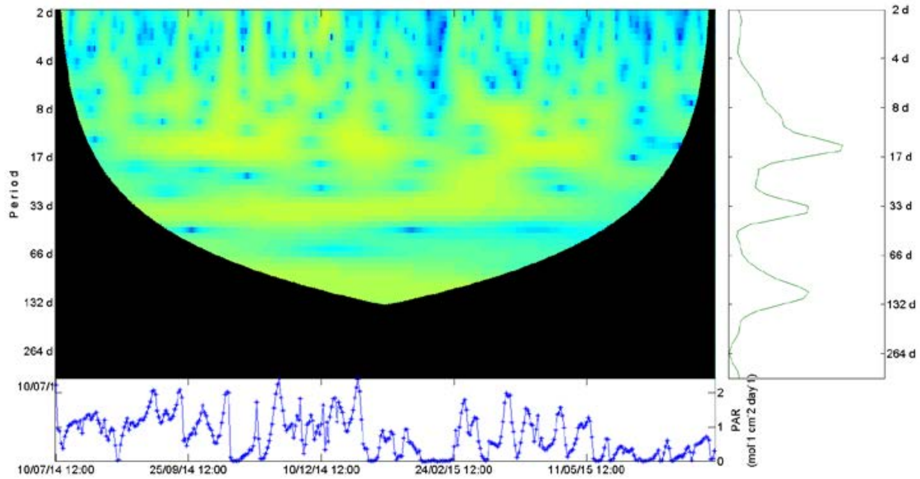
3.3.2 Periodicity of PAR data

Wavelet and Fourier analysis was conducted on total daily PAR over the course of the year at a representative inshore site (AMB 10, Victor Islet), a representative deeper coastal site (AMB3, Round Top Island), and offshore site (AMB 12, Keswick Island) to establish whether there were periodic patterns (sinusoidal) in data throughout the year (Figure 2.3.2). At the three sites, there was a distinct peak in total daily PAR occurring at approximately fortnightly intervals. These peaks are likely indicative of the influence of local tidal cycles where neap tides occur twice every lunar month. During these periods there is a large reduction in the daily tidal range and therefore tidal flows. A secondary peak occurs approximately every 33 days and this is strongest at AMB 3 Round Top Island site, and also likely to align with lunar periods.

a)



b)



c)

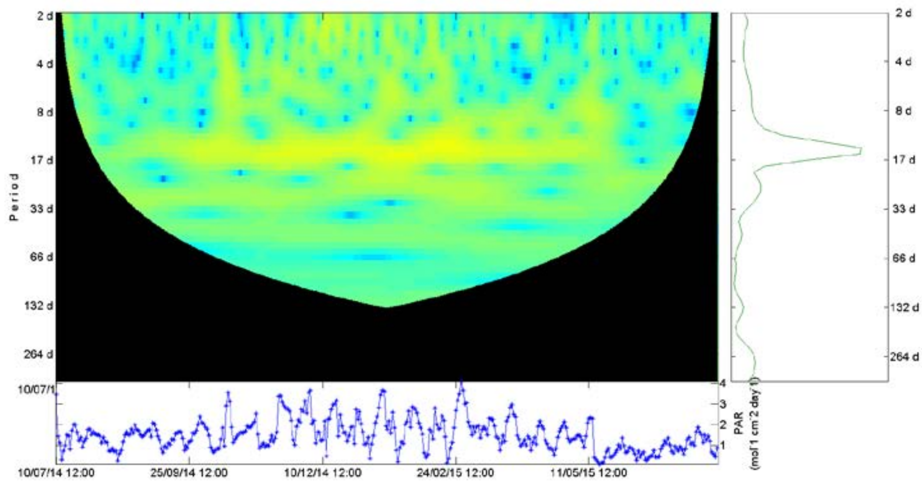


Figure 3.26 Wavelet and Fourier analysis of average daily PAR at a representative inshore site: a) AMB 10, Victor Islet); b) deeper coastal site (AMB 3, Round Top Island); and c) offshore site (AMB 12, Keswick Island) during the first year of the program

3.3.3 Environmental effects on PAR during episodic weather events

Photosynthetic active radiation in the period between 1 October 2014 and 31 March 2015 was selected to show the effects of different environmental parameters on PAR at finer detail. PAR was graphically compared against river flow (Pioneer and Waterpark rivers), RMS of water depth and wind speed, and direction. For this period of time, loss of PAR coincided with substantial environmental events, particularly periods of high RMS and wind speeds or river flow events (Figure 3.3.4). For example, in mid-October 2014 (first grey highlighted period), loss of PAR at Round Top Island and Victor Islet coincided with wind speeds that were greater than 20 km/hr, while at the same time RMS was greater than 0.05; there was no rainfall or river event at this time. In contrast, the event driving a decline in PAR around the 26 January 2015 (third grey highlighted period) coincides with the highest rainfall event experienced during this monitoring period, which contributed to catchment flows during a time of low wind speed and RMS. The effects of Tropical Cyclone Marcia in February 2015 were also evident in the dataset (fourth grey highlighted period in figure). PAR decreased for a long period of time in February 2015 (several weeks) coinciding with high RMS, wind speed and river flows.

An interesting fact in the data is that PAR measured at Keswick Island was not affected to the same extent by these events, compared to Round Top Island and Victor Islet. This is likely due to the site being protected from NE winds by Keswick and St Bees Islands, and the fact that the site is offshore and therefore probably not affected by catchment/river flow events, and the fact that the site is offshore and therefore probably not affected by catchment/river flow events to the same extent as Round Top Island and Victor Islet, which are both much closer to shore and therefore discharge from catchments (also see Figure 3.23). In addition, the deposition logging data presented previously shows that at Keswick Island, while deposition is highest, turbidity is lowest, which is therefore supported here with the high PAR results.

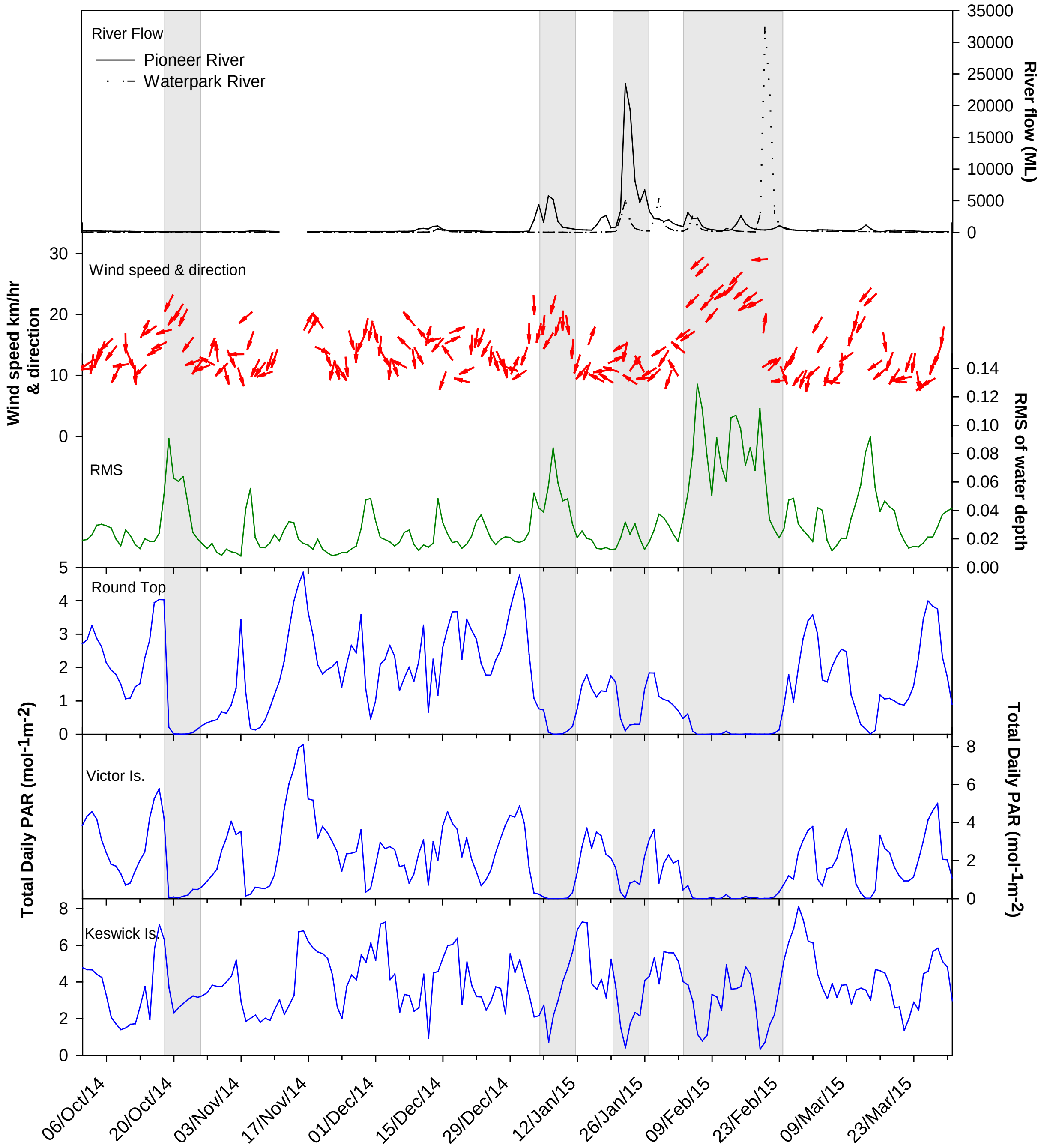


Figure 3.27 Levels of total daily PAR (mol photons m/day) and potential environmental drivers; river flow of the Pioneer and Water Park Rivers (ML/day) wind speed (km/hr) and direction and RMS of water depth as a proxy for wave energy at a representative inshore site (AMB 3, Victor Islet) a representative deeper coastal site (AMB 3, Round Top Island) and the offshore site (AMB 12, Keswick Island) during the first year of the program

3.3.5 Relationship between PAR and suspended solid concentrations

Significant relationships were found between SSC and total daily PAR at all six sites where both variables were measured using a generalized additive mixed model (GAMM, Table 3.13). Although the relationships in all cases were strong, there is a high level of unexplained variance within the relationship as indicated by the R^2 values. Round Top Island had the strongest relationship between the two variables with suspended solid concentration explaining around 70 % of the variation in total daily PAR at the site, however, at most sites between half and three quarters of the variation remained unexplained, among the factors used in the model. Graphical examples of the relationship at three sites (Victor Islet, Round Top Island and Keswick Island) are provided (Figure 3.29), showing that between 38 and 71 % of the variation in daily PAR can be explained by measures of suspended solid concentration.

Table 3.13 Summary of generalized additive mixed model (GAMM) examining the relationship between suspended solid concentration (SSC - mg L) and total daily PAR (mol photons m/day) at sites where both variables were logged. Overall fit of smooth terms of selected model including number of observations (n), degrees of freedom (*df*), *F*-statistic, *p*-values and R^2 values

Location	n	df	F	p-value	R^2
AMB 1, Freshwater Point	355	4	70.0	< 0.001	0.438
AMB 10, Victor Islet	383	4	109.2	< 0.001	0.531
AMB 2, Hay Reef	192	4	17.2	< 0.001	0.253
AMB 3, Round Top Island	376	4	228.9	< 0.001	0.709
AMB 5, Slade Islet	386	4	83.21	< 0.001	0.461
AMB 12, Keswick Island	277	4	42.78	< 0.001	0.377

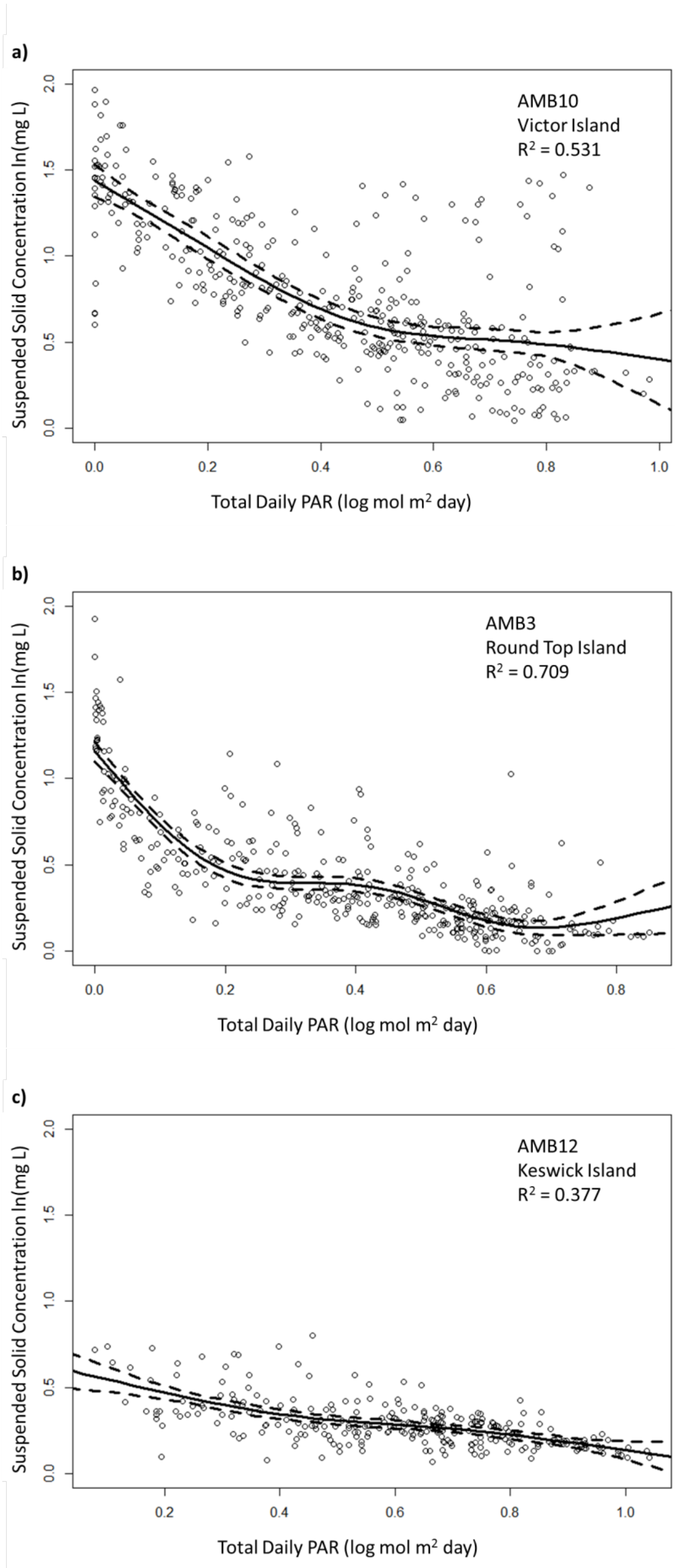


Figure 3.29 Examples of an observed relationship between *in-situ* turbidity (Suspended solid concentrations) and total daily PAR at: a) Victor Islet; b) Round Top Island; and c) Keswick Island between July 2014 and July 2015. Data were log transformed to reduce heterogeneity of variance. The solid line indicates the best fit of the GAM model smoother and the dotted lines indicate 95% confidence intervals

3.4 River plumes

3.4.1. Site specific outputs

Freshwater Point

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 75% 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. Both together explained about 64% of SSC variability at Freshwater Point (Figure 3.32). NESW wind component, tide amplitude and the Pioneer River discharge explain combined less than 11% of SSC variability. Results of the partial effect plots (Figure 3.33) followed expected trends for SSC in relation to each environmental parameter selected in the stepwise analysis. Clearer patterns for SSC were observed against most of the variables in the model, except for the Pioneer River discharge, which exhibited wider confidence intervals. Overall, an increase in SSC was observed with increases in all the variables, including winds from the east. The stronger the winds coming from east (i.e., NE, positive values on wind NESW axis or SE, negative values on wind_NWSE axis) the higher the SSC readings were.

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

```
Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)       4.218956   0.571669   7.380 2.53e-12 ***
log(RMS)          1.402139   0.121610  11.530  < 2e-16 ***
log(Pioneer + 1)  0.237906   0.049442   4.812 2.63e-06 ***
wind_NESW         0.064326   0.008071   7.970 6.25e-14 ***
wind_NWSE        -0.031015   0.009839  -3.152  0.00183 **
amplitude         0.162641   0.038401   4.235 3.24e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.6567 on 242 degrees of freedom
Multiple R-squared:  0.751,  Adjusted R-squared:  0.7459
F-statistic:   146 on 5 and 242 DF,  p-value: < 2.2e-16
```

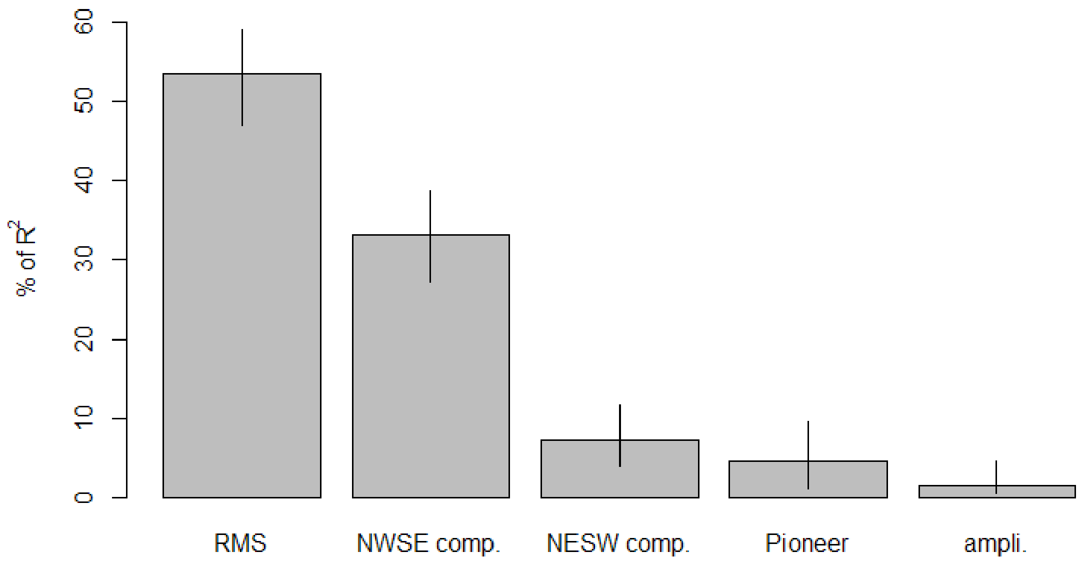


Figure 3.32 Freshwater Point bootstrapping relative importance analysis followed by a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r-squared values are normalized to sum 100%. Overall $R^2 = 0.75$

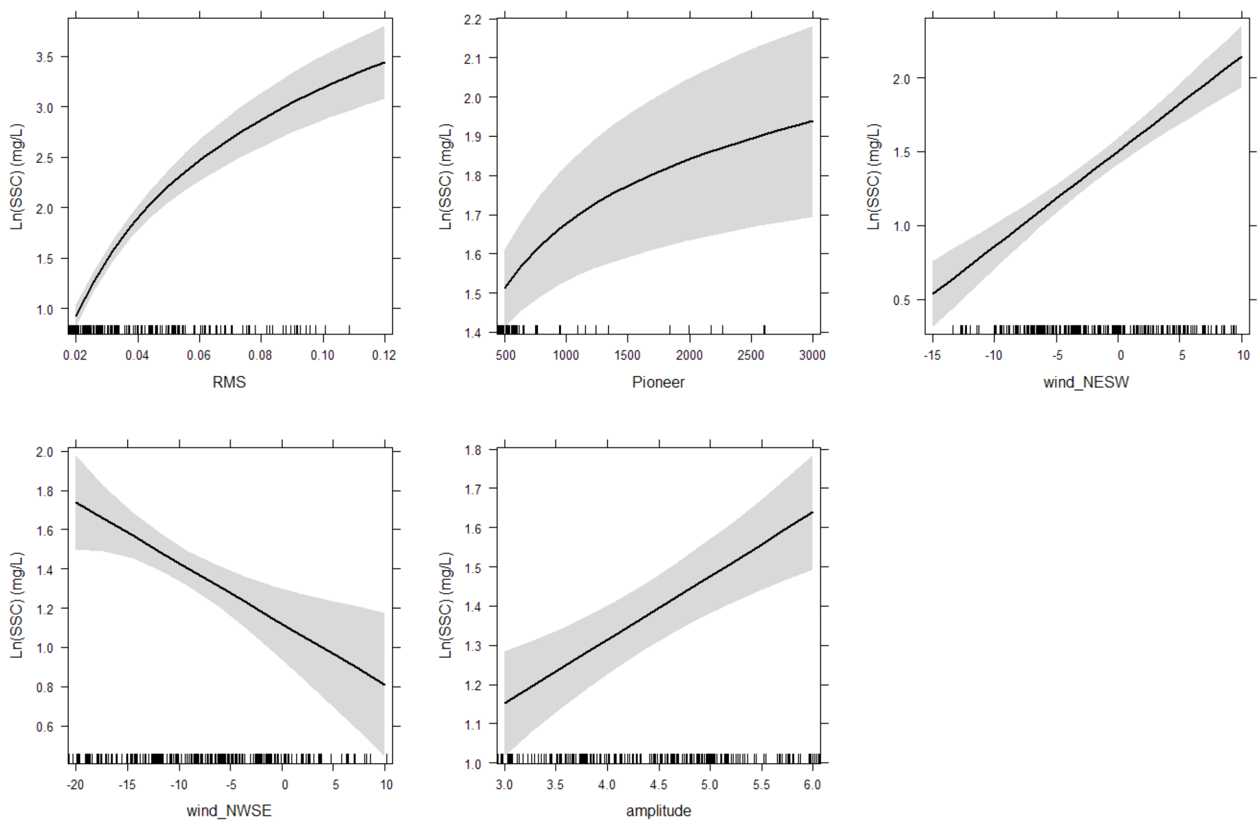


Figure 3.33 Partial Effect Plots for Freshwater Point parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

Hay Point Reef

A stepwise regression analysis, was run against the Hay Point Reef data to identify the appropriate variable selection, excluding autocorrelation and outliers, for the multiple regression analysis. RMS of water depth, tide amplitude and wind NESW component explained 53% of 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 49% of SSC variability at Hay Point Reef (Figure 3.34). Wind NESW component and tide amplitude together explained 4% of the SSC variability. Results of the partial effect plots (Figure 3.35) followed expected trends for SSC in relation to each environmental parameter selected in the stepwise analysis. Clearer patterns for SSC were observed against with RMS and wind. Tide amplitude exhibits wider confidence intervals compared to the other two variables. Overall, an increase in SSC was observed with increases in all the environmental variables.

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

```
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  6.87469    0.45175  15.218  < 2e-16 ***
log(RMS)     1.64283    0.10362  15.854  < 2e-16 ***
wind_NESW    0.07033    0.01185   5.937 1.11e-08 ***
amplitude    0.10777    0.06071   1.775   0.0772 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.001 on 222 degrees of freedom
Multiple R-squared:  0.535,  Adjusted R-squared:  0.5288
F-statistic: 85.16 on 3 and 222 DF,  p-value: < 2.2e-16
```

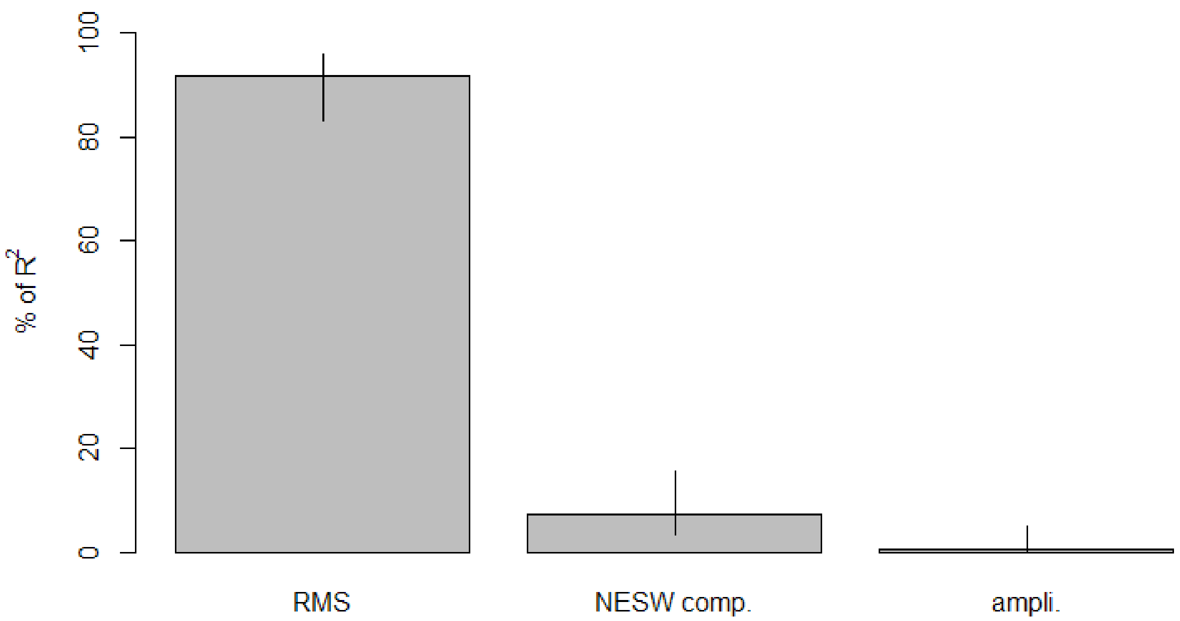


Figure 3.34 Hay Point Reef bootstrapping relative importance analysis followed by a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r-squared values are normalized to sum 100%. Overall R^2 = 0.53

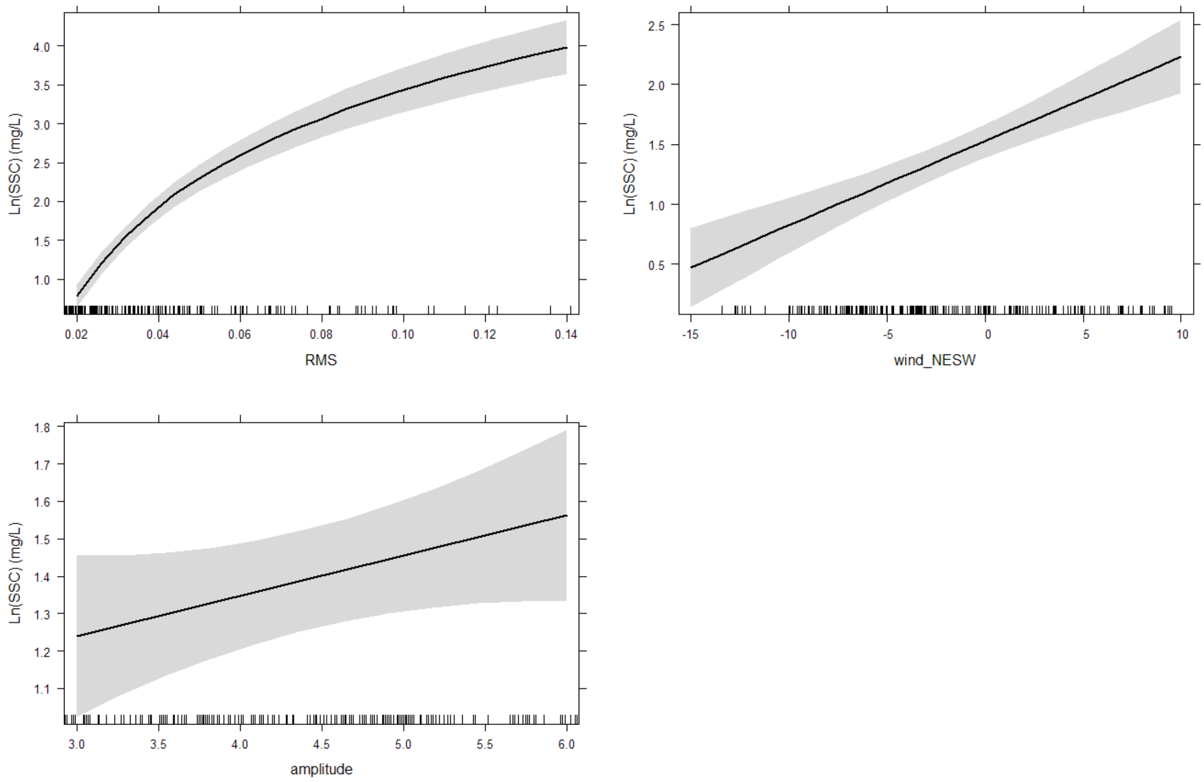


Figure 3.35 Partial Effect Plots for Hay Point Reef parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

Keswick Island

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, tide amplitude, NESW wind component and the Pioneer and Sandy River discharges explained 50% of SSC variability. The relative importance analysis suggested that RMS of water depth and tide amplitude explain together 39% of the SSC variability at Keswick Is site. Minor importance was attributed the Pioneer and Sandy River discharges that explained together < 3% of the SSC variability (Figure 3.36). Results of the partial effect plots (Figure 3.37) followed expected trends for SSC in relation to each environmental parameter selected in the stepwise analysis. Clearer patterns for SSC were observed against RMS and tide amplitude, which exhibit narrower confidence intervals compared to those presented in the other plots. Overall, an increase in SSC was observed with increases in RMS of water depth and tide amplitude. The wide confidence intervals for the Pioneer and Sandy River discharges made the relationship uncertain. The partial plot suggests that the stronger the SW winds, the higher the SSC, which is probably a consequence of the special location of the Keswick Is site protected from NE winds by the Keswick Island and the St Bees Island. Moreover, tide amplitude must have a strong influence on SSC variability due to the site location, close to the channel between Keswick Is and St Bees Is, potentially amplifying the tidal currents.

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

```
Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)       0.443226   0.329320   1.346  0.17999
log(RMS)          0.414853   0.053557   7.746 6.05e-13 ***
log(Pioneer + 1)  0.124037   0.040056   3.097  0.00226 **
log(Sandy + 1)   -0.078243   0.035366  -2.212  0.02816 *
wind_NESW        -0.012240   0.005875  -2.083  0.03860 *
amplitude         0.268174   0.030973   8.658 2.32e-15 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4724 on 185 degrees of freedom
Multiple R-squared:  0.508,  Adjusted R-squared:  0.4947
F-statistic:  38.2 on 5 and 185 DF,  p-value: < 2.2e-16
```

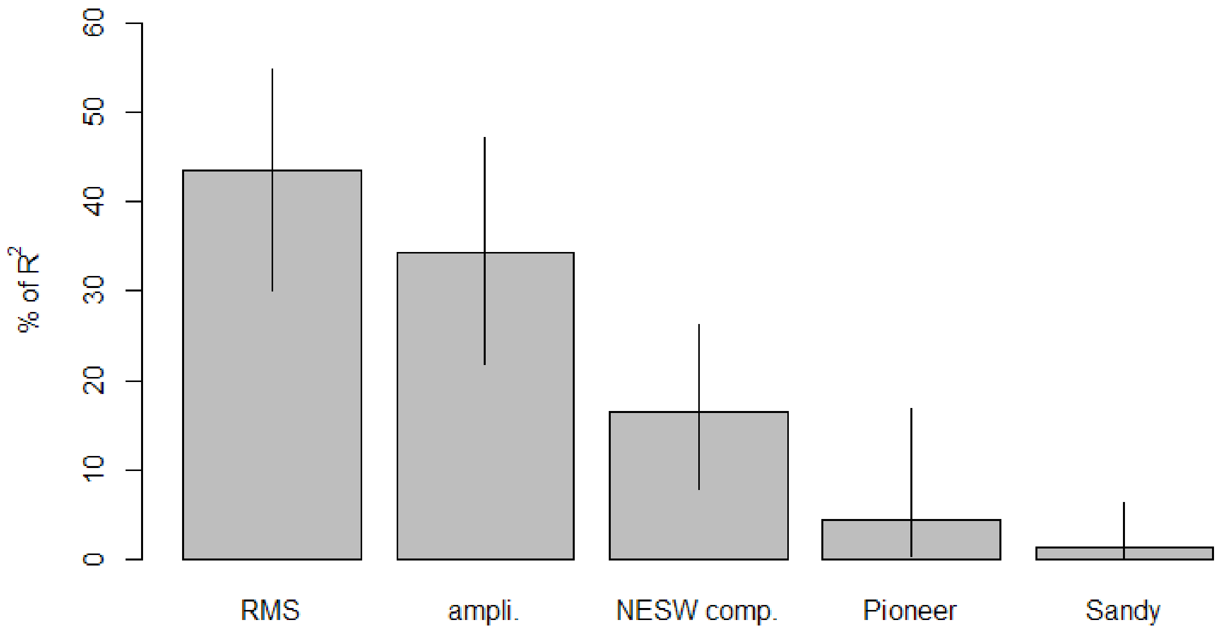


Figure 3.36 Keswick Is bootstrapping relative importance analysis followed by a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r-squared values are normalized to sum 100%. Overall R^2 is 0.49

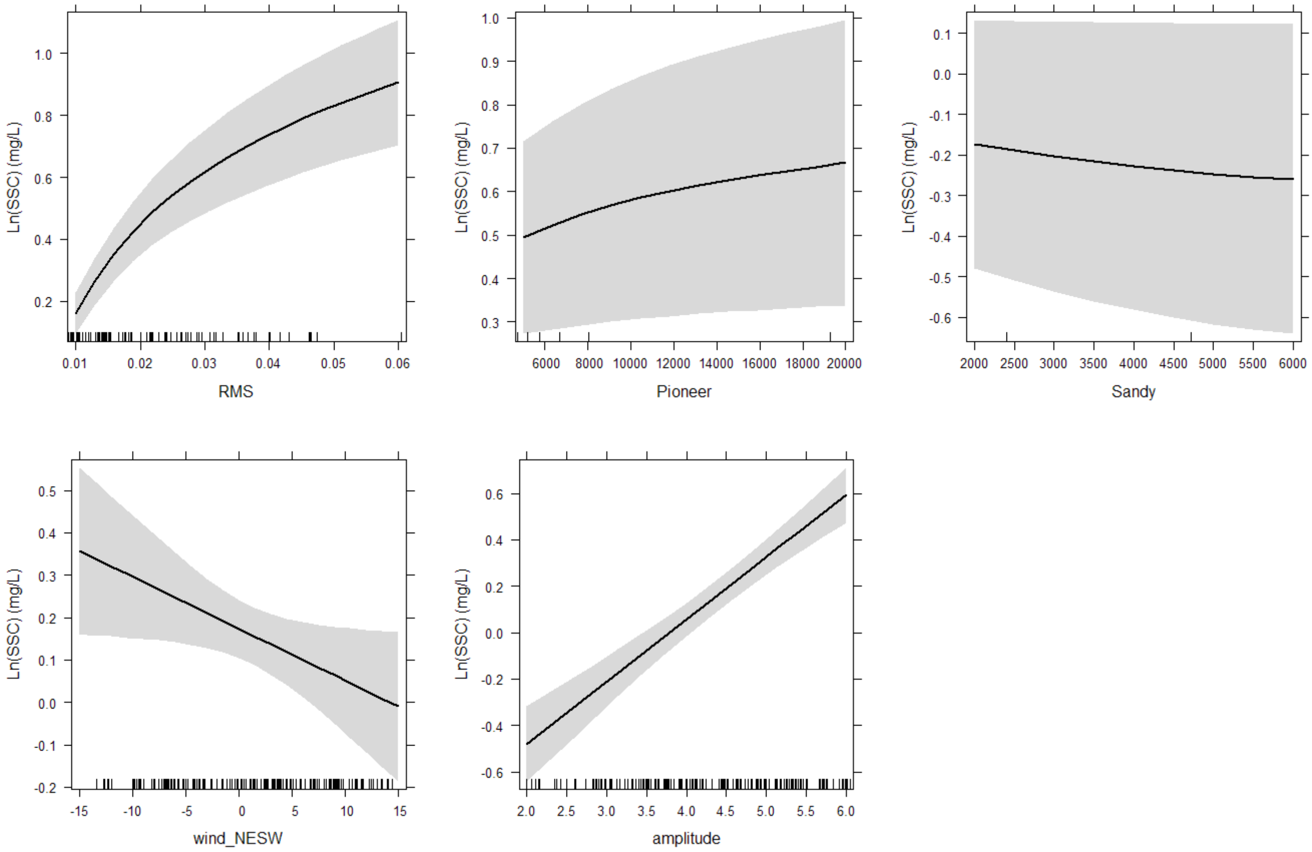


Figure 3.37 Partial Effect Plots for Keswick Island parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

Round Top Island

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, wind NESW component, tide amplitude and the Pioneer River discharge explained 48% of SSC variability (Box 4). The relative importance analysis suggested that RMS of water depth is by far the most influential parameter on SSC, explaining 40% of SCC variability. Tide amplitude, wind and Pioneer River discharge explained together 8% of the SSC variability (Figure 3.38). The partial effect plots (Figure 3.39) suggested that the clearer patterns are observed between SSC and RMS and most of the variables, except the Pioneer River discharge (wider confidence intervals). Overall, an increase in SSC was observed with increases in all the environmental variables, including wind. Similar patterns were observed as with the Freshwater Point site, i.e., the stronger the winds coming from east (i.e., NE, positive values on wind_NESW axis or SE, negative values on wind_NWSE axis) the higher were the SSC measurements.

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

```
Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)      4.140561   0.563543   7.347 2.76e-12 ***
log(RMS)         1.419943   0.099932  14.209  < 2e-16 ***
log(Pioneer + 1) 0.162971   0.051824   3.145  0.00186 **
wind_NESW        0.040074   0.008938   4.483 1.11e-05 ***
amplitude        0.107435   0.049137   2.186  0.02970 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.8954 on 254 degrees of freedom
Multiple R-squared:  0.4892, Adjusted R-squared:  0.4812
F-statistic: 60.83 on 4 and 254 DF,  p-value: < 2.2e-16
```

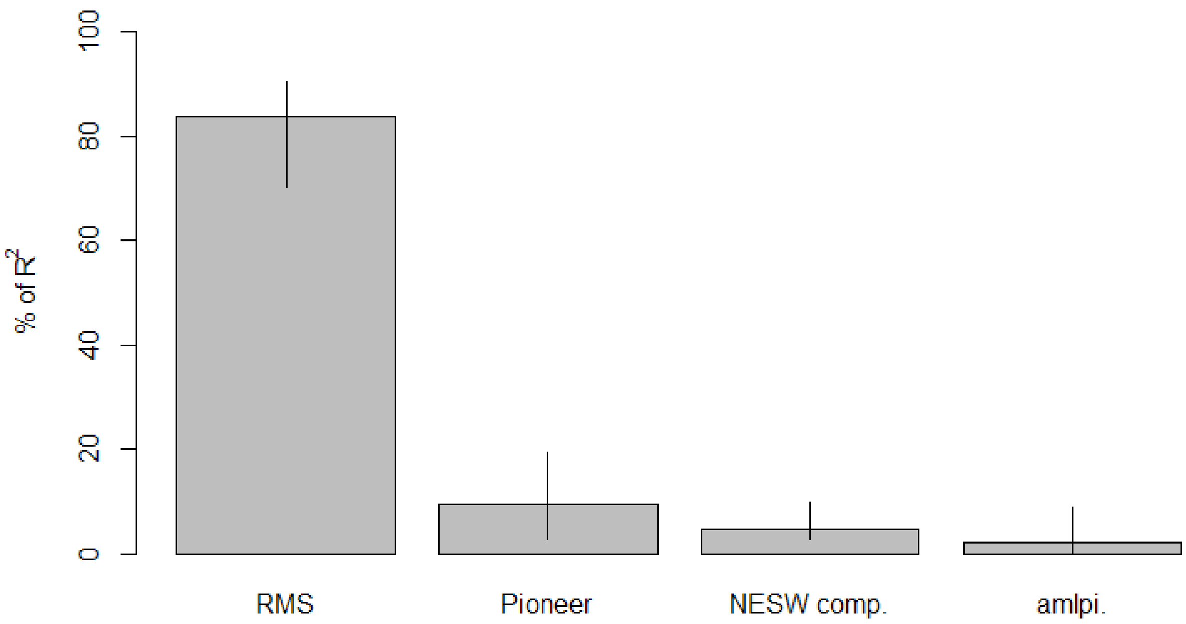


Figure 3.38 Round Top Island bootstrapping relative importance analysis followed by a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r-squared values are normalized to sum 100%. Overall R^2 is 0.48

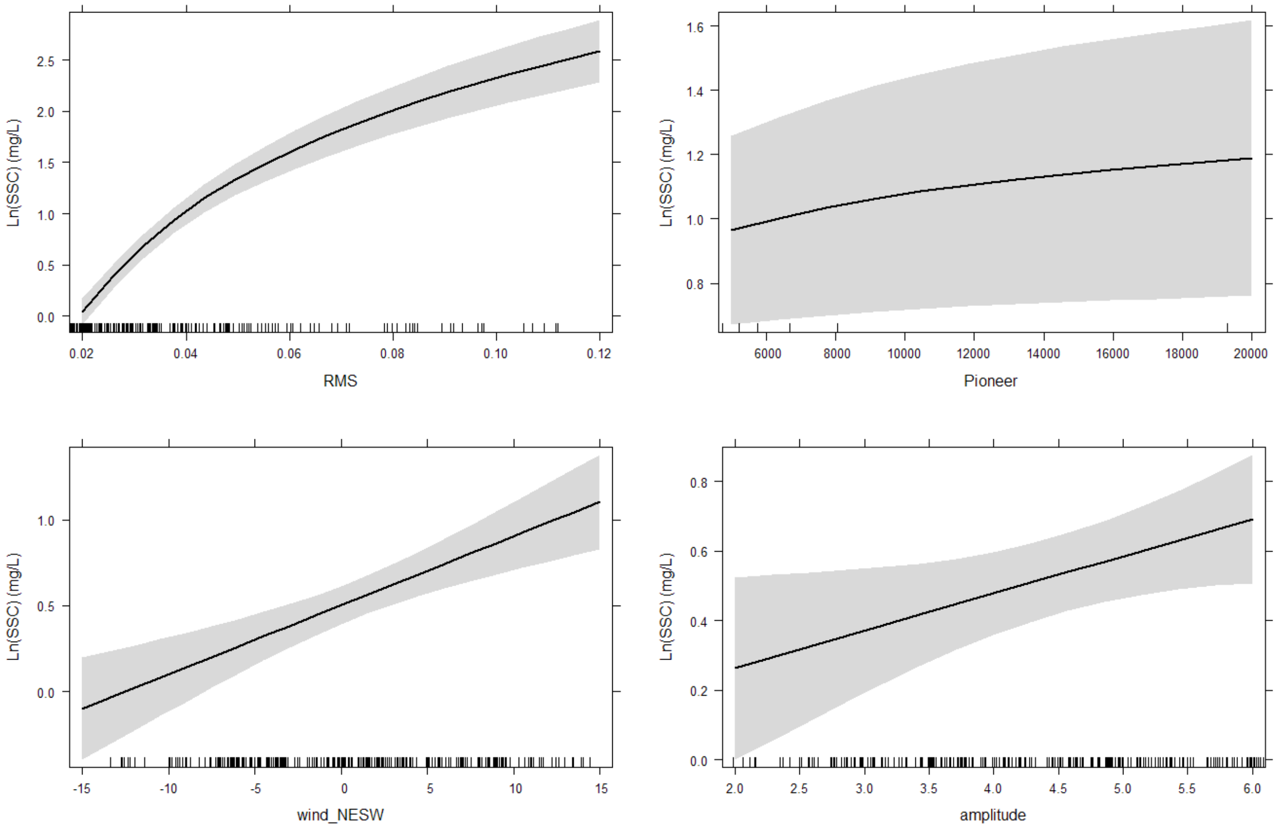


Figure 3.39 Partial Effect Plots for Round Top Island parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

Slade Islet

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, tide amplitude and wind NEWS component explained 24% of SSC variability (Box 5). The relative importance analysis suggested that deposition and RMS of water depth together explain 23% of SSC variability and the wind NESW component explains only 1% (Figure 3.40). Results of the partial effect plots (Figure 3.41) suggested clearer patterns for all selected variables. Overall, an increase in SSC was observed with increases in all the environmental variables, including wind. Similar patterns were observed as with the Freshwater Point site, i.e., the stronger the winds coming from east (i.e., NE, positive values on wind_NESW axis or SE, negative values on wind_NWSE axis) the higher the SSC measurements.

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

```
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  4.17259    0.56442   7.393 1.71e-12 ***
log(RMS)     1.02924    0.13758   7.481 9.78e-13 ***
wind_NESW    0.08323    0.01344   6.191 2.15e-09 ***
amplitude    0.15893    0.08068   1.970   0.0499 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.503 on 277 degrees of freedom
Multiple R-squared:  0.245,  Adjusted R-squared:  0.2368
F-statistic: 29.96 on 3 and 277 DF,  p-value: < 2.2e-16
```

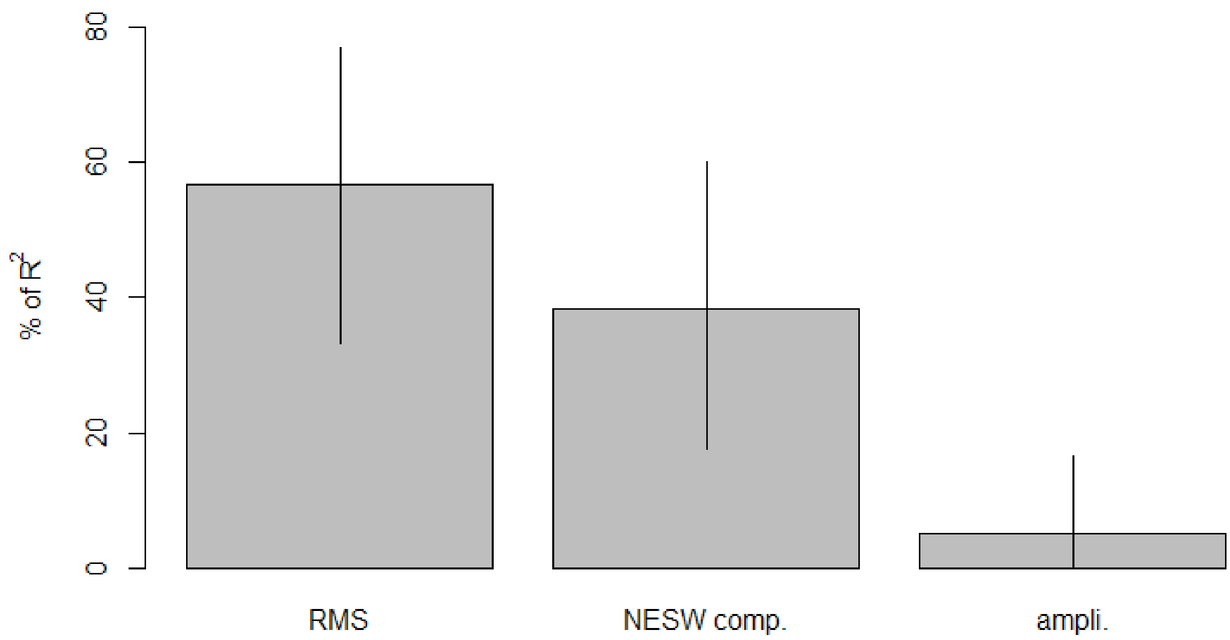


Figure 3.40 Slade Islet bootstrapping relative importance analysis followed by a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r-squared values are normalized to sum 100%. Overall R^2 is 0.24

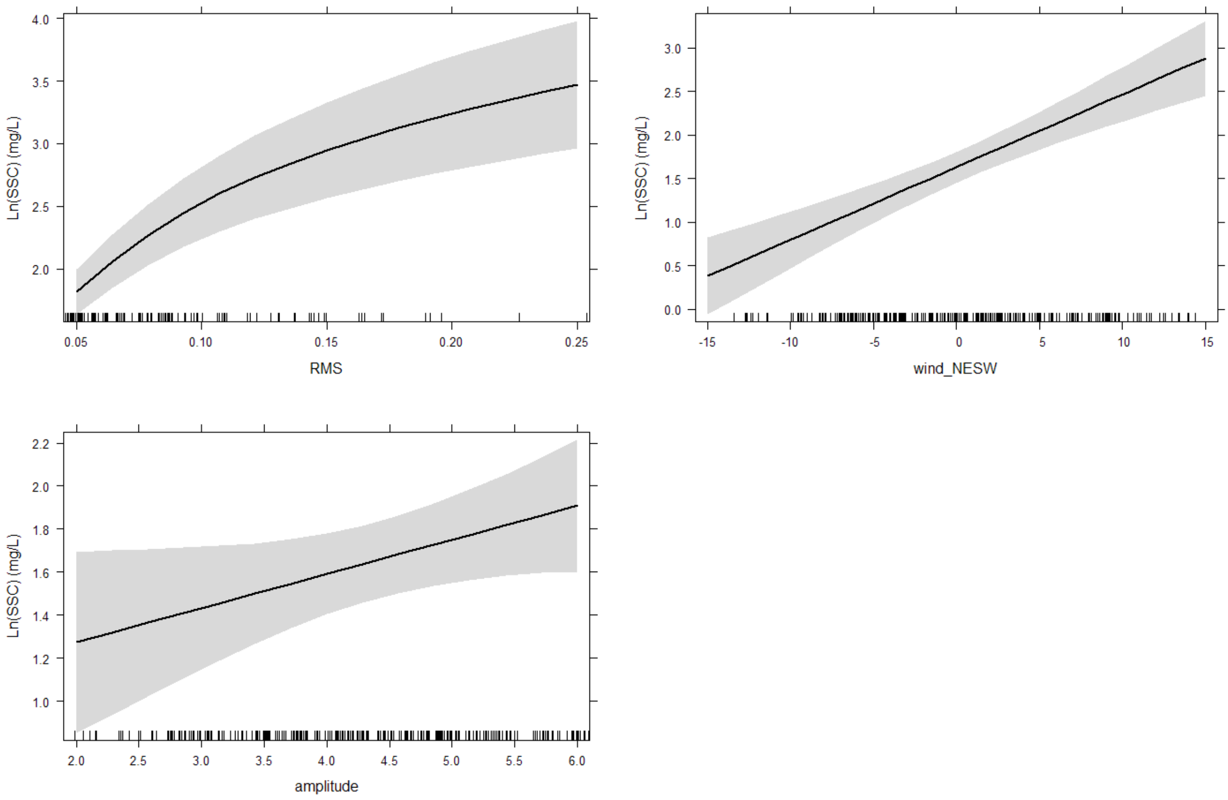


Figure 3.41 Partial Effect Plots for Slade Islet parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

Victor Islet

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, tide amplitude and the Sandy River discharge explained 47% of SSC variability (Box 6). The relative importance analysis suggested that RMS of water depth and the Sandy River discharge together explain 44% of SSC variability (Figure 3.42). Results of the partial effect plots (Figure 3.43) suggested clearer patterns for most of the selected variables except for the Sandy River discharge (wider confidence intervals). Overall, an increase in SSC was observed with increases in all the environmental variables.

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

```
Coefficients:
               Estimate Std. Error t value Pr(>|t|)
(Intercept)     4.13958    0.52362   7.906 1.17e-13 ***
log(RMS)        1.09374    0.11406   9.589  < 2e-16 ***
log(Sandy + 1)  0.38573    0.04267   9.041  < 2e-16 ***
amplitude       0.14960    0.05182   2.887  0.00426 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8566 on 226 degrees of freedom
Multiple R-squared:  0.4747, Adjusted R-squared:  0.4678
F-statistic: 68.09 on 3 and 226 DF,  p-value: < 2.2e-16
```

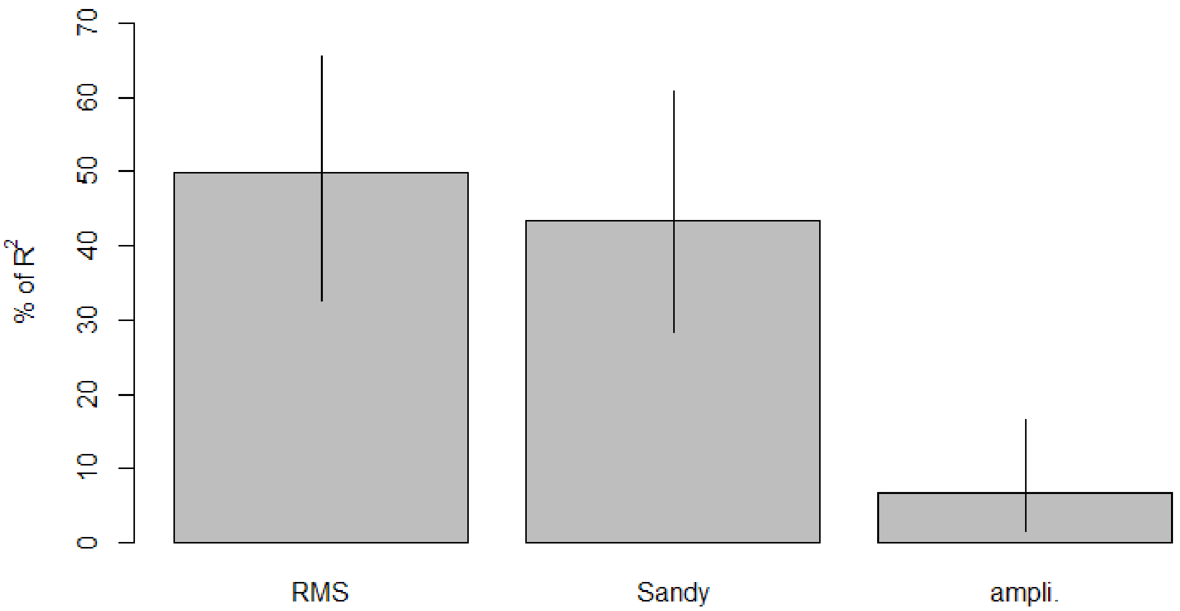


Figure 3.42 Victor Islet bootstrapping relative importance analysis followed by a stepwise multiple regression analysis. Bars represent 95% bootstrap confidence intervals, and % of r-squared values are normalized to sum 100%. Overall R^2 is 0.47

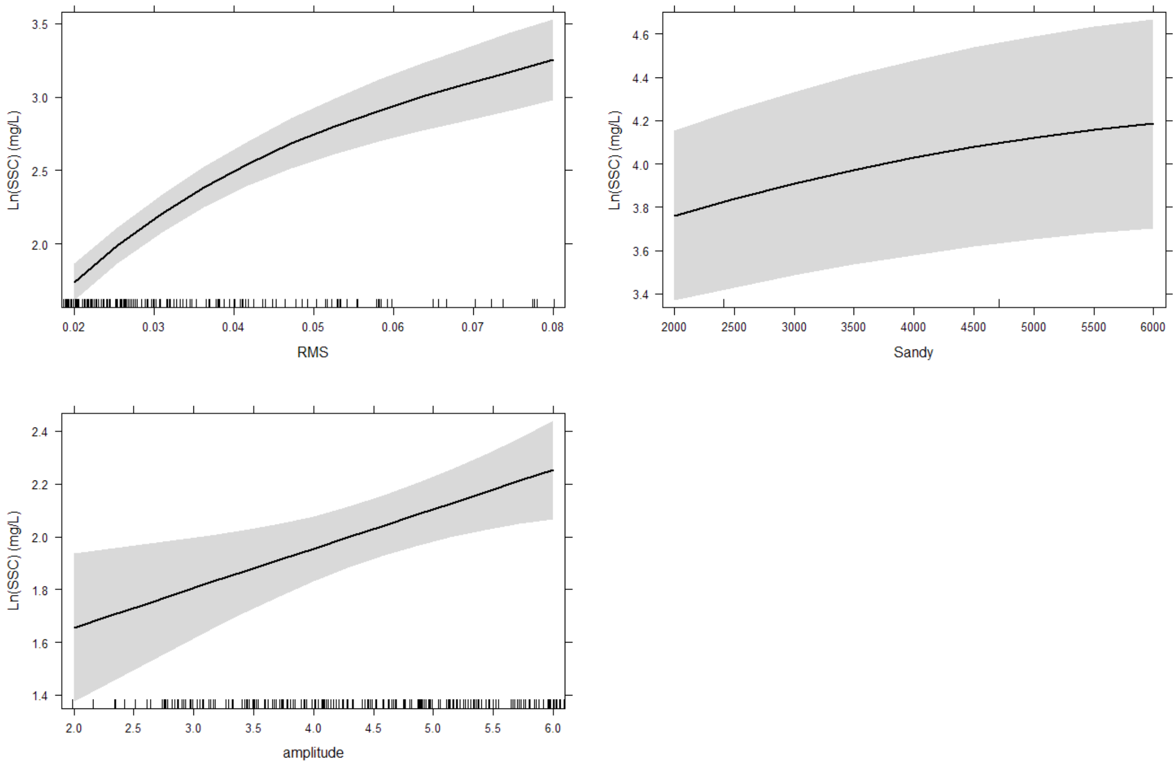


Figure 3.43 Partial Effect Plots for Victor Islet parameters affecting the concentration of suspended solids in the water column. Grey area indicates 95% CI and rug on x-axis stand for data density

3.4.2 MODIS Rrs(645) data as a proxy for turbidity

Using the daily values retrieved from the daily MODIS images (Figure 3.44), correlations between the Rrs(645) nm and the SSC measured using the deposition loggers were generated for the monitoring period. Examination of the these data revealed a weak relationships for the six monitored sites (Freshwater Point, Hay Point Reef, Keswick Island, Round Top Island, Slade Islet and Victor Islet), with R^2 ranging between 0.0 and 0.3. The stronger correlations were observed at the Freshwater Point and Hay Point reef monitoring sites (R^2 = 0.22 and R^2 = 0.26, respectively). These weak relationships are the result of noise in the dataset, in other words, there are times where the RS over or under estimates the measured turbidity levels at sites, which contributes to the weakness in the ability to accurately predicted field measurements. There are several reasons for this, including low capacity to determine turbidity in the RS over the past 12 months as turbidity has been very low because of no rainfall (meaning that under more average rainfall years this modelling would be more beneficial). A second reason might also be the proximity of sites to the coastline, and shallow waters, where the remote sensed data may not able to detect nearshore turbidity plumes, unlike in large bay locations where MODIS has been able to achieve greater predictability (Devlin et al., 2015).

Correlations were generated using the mean weekly data to smooth measurement error of daily Rrs(645)(Figure 3.45). These correlations revealed a stronger relationships (Table 3.13), up to 0.69 measured again at Hay Point reef (and Freshwater Point was R^2 = 0.59). At both sites the Rrs(645) data showed similar trends as the mean weekly SSC data (Figures 3.46). Despite a lower correlation coefficient at Round Top Island (Table 3.13, R^2 = 0.24), trends between the satellite Rrs(645) and *in-situ* SSC data were similar. The exception was at Slade Islet, Victor Islet and Keswick Island monitoring sites where the R^2 was low (< 0.1). These 3 sites are the shallowest sites analysed and bottom perturbations may contribute to some noise on the satellite signal and may explain the lowest correlations observed.

Table 3.13 Correlation statistics calculated between the Rrs(645) and SSC values (mean daily value calculated between 11 am and 3 pm) and depth at each monitoring site

Site	Daily			Weekly	
	Depth (m)	r-squared	p-value	r-squared	p-value
Freshwater Point	10.3	0.22	<0.01	0.55	<0.01
Hay Point Reef	11.0	0.26	<0.01	0.69	<0.01
Round Top Is	9.5	0.08	<0.01	0.24	<0.01
Slade Is	4.4	0.03	0.03	0.08	0.04
Victor Is	4.3	0.04	<0.01	0.16	<0.01
Keswick Is	5.2	0.00	0.45	0.01	0.66
Mean		*0.11*		*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 Islet, Victor Islet, Keswick Island) may be a result of a single or combination factors, including:

- Optical complexity of the Hay point coastal water zone;
- Potential 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 this disparity may limit the ability to predict surface turbidity (see Figure 3.2 where field

in-situ data shows high turbidity at bottom horizon compared to surface horizon, supporting this point).

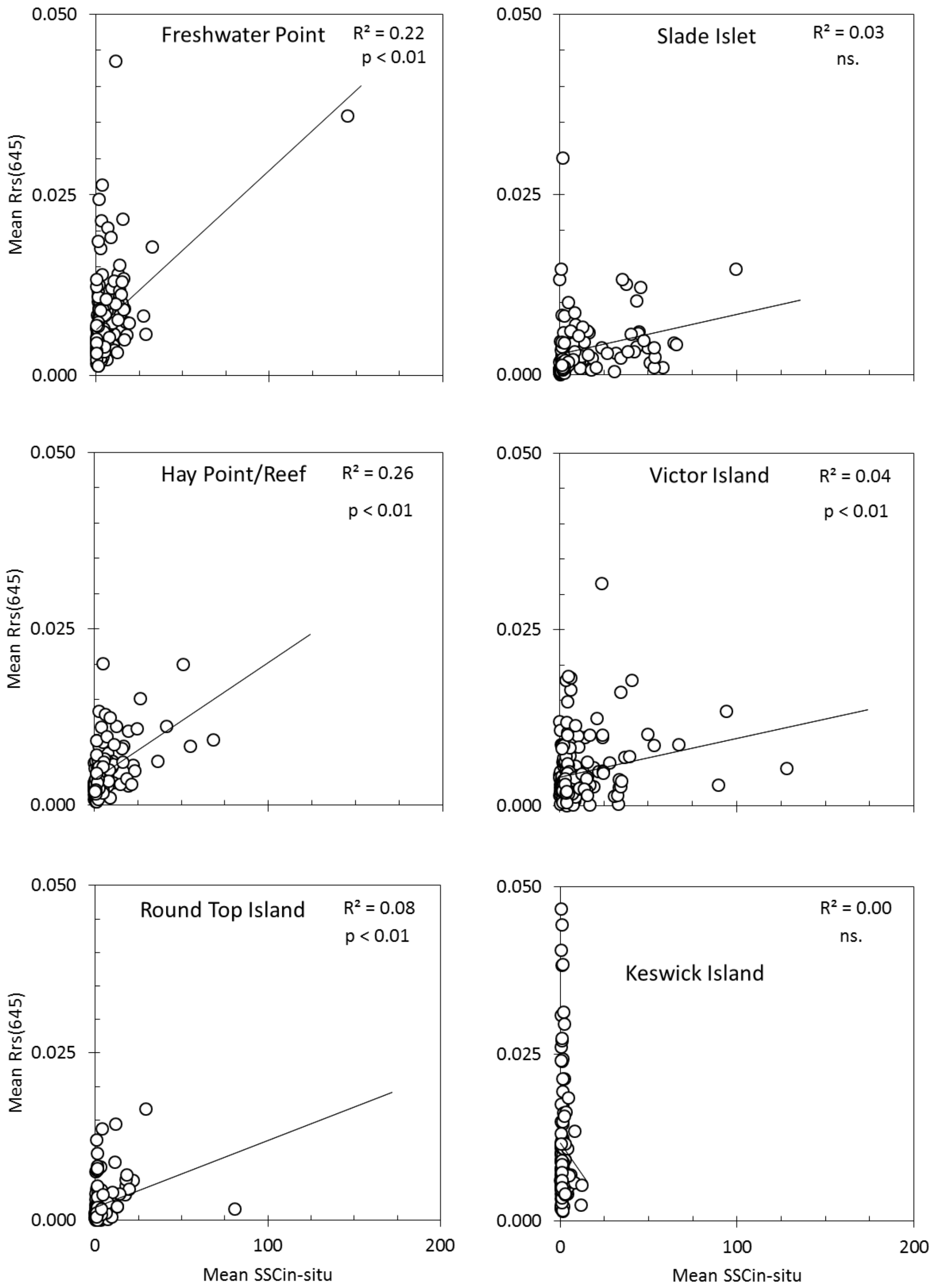


Figure 3.44 Correlations between the daily mean Rrs(645) (satellite proxy for turbidity) and mean SSC (between 11 am and 3 pm) at the six monitored sites (Freshwater Point, Hay Point Reef, Keswick Island, Round Top Island, Slade Islet and Victor Islet)

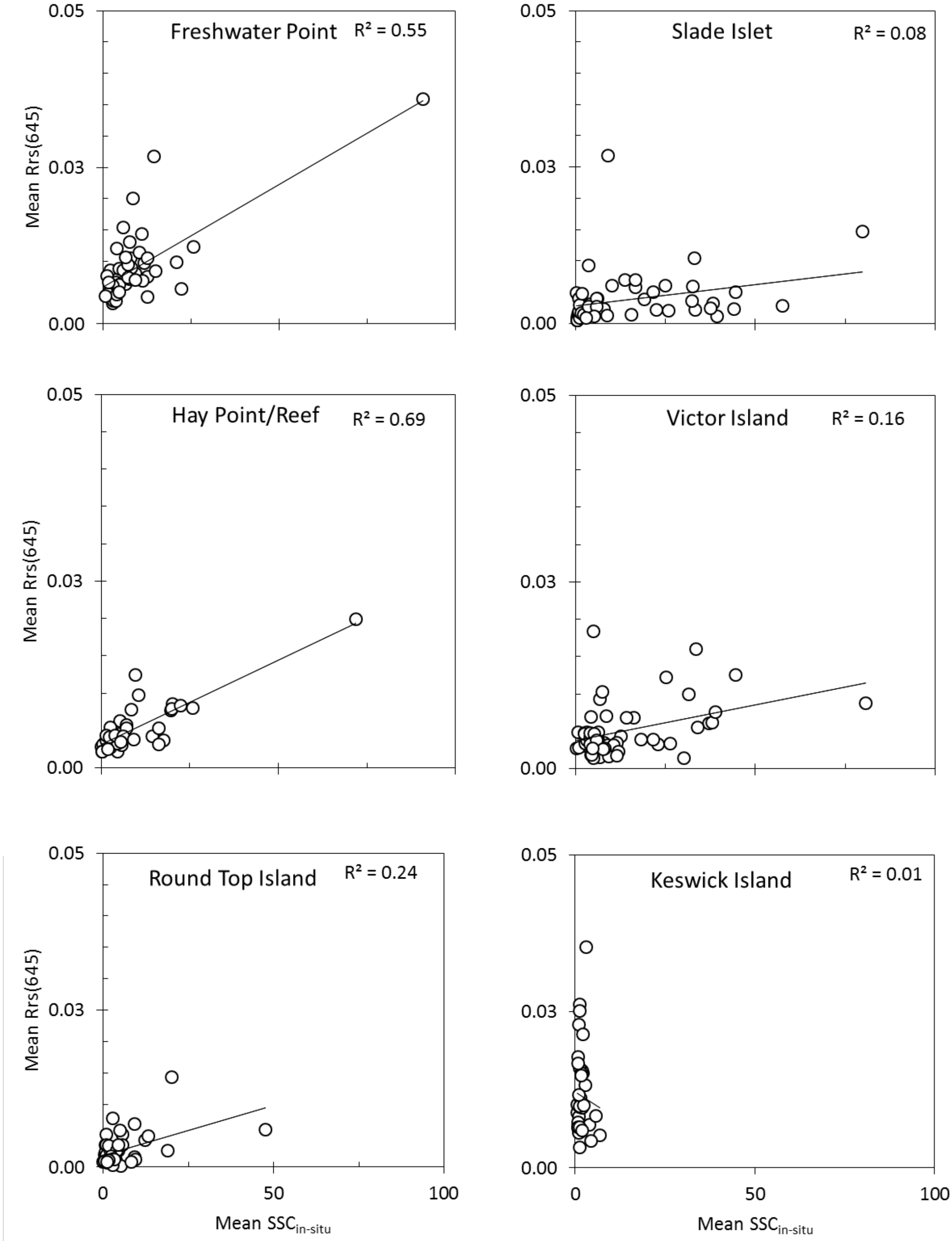


Figure 3.45 Correlations between the mean weekly Rrs(645) (satellite proxy for turbidity) and mean weekly SSC (between 11 am and 3 pm) at the six monitored sites. ns. non significant

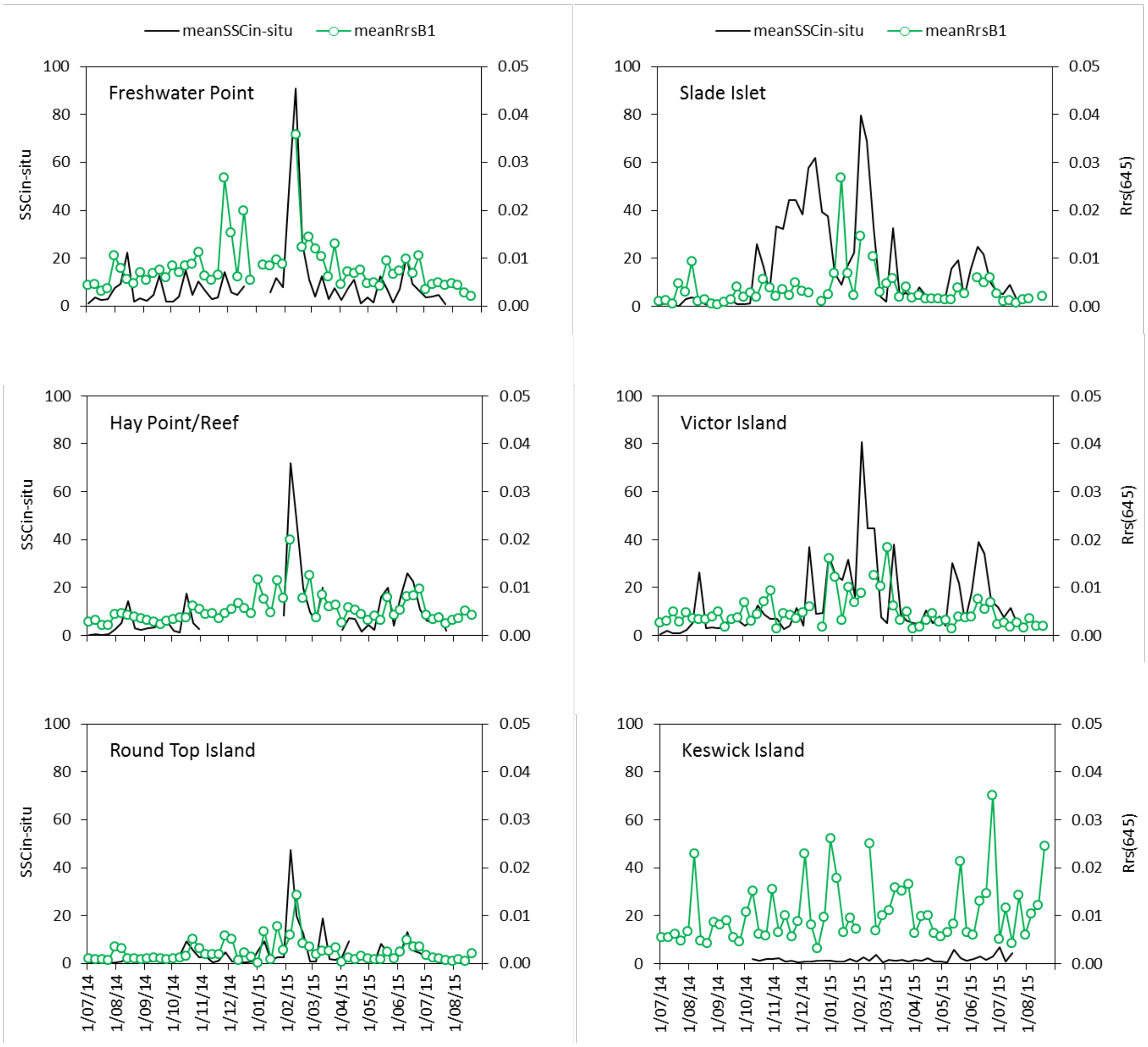


Figure 3.46 Comparisons between the mean weekly Rrs(645) (satellite proxy for turbidity) and mean weekly SSC (between 11 am and 3 pm) at the monitored sites

3.4.3 MODIS Rrs(645) data as a proxy for turbidity levels – February 2015

At the Hay Point reef, Freshwater Point and Round Top Island monitoring sites, the mean weekly satellite data were able to reproduce the increase in SSC following the main rainfall event of late January/February 2015 (Figures 3.47 and 3.48). Using only daily data of January and February 2015, coefficient of determination between the Rrs(645) nm and the SSC were R^2 = 0.68, R^2 = 0.32 and R^2 = 0.31 at freshwater, Hay Point Reef and Round Top Island, respectively (Figure 3.48). The correlation was, however, not significant at Hay Point reef due to a limited number of satellite data available at this site during the January - February 2015 period. No correlation was observed at Slade Islet, Victor Island and Keswick Island (not shown, R^2 < 0.1, ns.). Figure 3.49 presents weekly plume water composite maps for weeks starting the 19 January, the 26 January and the 2 February 2015. These maps show river flood plumes formed at the Sandy and Pioneer River mouths. It would be expected that the mapping of true colour in the nearshore shallow environment, on cloud-free days would still allow the edge of the river and dredge plumes to be distinguished, if sufficient spatial resolution is obtainable from the MODIS satellite images (finer resolution: 250m).

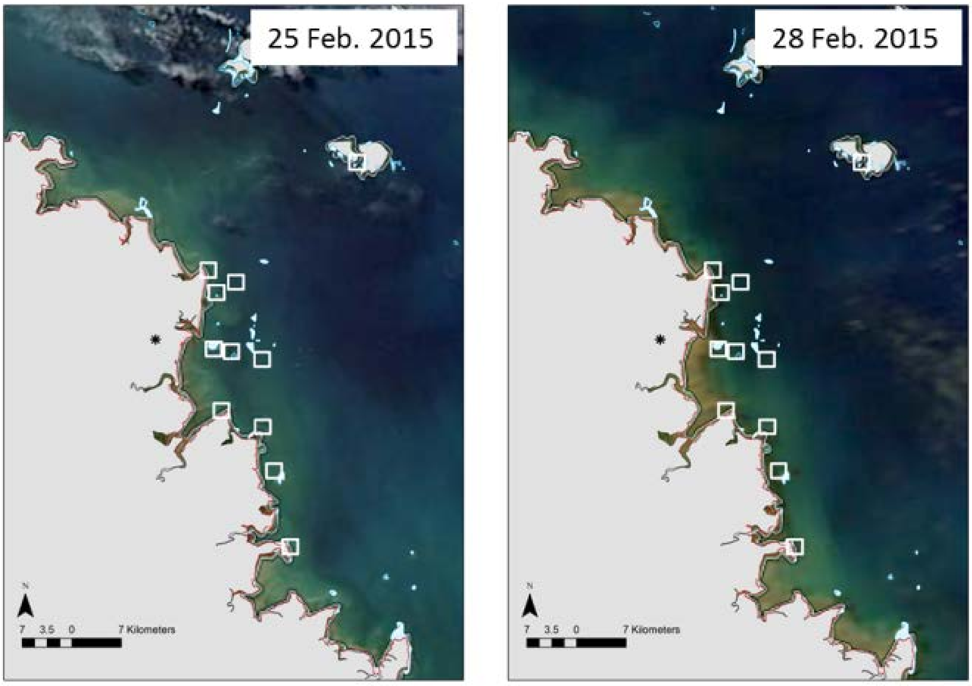


Figure 3.47 MODIS true colour images illustrating the relatively high turbidity measured in the coastal areas of Mackay and Hay Point at the end of February and early March 2015. Squares shown are location of ambient marine water quality monitoring sites

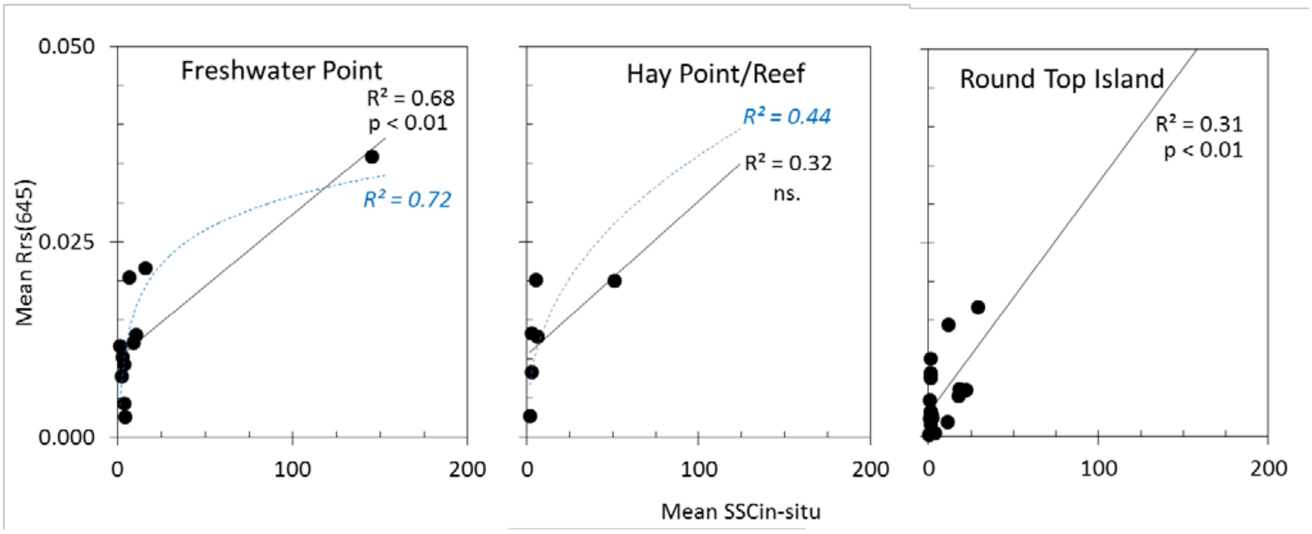


Figure 3.48 Correlations between the daily mean Rrs(645) (satellite proxy for turbidity) and mean SSC (between 11 am and 3 pm) measured between January and February 2015 at Freshwater Point, Hay Point Reef and Round Top Island

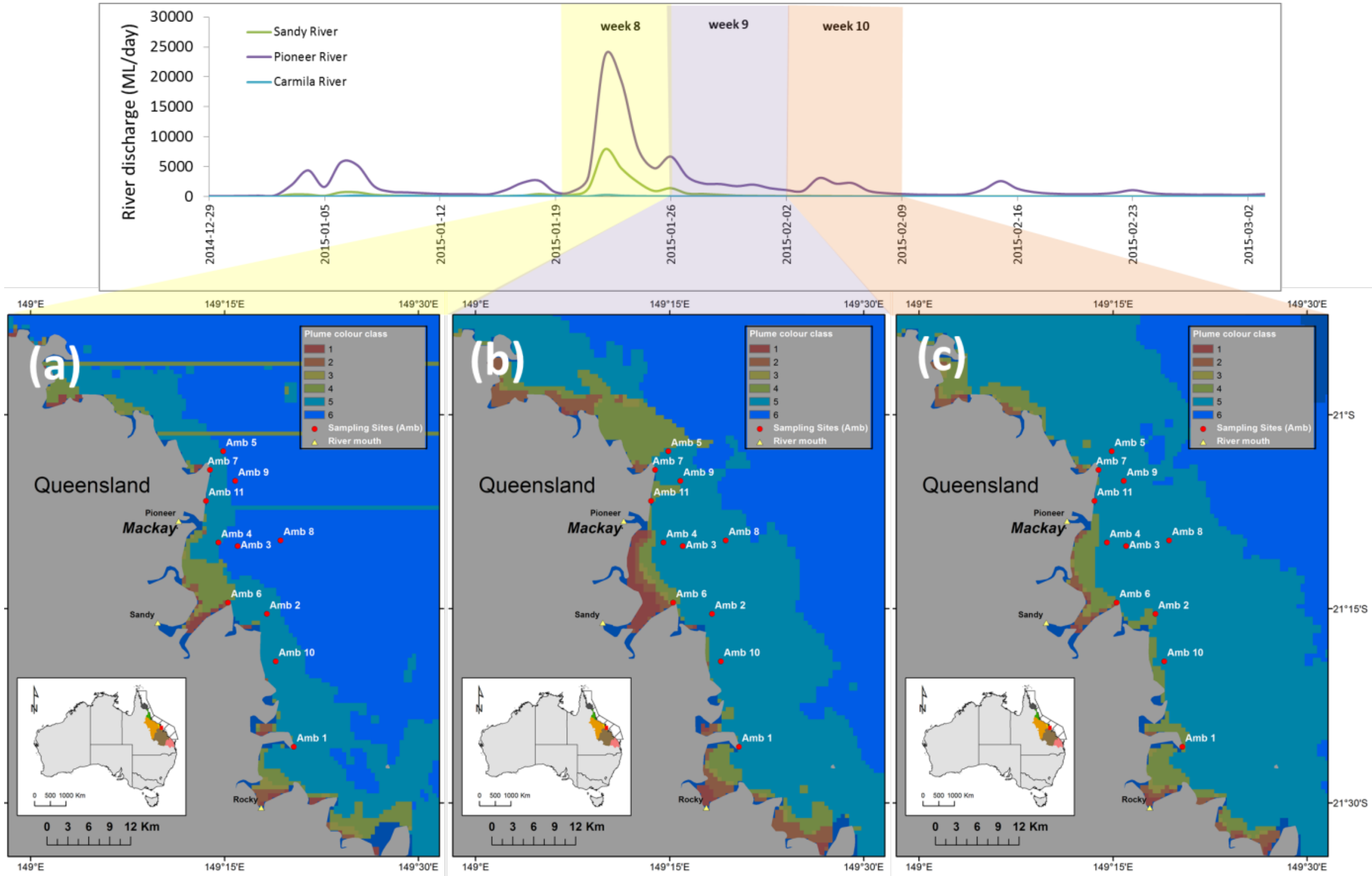


Figure 3.49 Plume water maps for weeks starting the: (a) 19 January 2015 (week 8); (b) 26 January 2015 (week 9); and (c) 2 February 2015 (week 10). Top graph presents the Sandy, Pioneer and Carmila River discharges (Source: DNRM, https://www.dnrm.qld.gov.au/water/water-monitoring-and-data/portal) and the corresponding weeks from which MODIS-Aqua images were selected to produce the plume maps. The different water types (plume color classes 1 to 6) inside the river plumes are mapped using a supervised classification of daily MODIS true color following the method of Alvarez-Romero et al., (2013)

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

4.1.1 Climatic conditions

- An important factor to consider in interpreting the first 12 months of ambient monitoring data is that the failed wet season limited the ability to characterise the full range of water quality conditions in 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 observed in this data set.
- Rainfall over the several years prior to this assessment period was much greater, 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 necessary before any statistical rigor can be given to the information presented.
- While rainfall and river flow was low, the first 12 month of monitoring has provided the opportunity to capture data during a low rainfall wet season. Such opportunities are rare, and therefore monitoring to date provides valuable insight into water quality characteristics driven by factors other than rainfall runoff and plumes. Specifically, the low rainfall period has provided the rare opportunity to examine wave energy conditions and the relationship with water quality conditions.
- Comparison of these data with future years will be important to more fully characterise ambient water quality conditions for this region, particularly should the program continue and capture above average rainfall years in the future.
- Tropical cyclone Marcia that passed to the south of Mackay generated some rainfall and flow in the river catchments in the region, however, the hydrograph was short, with flow returning to low flow or no flow again with a few weeks; this is probably atypical and again, reflects the failed wet season.
- 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, and regularly reaches 24km (daily average). This localised weather pattern is probably an important factor that requires consideration in similar water quality campaigns for the region.

4.1.2 Ambient water quality

- There is a strong seasonal pattern for water temperature, which are higher during summer months and cooler during winter months. The differences in water temperature across the region between winter and summer is almost 10^{o}C, throughout the entire water column.
- The water column profile for dissolved oxygen, temperature, electrical conductivity and pH seems to be well mixed. The exception was turbidity which was higher at bottom horizon, which contributed to a distinct separation of water horizons in the ordination plot. This pattern for turbidity is probably related to the bottom horizon

being proximal to the sea floor and the remobilisation of sediments during increasing wave energy and tidal current.

- The most noteworthy patterns in the ambient water quality monitoring were elevated concentrations of nutrients. Nutrients, particularly total and dissolved nitrogen, were detected at most sites, with concentrations above the relevant guidelines for the region. The contributing factors to these data 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 elevated supply of dissolved nutrients is a concern for the region and requires further investigation and management. 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).
- Trace heavy metals, TBT and pesticides were non-detectable across the monitoring period. This result is probably a reflection of low rainfall and therefore contribution of contaminants from more wide scale diffusive land use sources, such as heavy industry, urban stormwater and wastewater which are known to contribute to these contaminants in coastal waters. The exception was Mackay marina, where copper was detected during each survey, with concentrations above the relevant guidelines for aquatic ecosystem protection. The source of the copper (along with arsenic which was also detected) in the marina is not known, and would require further investigation, possibility through the use of diffusive gradients in thin gel (DGT's). The use of DGTs is becoming a useful marine monitoring tool for heavy metals in the marine environment as it provides a time integrated measure of contamination (see Dunn et al., 2007; Waltham et al., 2011; Warnken et al., 2004), as opposed to grab water samples. In addition, sediment samples also provide a time integrated measure of contaminants, which may also be useful in determining a more detailed understanding of the source of these heavy metals, and at least for sediments, an indication of the potential release during sediment disturbances.
- Despite these elevated heavy metal concentrations, they are localised given that each metal contaminant was not detected at the next closest monitoring sites (AMB 5, Slade Islet, or AMB 9B, East cardinal marker) to the marina.
- Diuron was the only herbicide detected across the site network. This herbicide is 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. 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 (see Bell & Duke, 2005).
- As this database continues to expand, with more data generated under various environmental conditions, 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).

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.

- 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.
- A multivariate predictive NTUe/SSC model has been developed at sites AMB 1, AMB 2, AMB 3, AMB 5, 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, though already the model can predict turbidity at sites with a high degree of accuracy, when compared to logging data.
- The model developed here provides management with a powerful tool, for example, as the differentiation between natural turbidity and that recorded during anthropogenic activities that relate to turbidity may be evaluated. This means that the difference in the measured turbidity compared to the predicted using this model, represents the contribution associated with local anthropogenic activities.
- Wavelet and Fourier analysis provides a long term picture of the typical patterns in NTUe/SSC. These analyses can be used comparatively over time to provide an indication of whether patterns describing trends in turbidity are stable or have changed.

4.1.4 Photosynthetically active radiation (PAR)

- Fine-scale patterns of PAR are primarily 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 (Orpin and Ridd 2012), and rainfall events resulting from storms leading to increased catchment flows and an input of suspended solids (Fabricius et al., 2013). During the initial 12 month sampling period Root Mean Squared (RMS) of water depth which is a proxy for wave energy was the major driver of changes in PAR. As this period coincided with a strong El nińo cycle that was characterised by low precipitation throughout the year the continuation of the program may pick up the influence of rainfall events in future years with more typical wet seasons.
- Patterns of light were similar among all the coastal sites. Light penetration in water is affected in an exponential relationship with depth as photons are absorbed and scattered by particulate matter (Kirk 1985; Davis-Colley and Smith 2001). Therefore variation in depth at each location means benthic PAR is not directly comparable among sites as a measure of water quality. Generally, however, shallow inshore sites reached higher levels of benthic PAR and were more variable than deeper water coastal sites and sites of closer proximity to one another were more similar than distant sites.
- 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 to many of the episodic weather events that impacted heavily on the coastal sites.

- 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 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 (e.g., Chartrand et al., 2012), algae and corals it is becoming more useful as a management response tool when used in conjunction with known thresholds for healthy growth for these habitats. For this reason, it is important to include photosynthetically active radiation (PAR) in the suite of water quality variables when capturing local baseline conditions of ambient water quality.
- The PAR monitoring component of the program has been consolidated by reducing the number of sites from eleven to eight. This change has been designed with the maintenance of the integrity of the sampling program as the highest priority. Sites that have been decommissioned were located in close proximity and shared closely correlated patterns of PAR to sites that will remain within the program (see justification below). This will allow the program to continue to provide a strong spatial representation that will characterise the local and regional patterns in benthic light around the ports of Hay Point and Mackay.

4.1.5 River plumes

- On average, the proposed models to relate 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). RMS of water depth was the main driver of SSC in the water column, and accounted for 63 % of the explained variability by the fitted models (Table 4.1). Except for Victor Islet, the river discharge importance to the SSC variability was low, and on average 3 % for the Pioneer River and 7 % for the Sandy River. The low river influence on SSC is probably, once again, the result of the dry period experienced in the 2014/15 wet season.

Table 4.1 Relative importance of each variable to explain SSC variability in the water column

			Variable Importance as % of r-squared					
Site	**r-squared**	**p-value**	**RMS**	**wind NESW**	**wind NWSE**	**tide amplitude**	**Pioneer**	**Sandy**
Freshwater Point	0.75	<0.01	53	7	33	2	5	0
Hay Point Reef	0.53	<0.01	92	7	0	1	0	0
Round Top Is	0.48	<0.01	84	5	0	2	9	0
Slade Is	0.24	<0.01	57	38	0	5	0	0
Victor Is	0.47	<0.01	50	0	0	7	0	43
Keswick Is	0.49	<0.01	44	17	0	34	4	1
Mean	*0.49*		*63*	*12*	*6*	*9*	*3*	*7*

- Match-ups analyses of MODIS and *in-situ* SSC data from the ambient marine monitoring program were undertaken to test agreements between the satellite and *in-situ* water turbidity measurements on seafloor. Correlations between the daily Rrs(645) and the mean SSC (between 11 am and 3 pm) were generally weak at the six monitored sites (Freshwater Point, Hay Point Reef, Keswick Island, Round Top Island, Slade Islet and Victor Islet), with an average R^2 of 0.11.
- However, 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: $R^2 < 0.1$). The stronger correlations were observed at the Freshwater Point ($R^2 = 0.69$) and Hay Point reef monitoring sites ($R^2 = 0.59$), which is probably associated to the shallowness of both sites, where the continuous loggers measuring SCC can be more accurately examined.
- 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. These were likely to be important contributing factors to the low predictability in application during the 2014/2015 period.
- Another important factor to consider in interpreting the satellite data is that the 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. The satellite data were, however, able to reproduce the increase in SSC observed around late February 2015 at Hay Point reef, Round Top Island and Freshwater Point. This evidence provides important insight into the ability of this water quality tool during average or above average rainfall years.
- During this period of monitoring, there was no dredging or river flow, and thus the ability to identify and map river and dredge related plumes was not tested. It would be expected that the mapping of true colour in the nearshore shallow environment, on cloud-free days, would still allow the edge of the plumes to be distinguished. However, if tracking the plume associated with a dredging campaigns is necessary, then employing higher resolution satellite images might be necessary.
- Whilst there are limitations in the small areas associated with the nearshore coastal zone (shallower sites; <5m depth), the ability to retrieve remote sensed data is improved as the mapping moves further away from the complex nearshore environment. Thus, in combination with a monitoring program targeting high frequency sampling in the near shore environment through appropriate loggers and *in-situ* sampling for the validation of the RS data, the extraction of data from large spatial images still provides a useful tool for characterising the water quality around the coastal sites.
- Comparison of satellite and *in-situ* data with future years will be important in more fully characterising potential of using MODIS satellite data as a complementary source of operational data for dredging monitoring in this region.

4.2 Recommendations

4.2.1 Consolidation of the water quality loggers and chemistry

As part of a review of the data during the March 2015 progress report, it was determined that some refinements to the ambient marine water quality program where possible. These refinements were most apparent in the reducing the number of sites with high frequency loggers, refinement to logging configuration, and some reduction in the water chemistry, while increasing frequency of monitoring for targeted water quality parameters. After a review of the data available to March 2015, consolidation of the program was determined and was implemented in consultation with NQBP. The changes were enacted in July 2015.

Key to these changes were to not compromise on the data and statistical integrity of the program, particularly given the low rainfall season, and the ability to characterise the full range in water quality conditions for the region. Also, where there were obvious similarity among sites, a reduction was identified and made. As an example, a comparison of continuous loggers that provided similar data patterns could be reduced to a single site. This was the case for the comparison in PAR data between Flat Top Island and Round Top Island, which are located approximately 2km a part, where regression analysis yielded a strong correlation, providing evidence that only a single logger is probably sufficient (Figure 4.1). As part of this refinement, ambient marine monitoring sites that aligned with sensitive receptor habitats (e.g., coral and seagrass) where given high priority, as the water quality data may assist in the assessment of ecological patterns and trends at a future time.

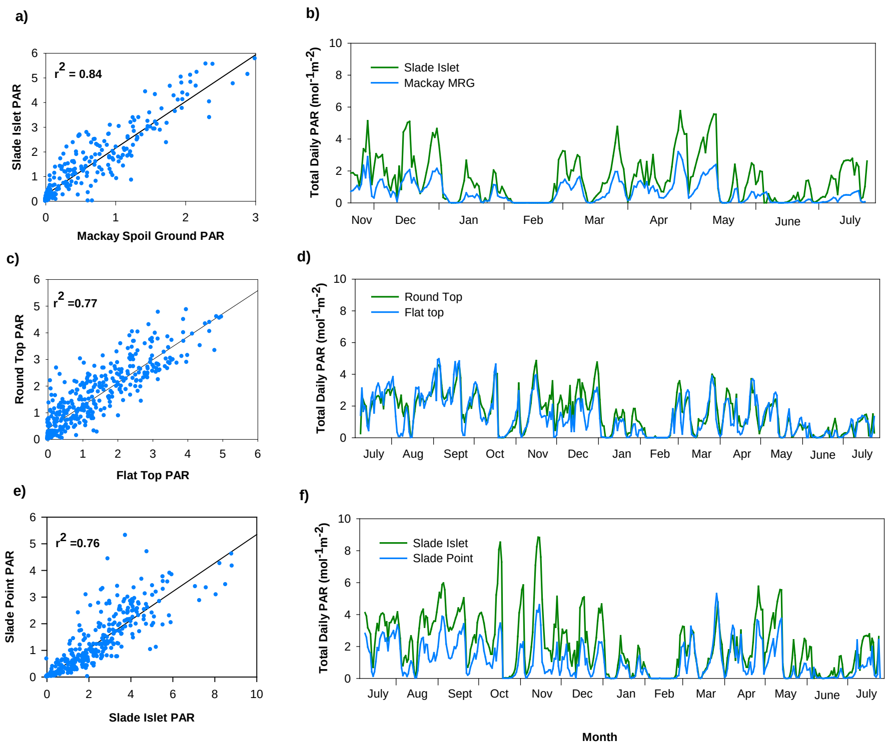


Figure 4.1 Comparison of patterns of daily benthic PAR between sites recommended for decommissioning and nearby ambient sites that will remain in the program. Scatterplots and line graphs compare: a) and b) Slade Islet and the East Cardinal Marker site; c) and d) Round Top and Flat Top Island; and e) and f) Slade Point and Slade Islet

4.2.2 Relocation of sites

As part of the revision and refinement to the program, logger position at Dudgeon Reef (AMB 6) and Round Top Island (AMB 3) were relocated to nearby locations in an attempt to reduce loss of equipment (and data), which has occurred during the monitoring period. In addition to ensuring logger instruments are safe, an additional benefit is that the loggers are now located next to important sensitive habitats (coral and seagrass), and so the data might become important when assessing development activities on these sensitive benthic habitats.

The Dudgeon Reef site has been problematic due to the strong tidal currents resulting in a very dynamic substrate of shifting sand that has led to the scouring, burial and loss of equipment (both PAR loggers and moorings) as highlighted in quarterly progress reports. This new site is at a similar depth to the current location and is situated in seagrass habitat (mapped in 2010 and 2014) (York et al., 2015), as well as being adjacent to coral habitat. The presence of seagrass at the site would indicate a more stable substrate in which to deploy logging equipment and moorings and would allow for coupling of light levels with important benthic habitats that would also be useful as a sensitive receptor site for future dredging events and data could also be used in future seagrass monitoring program.

The Round Top Island site has also been problematic due to continuous loss of marker buoys and the need to conduct dive searches to relocate the site. The site was located in an area of high boat traffic and trawling grounds with strong currents limiting diving to slack water at the turn of tides. It is also likely that vessels had been using the marker buoy as a mooring and dragging it off the site. In the past we have lost equipment at this site due to trawling when the marker has been absent. Relocating this site should be a more feasible long term monitoring site for deposition and PAR loggers.

For historical documentation, the relocation of sites has been reflected by adding a "B" to the main site code names. For Round Top Island (AMB 3), the new site code is AMB 3B, while for Dudgeon Reef (AMB 6) the new site code is AMB 6B. These new site codes provide an important historical reference, linked back to the original sites presented in this report. Future reports will need to use the new site codes, for historical comparison and interpretation. The new program has been endorsed by NQBP, along with a revised ambient marine water quality monitoring table for inclusion into the EMP for these operations. The new logger configuration and monitoring commenced in August 2015.

4.2.3 Laboratory analysis

Some refinements to laboratory analyses are possible. Although most heavy metals and organic concentrations have been below their respective limits of reporting, this is likely a consequence of the lower than average rainfall experienced during this 2014/15 wet season.

Elevated nutrient concentrations has been met with further investigation in order to more appropriately characterise nutrient processes in the region. Over the next 12 months of monitoring (2015/16), water samples will be collected for analysis of particulate nutrients, in addition to chlorophyll-*a* as part of the 6 week logger maintenance schedule. This increased frequency of water sampling will assist in the ability to understand the nutrient processes occurring in the region, and particularly if the next 12 months are an average year for rainfall. In addition, water samples will be collected sporadically for algal identification and counts, in an attempt to further qualify the contribution that algal populations have on water quality.

4.2.4 River plumes

The river plume modelling using MODIS will continue over the 2015/16 period. As part of this modelling of river plumes, it is hoped that rainfall event occurs in the region and contributes to greater flow in the major rivers. However, the long range forecast does not look promising, and the expectation that another below average wet season is expected.

TropWATER is investigating advancements in satellite imaginary, where a new stationary satellite will be soon available that will capture regular (approx. 10min) images over eastern Australia. The Himawari–8 (http://www.data.jma.go.jp/mscweb/data/himawari/index.html), may possibly increase the capacity to use RS in predicting coastal turbidity and plumes. The current MODIS imaginary is available for the region daily, between 11am and 3pm, however, increased access to imaginary could result in more data available (particularly on cloudy days) to use in this modelling. The applicability of this new advancement in imaginary will be pursed over the 2015/16 monitoring period.

4.2.5 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 2015. This data base will continue to develop following the 2015/16 period.

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