Turbidity (NTU) to Suspended Sediment Concentration (SSC) Conversion Protocol: Technical Report

Report no. 22/35

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July 2022

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Information should be cited as:

Cartwright, P.J., Iles, J.A., Mattone, C., O'Callaghan, M., Waltham, N, 2022, 'Turbidity (NTU) to Suspended Sediment Concentration (SSC) Conversion Protocol', Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Report 22/35, James Cook University Press, Townsville, 46pp.

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

Executive Summary

The Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) at James Cook University (JCU) have partnered with North Queensland Bulk Ports (NQBP) to undertake long-term environmental monitoring and research programs in the Ports of Mackay, Hay Point and Weipa. TropWATER has also been commissioned to assist the 'Healthy Rivers to Reef Partnership' to collect ambient marine water quality data for the southern Mackay region as part of the Mackay-Whitsunday-Isaac regional report card that is released each year. As part of these agreements, a water quality monitoring program has been implemented that includes a suite of water quality parameters measured by both in-situ sampling (approx. every 6-8 weeks) and by continual logger deployments. One of the water quality parameters of particular interest is turbidity, due to its known association with dredging/maritime operations and the potential for suspended sediments to impact sensitive benthic habitats.

Suspended sediment concentration (SSC) may be measured *in situ* by collecting water samples and measuring the concentration of particulate matter in the water sample. In contrast, optical-based turbidity loggers allow long-term (6-8 week) deployments, providing a much higher resolution of data and more cost-effective monitoring. Water quality monitoring using turbidity loggers is often reported in Nephelometric Turbidity Units (NTU), a measure of the degree to which light is scattered by particulate matter suspended in the water column. It is usual for NTU sensors to be calibrated to provide estimates of SSC by determining the relationship between the two measurements.

Prior to September 2021, the NTU to SSC conversion had been undertaken by the Marine Geophysics Lab (MGL) at JCU who also supplied their 'in-house manufactured' loggers to the monitoring program. In September 2021, the TropWATER–NQBP partnership purchased new turbidity loggers, as well as multispectral light loggers, that will greatly enhance both the water quality monitoring and the research outcomes of the agreement. TropWATER is committed to providing best-practice quality assurance and control procedures (QA/QC) to all water quality monitoring practices and the purpose of this document is to report on the updated procedures implemented to derive the values for converting turbidity logger NTU to suspended sediment concentration, in SSC mg/L.

This report outlines the methods and results of a laboratory-based protocol for finding the site-specific conversion factor for NTU to SSC at 11 water quality monitoring locations

across North Queensland. Going forward, the NTU/SSC conversion values reported in this document will be monitored *in-situ* during routine field excursions. Further, in line with best practice recommendations, laboratory calibration will be repeated inter-annually or following any large disturbance events and the reported conversion factors updated accordingly.

Contents

Glossary of Terms

QA/QC	Quality Control and Assurance
SSC	Suspended Sediment Concentration
NQBP	North Queensland Bulk Ports
NTU	Nephelometric Turbidity Units
CF	Conversion Factor
PSD	Particle Size Distribution
TropWATER	Centre for Tropical Water and Aquatic Ecosystem Research
MGL	Marine Geophysics Laboratory
JCU	James Cook University

1. Introduction

Routine dredging is required for maritime safety around coastal ports, but this can result in turbid sediment plumes that require monitoring to ensure environmental standards are upheld. Turbidity is one of the most important water quality indicators due to its light-limiting effect in the water column that can impact photosynthesising benthic habitats such as corals and seagrasses (Gattuso et al., 2006). Turbidity can be measured in various ways including (from most basic to most complex) the Secchi-disk method, the gravimetric method (in-situ water sampling followed by laboratory filtering), optical based in-situ loggers and remote sensing satellites. There are advantages and disadvantages to each of these methods and monitoring programs often utilize a combination of them to ensure both fine scale accuracy and large-scale coverage. For example, the gravimetric method will result in retrieval of the actual suspended sediment concentration (SSC) in the sample of water taken however, the collection of data is costly and labour intensive. In contrast, turbidity loggers can be deployed *in-situ* to measure turbidity in frequent bursts every few minutes for weeks at a time, but the measurement units are in Nephelometric Turbidity Units (NTU) which are an optical measurement, not a direct measurement of SSC. Regulatory agencies often require turbidity to be reported as mg/L of SSC and therefore combining these methods to ensure adequate data coverage requires a conversion factor from NTU to SSC.

An understanding of the relationship between measured NTU and SSC may be determined by a regression analysis of coincident measurements of both parameters collected over a range of turbidity concentrations. However, for the case of dredge monitoring, the expected turbidity during dredge operations typically will far exceed the turbidity levels that occur naturally. One approach to estimate the full range of the SSC: NTU relationship is to collect sediment samples from the region of interest and resuspend the sediments in a controlled environment (laboratory tank). A turbidity sensor can be used to measure NTU while particulate concentration is increased, and water samples are collected to determine SSC concentration.

When undertaking the calibration of SSC measurements and optical turbidity sensors, it is important to consider the water column optical properties that will differ according to the size, shape, refractive index and absorption coefficient of the suspended sediments. The relationship between the scattered light intensity (the NTU) and the SSC is not constant between sediment types and is observed to vary significantly across different locations and as local conditions such as wind and wave energy drive sediment movements and change particle size distributions of suspended sediment.

A particle size distribution (PSD) analysis can provide valuable insight into understanding how sediment type is likely to affect turbidity in a region. For example, locations where sediments are dominated by fine silt/clay or fine sand particles will be more susceptible to turbidity during disturbance events such as storms (or dredging) than locations that are dominated by medium and coarse sand and coral particles (Bright et al., 2020). Even small changes in the contribution of the silt/clay size fractions to PSD in a region are significant to the NTU/SSC relationship (Landers & Sturm, 2013). For these reasons, robust calibration of NTU and SSC requires an analysis to be performed separately for each monitoring location and periodically reassessed/updated.

Monitoring Locations

Abbot Point: In November 2017, North Queensland Bulk Ports implemented an ambient marine water quality monitoring program surrounding the Port of Abbot Point (Figure 1). The Port of Abbot Point has three established logger sites (Euri Creek, Camp Island and Holbourne Island) for turbidity monitoring whose locations align with key sensitive receptor habitats (e.g. corals or seagrass), along with key features in the study region (e.g., river flow points).

Port of Mackay and Hay Point: TropWATER commenced an ambient marine water quality monitoring program around the Ports of Mackay and Hay Point in July 2014 (Figure 1). There are currently five water quality sites monitored in the region, four or which have loggers. Sites extend approximately 60km along the Mackay coastline, from Slade Islet and Round Top Island in the north to Victor Island and Freshwater Point in the south, aligning with key sensitive receptor habitats (e.g. corals or seagrass).

Weipa: The Port of Weipa is situated on the western side of Cape York Peninsula in northern Queensland (Figure 1). It is located within the township of Weipa, where the Embley, Mission and Pine River’s converge and discharge into the Gulf of Carpentaria. There are currently three water quality monitoring sites centred around port operations.

Southern Mackay: Three water quality monitoring sites were established in September 2017 at Aquila Island, Fanning Shoal, and Morning Cay. Ambient water quality monitoring was conducted at all three sites approximately every 6 weeks, while a water quality logger is deployed to collect high frequency data over at Aquila Island (MKY_CAM1) (Figure 1).

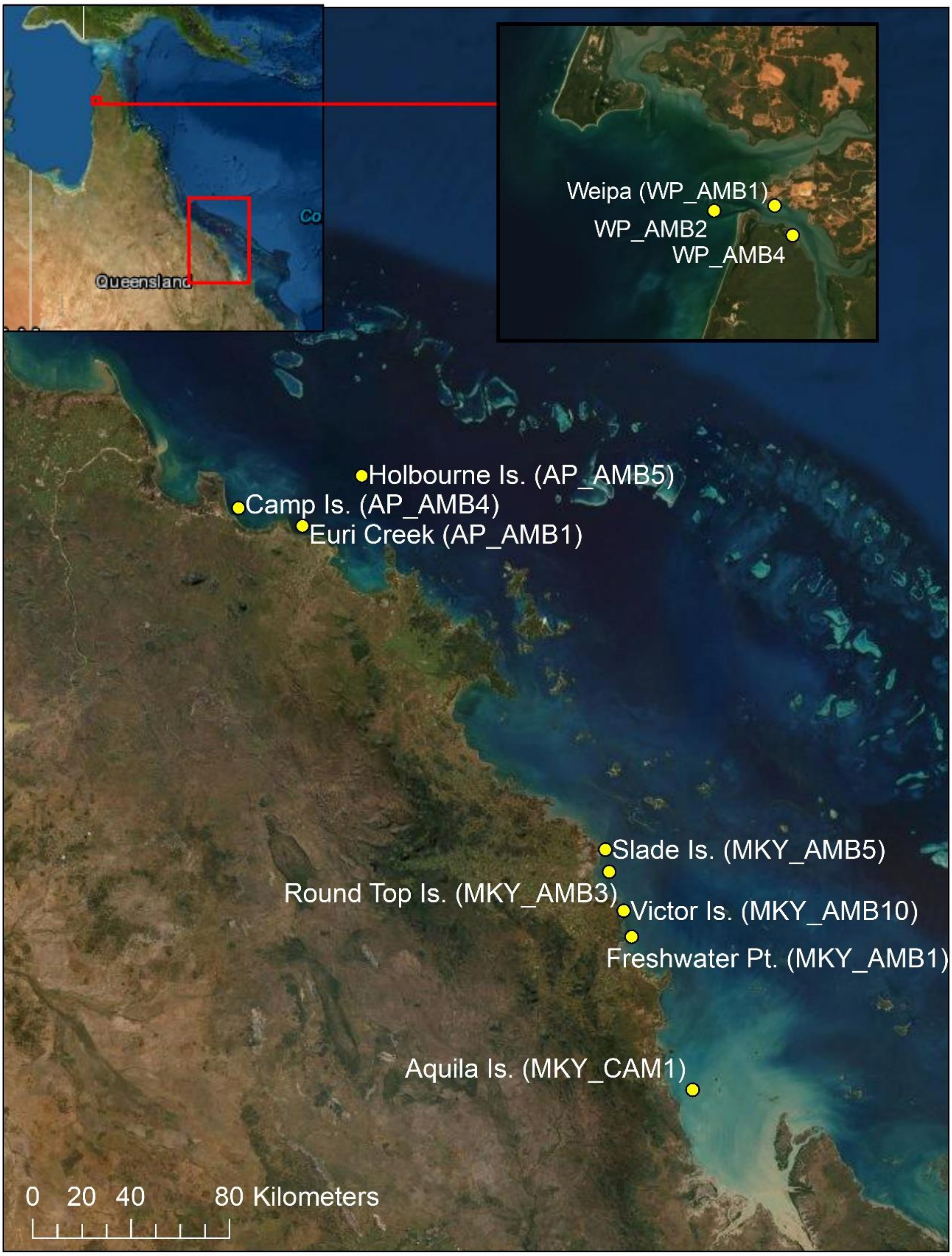


Figure 1: Water quality monitoring locations where sediments were collected for turbidity (NTU) to suspended sediment concentration (SSC mg/L) conversion analyses.

2. Materials and Methods

2.1 Sediment Samples

Samples of substrate sediments were collected from 11 locations between February and April 2022, where NTU loggers are deployed as part of the TropWATER-NQBP water quality monitoring partnership and the Health Rivers to Reef partnership (Figure 1; Table 1).

Table 1: Water quality monitoring locations where sediment samples were collected for determining the relationship between turbidity (NTU) and suspended sediment concentration (SSC mg/L).

ID	Site Description	Latitude	Longitude	Experiment Date
AP_AMB1	Euri Creek, Bowen	-19.9047	148.1418	9/06/2022
AP_AMB4	Camp Island, Bowen	-19.8417	147.9058	9/06/2022
AP_AMB5	Holbourne Is., Bowen	-19.7358	148.3593	9/06/2022
MKY_AMB1	Freshwater Pt., Mackay	-21.42	149.34	9/06/2022
MKY_AMB3B	Round Top Is., Mackay	-21.17	149.26	9/06/2022
MKY_AMB5	Slade Is. Mackay	-21.09	149.24	9/06/2022
MKY_AMB10	Victor Is., Mackay	-21.32	149.32	9/06/2022
MKY_CAM1	Aquila Island, Mackay	-21.974387	149.569387	10/06/2022
WP_AMB1	Weipa	-12.668283	141.846133	15/06/2022
WP_AMB2	Weipa	-12.673778	141.777081	15/06/2022
WP_AMB4	Weipa	-12.701431	141.8667	15/06/2022

2.1.1 Particle Size Distribution (PSD)

A small subsample of all sediments was removed for laser diffraction particle size analysis using a Mastersizer 3000LV, to give the particle size distribution (PSD) for each location. Samples were homogenised by inversion before sub-sampling and hydrogen peroxide digest undertaken to remove organic matter. Samples were passed through 2 mm sieve and greater than 2 mm fraction was determined as a percentage of initial dry weight. The sample was mechanically and chemically dispersed through shaking in a water softener solution (Calgon™), and the digested, dispersed sample homogenised in a baffled beaker with an overhead stirrer. Aliquots were pipetted to the dispersion unit of Calgon. Pump speed was set to 3000 rpm and 20 sec measurements were taken. The average results were reported from at least 3 measurements and laser diffraction data presented as a percent spherical equivalent volume.

2.1.2 Tank Experiment

Each independent sample was mixed with filtered seawater to form a slurry. Each slurry was agitated by hand prior to extraction of small subsamples that were added in increments to a 100 L black-lined tank filled with filtered seawater, that contained a submersible pump to ensure continual water movement. Each addition of sediment was designed to incrementally reach target concentrations of (approximately) 0.05, 0.3, 1.2, 3, 11, 35, 100, 310, and 420 NTU's.

2.2 NTU sensor

An NTU Sensor, the IMO-NTU (Slivkoff & Klonowski, 2018), was suspended in a frame at a downward-facing 45° angle in the tank. The NTU instrument was run continuously, and data logged at 5 Hz. After each addition of sediment sample the real-time readout of NTU was monitored to ensure the readings were stable, before a concurrent water sample was taken. Figure 2 shows an example of the NTU data series that was logged for each sediment sample.

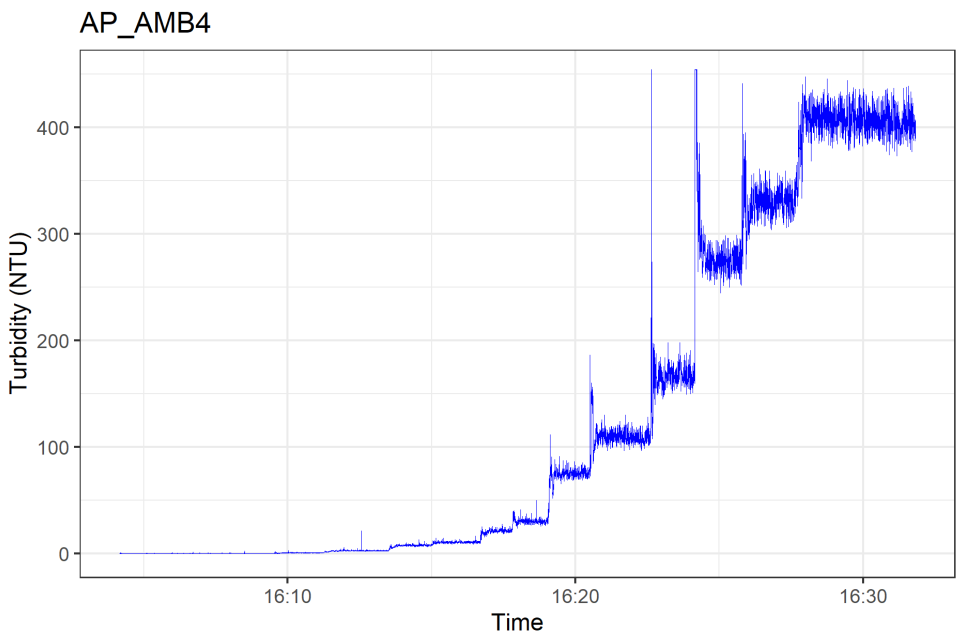


Figure 2: Time series of NTU logger readings as sediments were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC). A SSC sample was collected at each stable 'step'.

2.3 Suspended Sediment Concentration water samples

At each stable NTU concentration, water samples were collected adjacent to the sensor in one litre bottles and assessed gravimetrically to determine the SSC concentration. The water samples were filtered with the assistance of a low-pressure vacuum pump, through 0.7 µm Whatman GF/F glass-fibre filters that were pre-prepared by drying for 24 hours at 60 °C. Post-filtering, the filters were flushed with deionized water to remove any salt, then dried and weighed. Suspended Sediment Concentration (SSC) was calculated as the dry weight of suspended matter per volume of water (mg/L).

2.4 Data Analysis

The NTU logger data were screened manually in Microsoft Excel to capture the stabilised NTU output at each concentration of suspended sediment and to remove any outliers. The mean and standard error NTU were calculated from between 200 – 300 readings (across ~ one minute) for each concentration. Log transformation of data was tested due to positive skewness in the NTU and SSC, however, due to the strong linear relationship between points and a significantly higher root mean square error (RMSE) with log transformation, raw values were instead utilised. Regression analyses between mean NTU and SSC were performed in RStudio (RStudio.Team, 2015).

3. Results

Particle size distribution (PSD) varied across the 12 monitoring locations with some sites dominated by larger size fractions (e.g., Round Top Island, Slade Island), some dominated by small size fractions (e.g., Camp Island, Weipa WP_AMB4) and others showing a bi-modal distribution (e.g., Freshwater Point, Euri Creek; Figure 3, also see full PSD results in Appendix A).

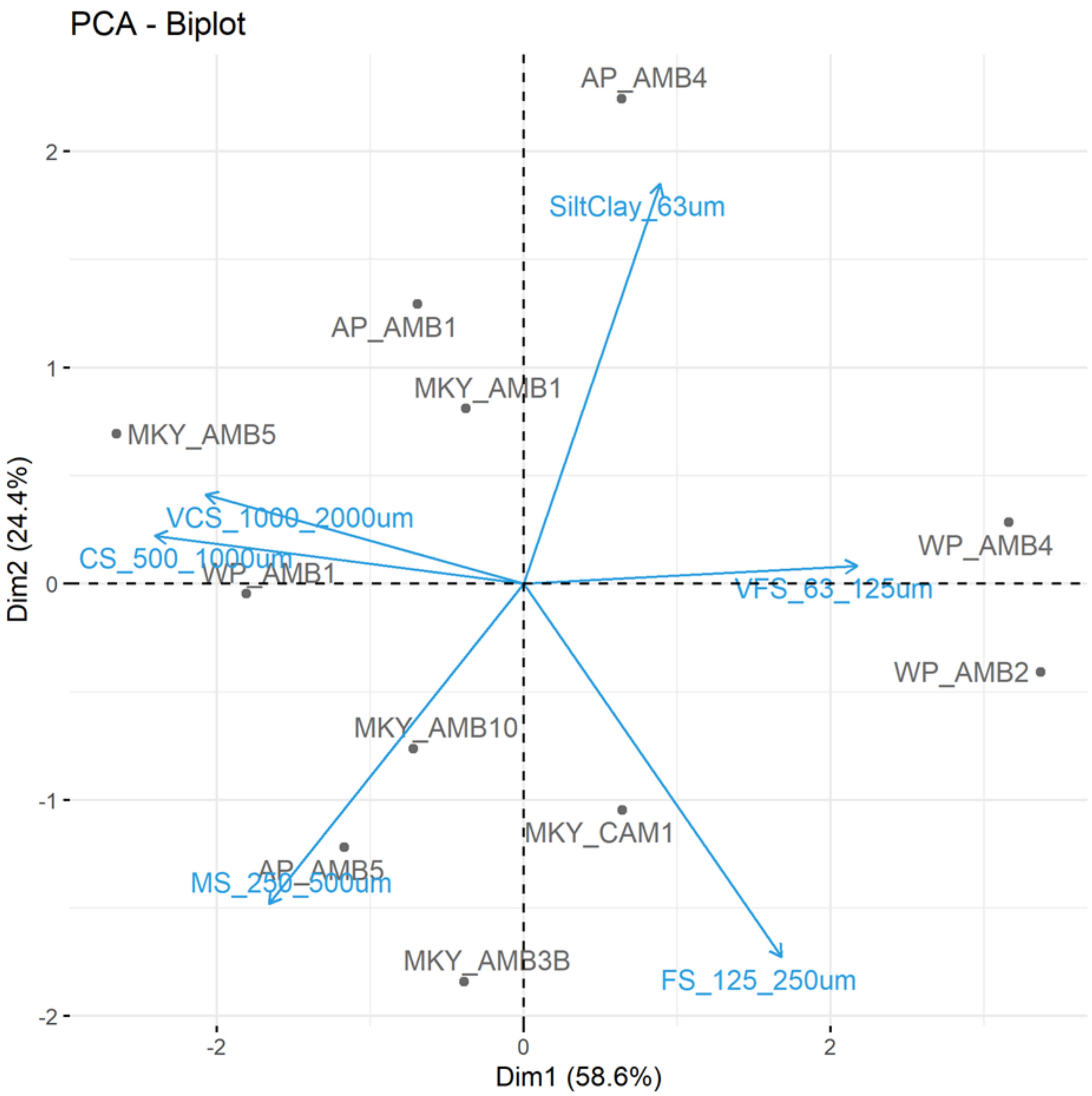


Figure 3: Principal components analysis biplot showing particle size distribution associated with 12 water quality monitoring sites in North Queensland. Vector overlay shows the particle sizes associated with each location; VCS – very coarse sand, CS – coarse sand, MS – medium sand, FS – fine sand, VFS – very fine sand, and silt/clay.

There was a strong linear relationship between turbidity (NTU) and suspended sediment concentration (SSC mg/L) for all sediment samples, with *r*-squared values ranging from 0.988 – 0.999 (Table 2; Figure 4; full regression tables in Appendix C).

NTU to SSC conversion factors varied between 1.59 and 2.5 across the different locations where water quality is monitored, with some sites in close proximity to each other found to have very similar values (e.g., Freshwater Point and Victor Island, Table 2).

Table 2: Values for converting turbidity (NTU) to suspended sediment concentraion (SSC) in mg/L at 11 sites monitored for water quality by TropWATER.

ID	Site Description	Conversion Factor	R^2	RMSE	Applicable range (NTU)
AP_AMB1	Euri Creek	1.90	0.998	8.02	0 - 400
AP_AMB4	Camp Island	2.00	0.999	7.76	0 - 400
AP_AMB5	Holbourne Island	1.60	0.992	2.32	0 - 50
MKY_AMB1	Freshwater Point	1.90	0.999	4.74	0 - 400
MKY_AMB3B	Round Top Island	1.68	0.999	1.66	0 - 100
MKY_AMB5	Slade Island	1.69	0.998	1.55	0 - 60
MKY_AMB10	Victor Island	1.90	0.999	2.39	0 - 400
MKY_CAM1	Aquila Island	1.59	0.998	3.41	0 - 400
WP_AMB1	WQ1	1.59	0.999	6.22	0 - 400
WP_AMB2	WQ2	2.50	0.988	6.65	0 - 70
WP_AMB4	WQ4	2.10	0.996	13.67	0 - 400

The following equation may be used to calculate suspended sediment concentration from logger data acquired from IMO-NTU turbidity loggers at each site:

$$SSC = Turb * Cf \pm e$$

Where:

SSC is the calculated suspended sediment concentration in mg L^{-1}

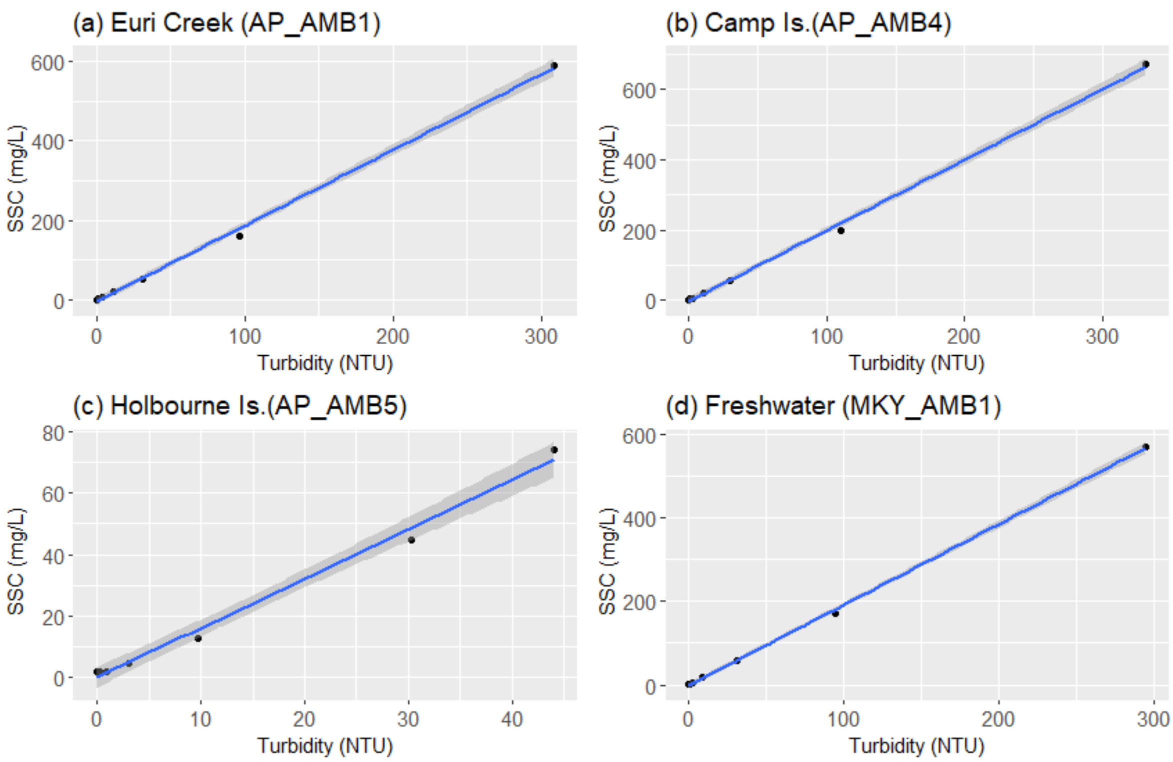
Turb is the measured turbidity value in NTU

Cf is the conversion factor

e is the root mean square error value

Sites that contained the highest levels of fine sediments (silts and clays below 125 μm) such as Weipa (WP_AMB2, WP_AMB4) and Camp Island (AP_AMB4) had the highest conversion factors (2.5, 2.1 and 2.0 respectively), closely followed by those with a bi-modal PSD, e.g., Euri Creek (AP_AMB1) and Freshwater Point (MKY_AMB1) both with conversion factors of 1.9.

Some sites (e.g., Holbourne Island, Round Top Island, and Slade Island) were unable to reach very high (> 100 NTU) turbidity due to being composed primarily of coarser coral reef sediments that settle quickly, and few fine sediments to create turbid water (Figs. 4c, e, f; also see Particle Size Distribution (PSD) results in Appendix A). The applicable range in turbidity values which the conversion factor should be applied is given in table 2 however, we would expect the linear relationship to continue at higher turbidity. For example, a linear relationship between turbidity and suspended sediment concentration and has been shown up to approximately 2500 NTU (Wang et al 2020).



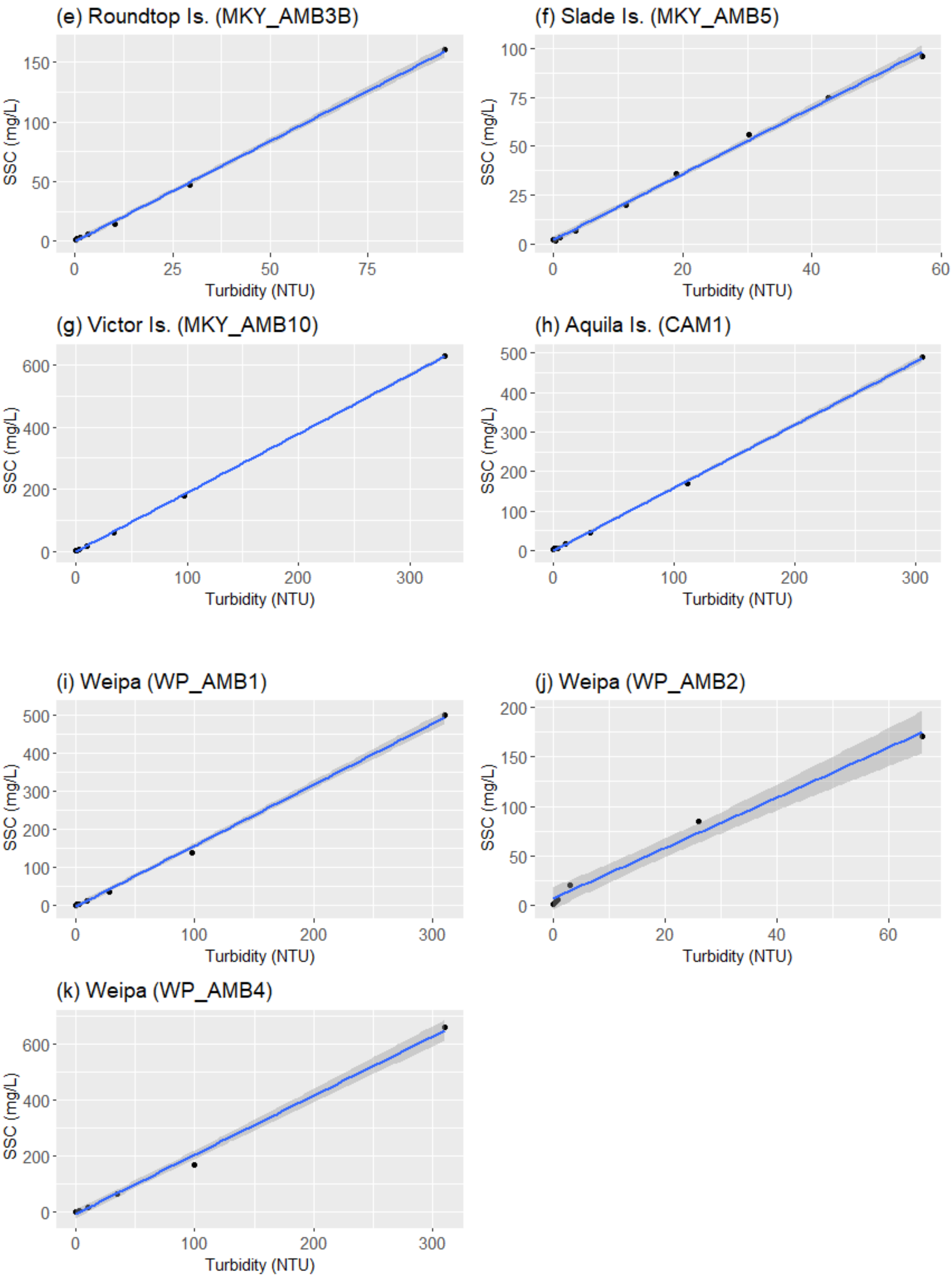


Figure 4: Linear regressions between turbidity (NTU) and suspended sediment concentration (SSC) at 11 water quality monitoring locations. Grey shading indicates standard error.

(Note: The historical NTU: SSC conversion values and supporting data that were provided by JCU's Marine Geophysics Lab prior to September 2021 are available in Appendix C).

4. Discussion

The NTU to SSC conversion factors presented in this report ranged from 1.59 – 2.5. These are similar values to those found by others, e.g., Fearns et al. (2018) where conversion factors ranged between 1.6 – 2.6. Sites with lower conversion factors tended to be those with proximity to coral reefs (such as the island sites), where sediments sizes are larger and less likely to stay in suspension. In contrast, sites with the higher conversion factors were those where sediments are higher in silt and clay sized particles that are easily suspended by water movement.

One aspect of laboratory tank experiments that has not been fully investigated is the level of mixing/stirring that is designed to replicate energy imparted in the field. The tank experiment is likely to represent a higher level of 'shear' than what would be experienced under average field conditions, leading to a different particle suspension and settling regime. This is due to laminar flow created under experimental tank conditions compared to more turbulent flow expected at the seafloor. Potentially, we can infer that these conversion values are toward the upper limit of what we would expect to occur from in-situ sampling. This was reported to be the case by Sun et al. (2019) who found a tank relationship of 2.2-2.8 compared to in-situ relationship of 1:1 based on water column samples of a dredge plume.

The close relationship between particle size distribution, turbidity and conversion factor emphasises the importance of collecting sediments that are fully representative of each site. The loss of fine sediments from a sample during collection is common, particularly when using a van Greer grab, as the water lost from the grab as it is pulled into the vessel, is often where these fines are located. Best practice is to collect sediment samples on SCUBA where loss of fines can be minimized.

Sources of variability should be noted that may affect actual SSC when using SSC data derived from conversion factors. The conversion factors are based on discrete sediment sample from each site to attempt to control for inter-site variability. If the properties of the sediment at a given site changes, or 'new' sediment is transported to a site, the conversion factor may be less applicable. These changes may be short-term (i.e., storm, flood plume events) or longer-term (i.e., sediment movement). The amount of energy present in the system (i.e., wave energy, currents etc.) may also change the nature of the sediments in suspension (i.e., more energy = coarser sediments). For this reason, it is recommended that the calibration process conducted here is repeated interannually and after major disturbance events.

There were a couple of limitations to the analysis. Firstly, Weipa (WP_AMB2) had a lower *r*-squared (r^2 = 0.941) indicating a reduced linear relationship compared to other sites. There was an outlier removed at ~ 11 NTU as it was suspected that a heavy particle or incorrect weighing had biased the sample and it did not represent the linear relationship of turbidity and suspended sediments concentration. Removal of the outlier improved the model fit (r^2 = 0.988). This a priority site for further sediment collection and a repeat of the analysis is to be conducted.

Another limitation was the NTU sensor that did not stabilize above ~ 400 NTU. Datapoints above this level were therefore considered invalid (as they would no longer uphold the linear relationship of NTU as further sediments were added) and removed as outliers. Future analyses will take this limit into account when designing the target concentrations so that a higher level of NTU and SSC than what we have reported here (~300 NTU) can be calibrated without overshooting the NTU sensors capability. Regardless, it is expected that the linear relationship would continue to apply at higher turbidities than 400 NTU.

This technical report has shown that it is possible to calibrate NTU turbidity to suspended sediment concentration and that there is a linear relationship between the two measurements. It is recommended that the procedure is repeated periodically to ensure that any changes to sediment properties in a region are captured. It is also recommended that in-situ measurements of concurrent NTU and SSC are made on each future field excursion to keep a check on the conversion factor values and identify when updated calibration may be required.

5. References

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Appendix A

Mastersizer Analysis -Particle Size Distribution (PSD)

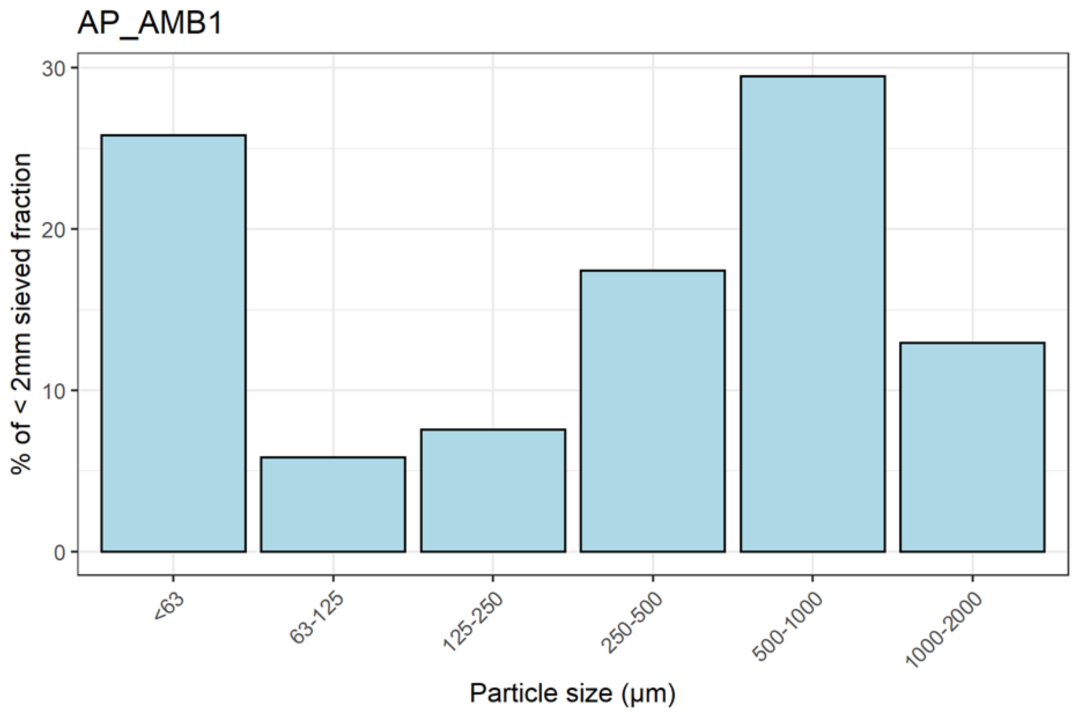

Figure A 1: Particle size distribution at Euri Creek showing a bi-modal distribution.

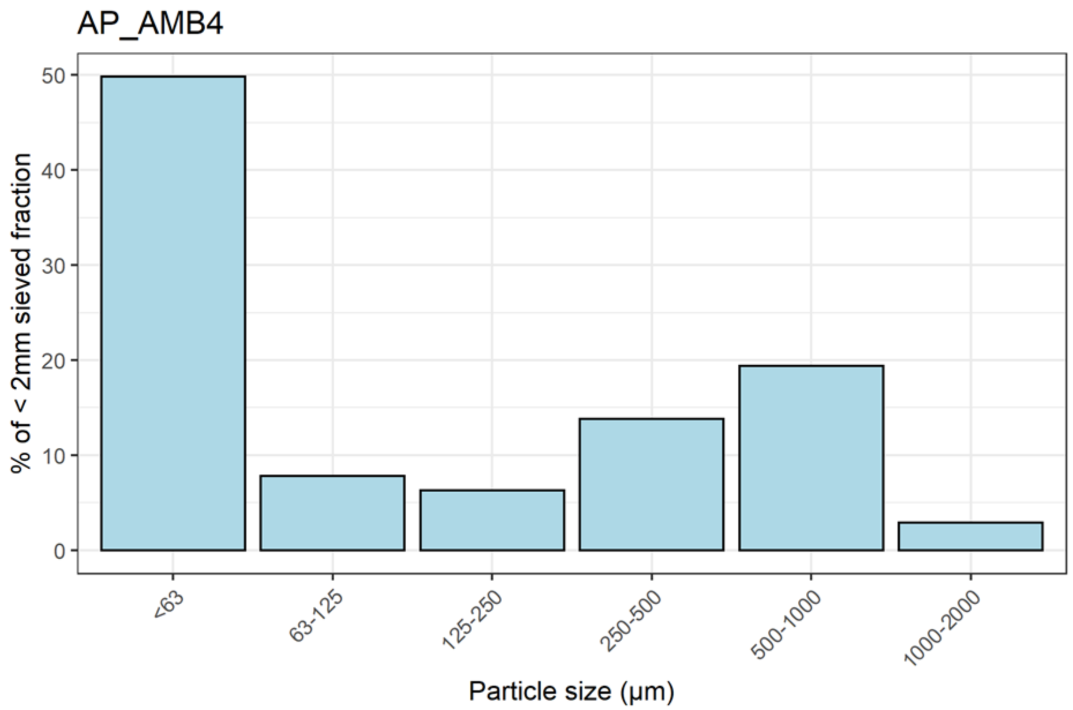

Figure A 2: Particle size distribution at Camp Island showing a dominance in silt/clay sediments.

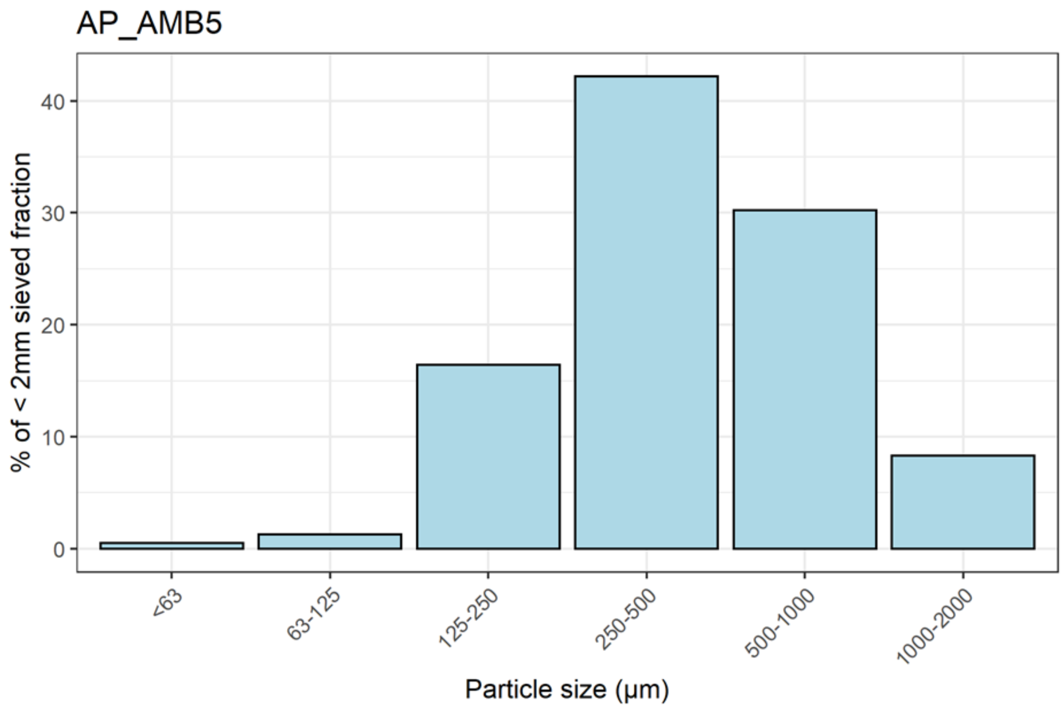

Figure A 3: Particle size distribution at Holbourne Island showing a dominance of medium to coarse sands.

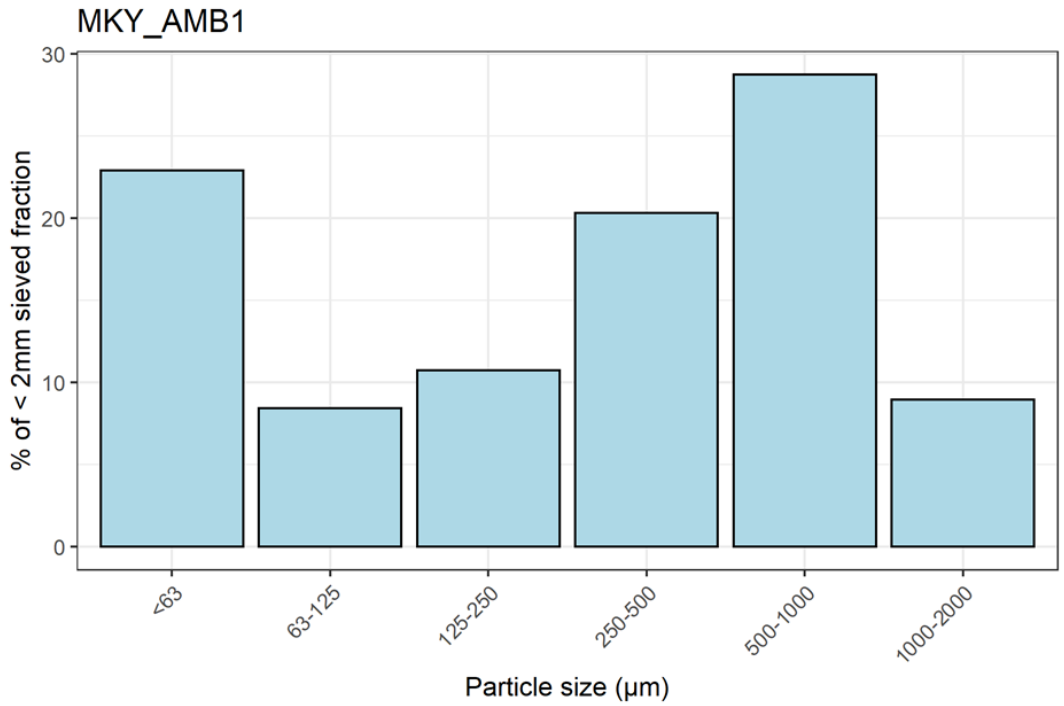

Figure A 4: Particle size distribution at Freshwater Point showing a bi-modal distribution.

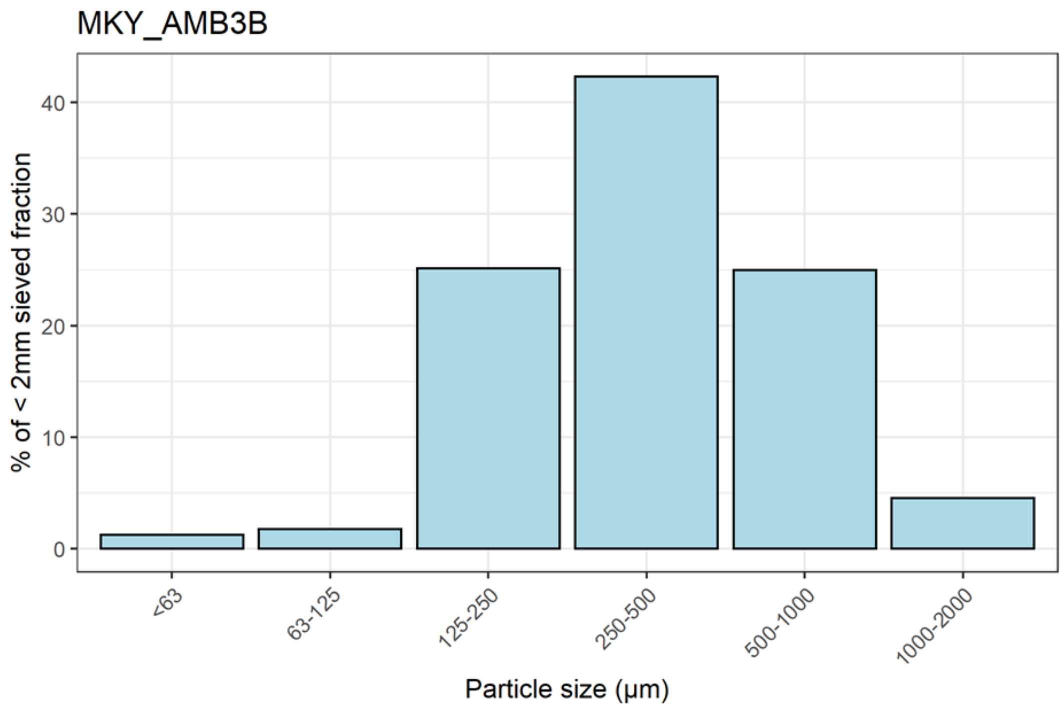

Figure A 5: Particle size distribution at Round Top Island showing a dominance of fine-medium-coarse sands.

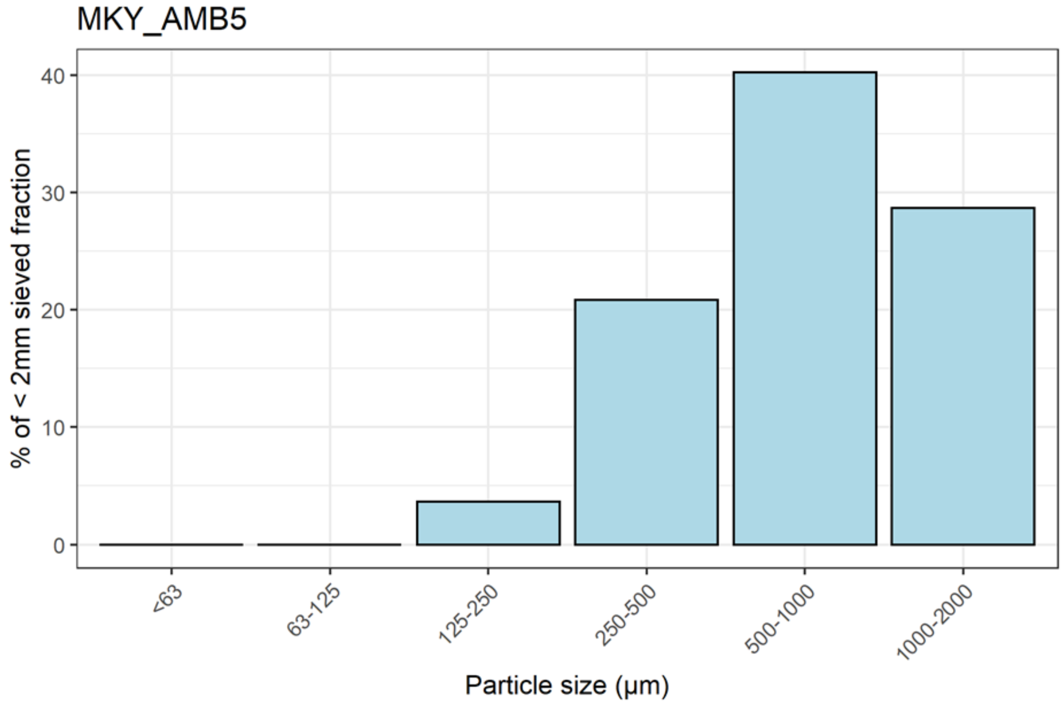

Figure A 6: Particle size distribution at Slade Island showing a dominance of coarse to very coarse sands.

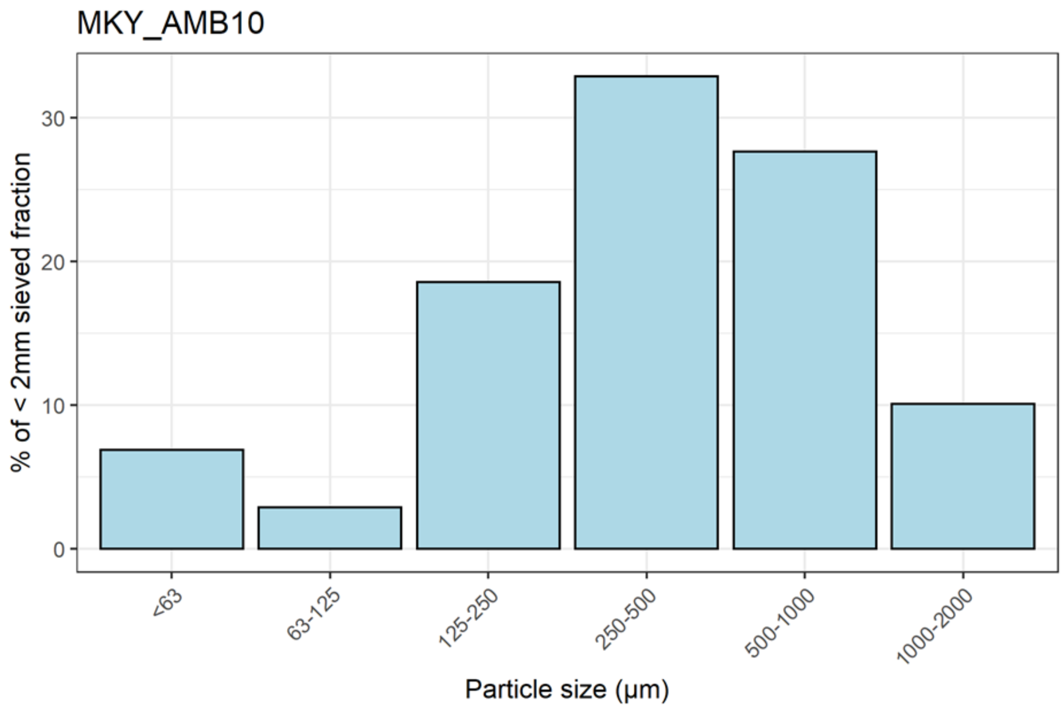

Figure A 7: Particle size distribution at Victor Island showing a dominance in medium to coarse sands.

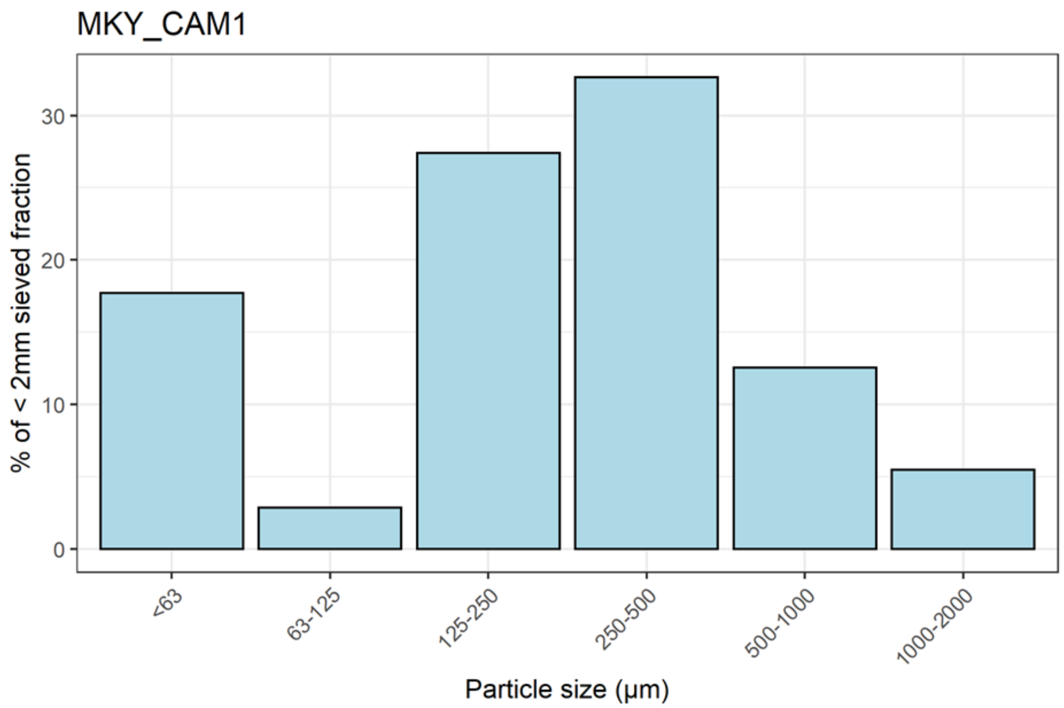

Figure A 8: Particle size distribution at Aquila Island showing a bi-modal distribution of sediments.

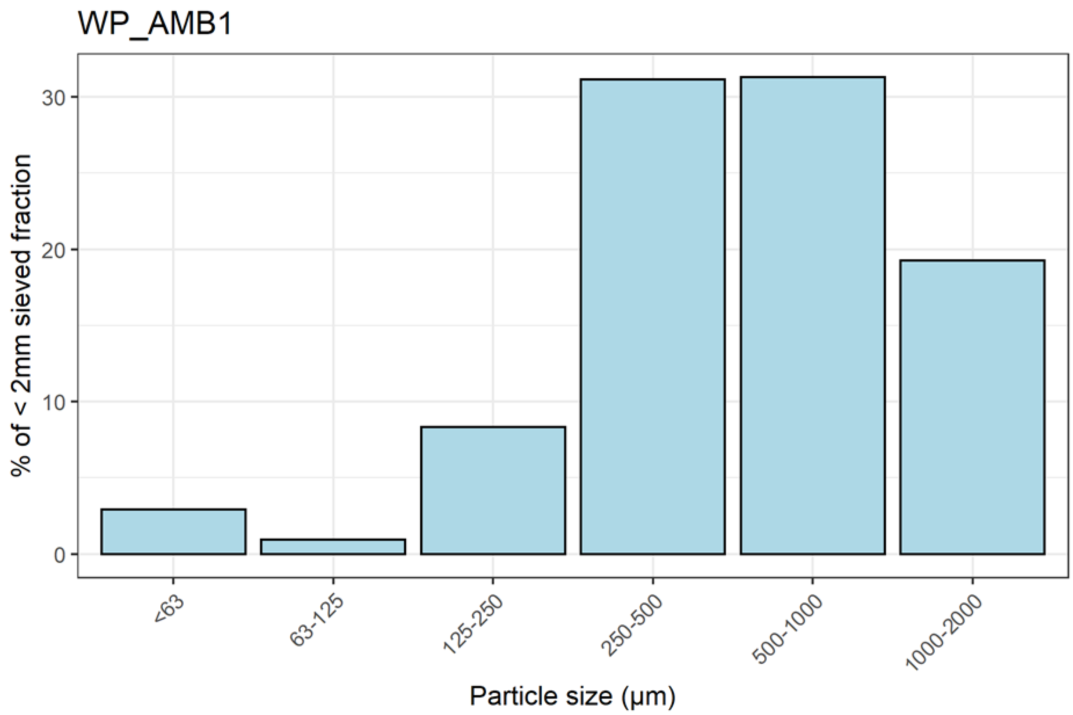

Figure A 9: Particle size distribution at Weipa (site 1) showing a dominance of medium to coarse sands.

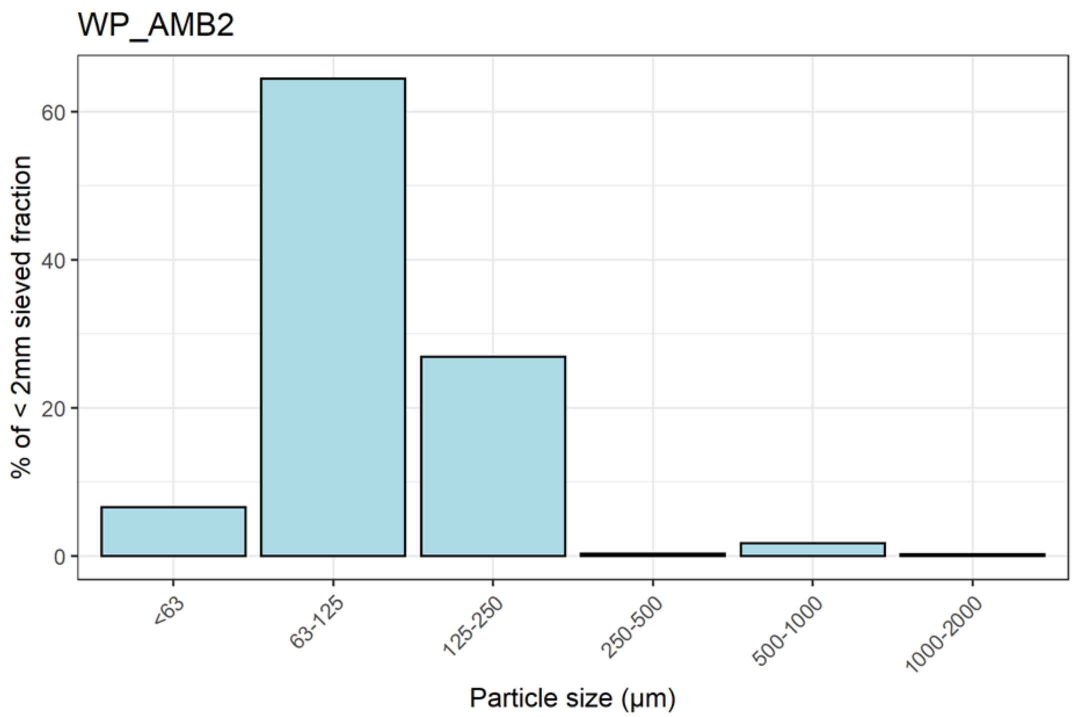

Figure A 10: Particle size distribution at Weipa (site 2) showing a dominance of very fine sands.

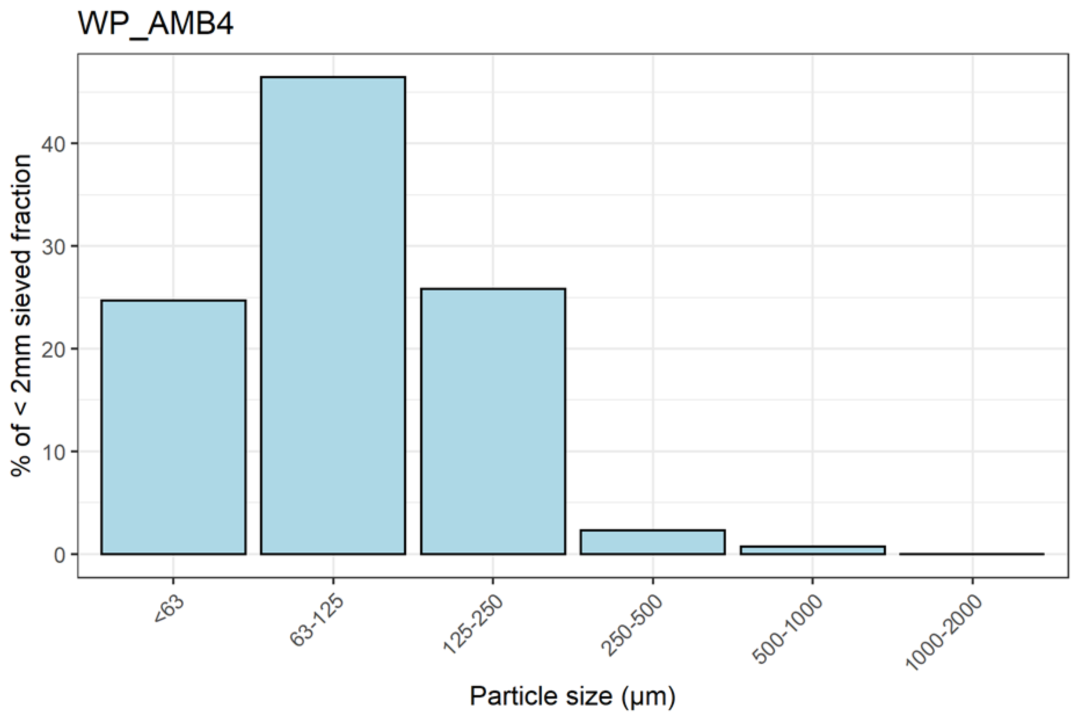

Figure A 11: Particle size distribution at Weipa (site 4) showing a dominance of small sediments in the silt/clay to very fine/fine sands

Appendix B

Raw NTU logger data

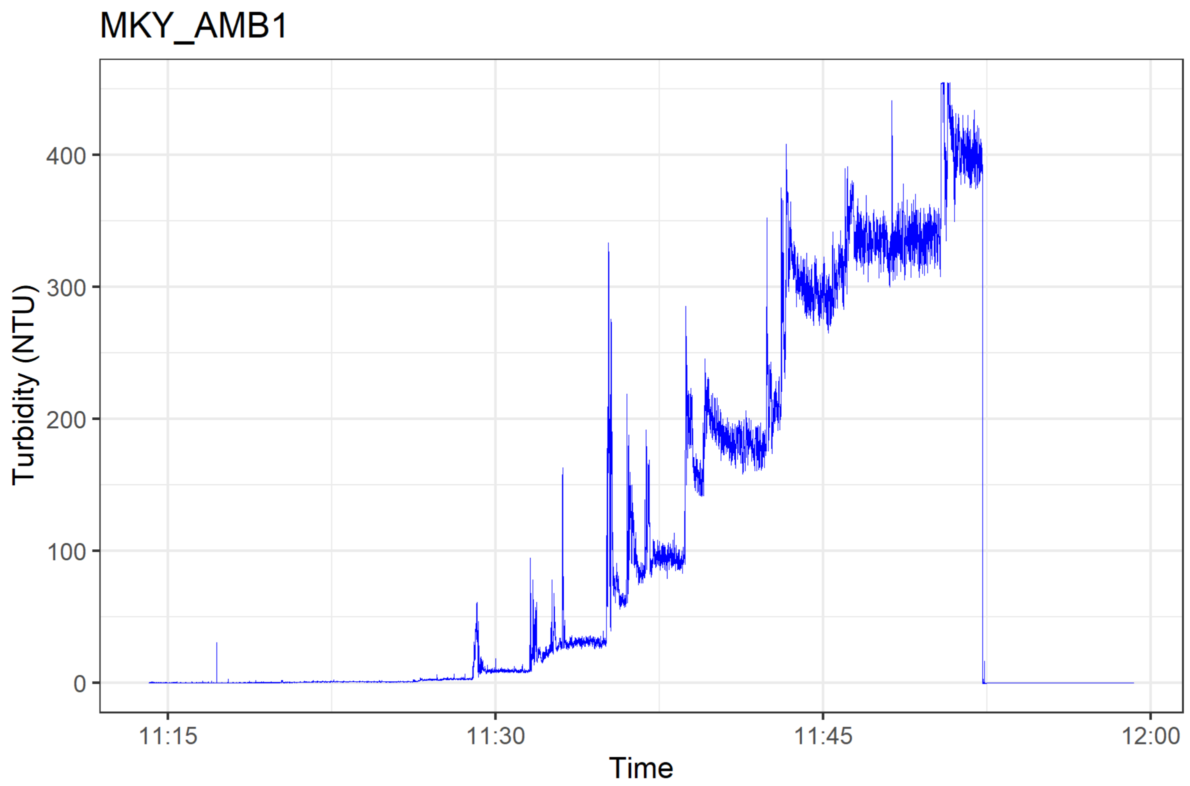

Figure B 1: Time series of NTU logger readings as sediments from Freshwater Point (MK_AMB1) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

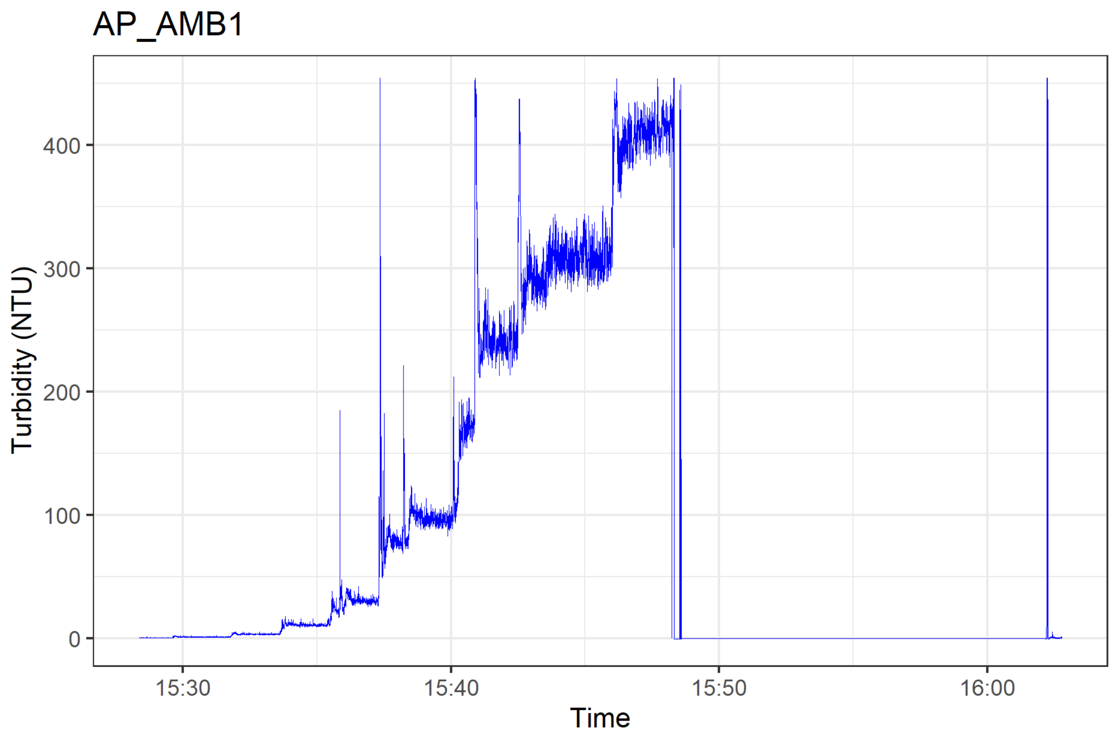

Figure B 2: Time series of NTU logger readings as sediments From Euri Creek (AP_AMB1) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

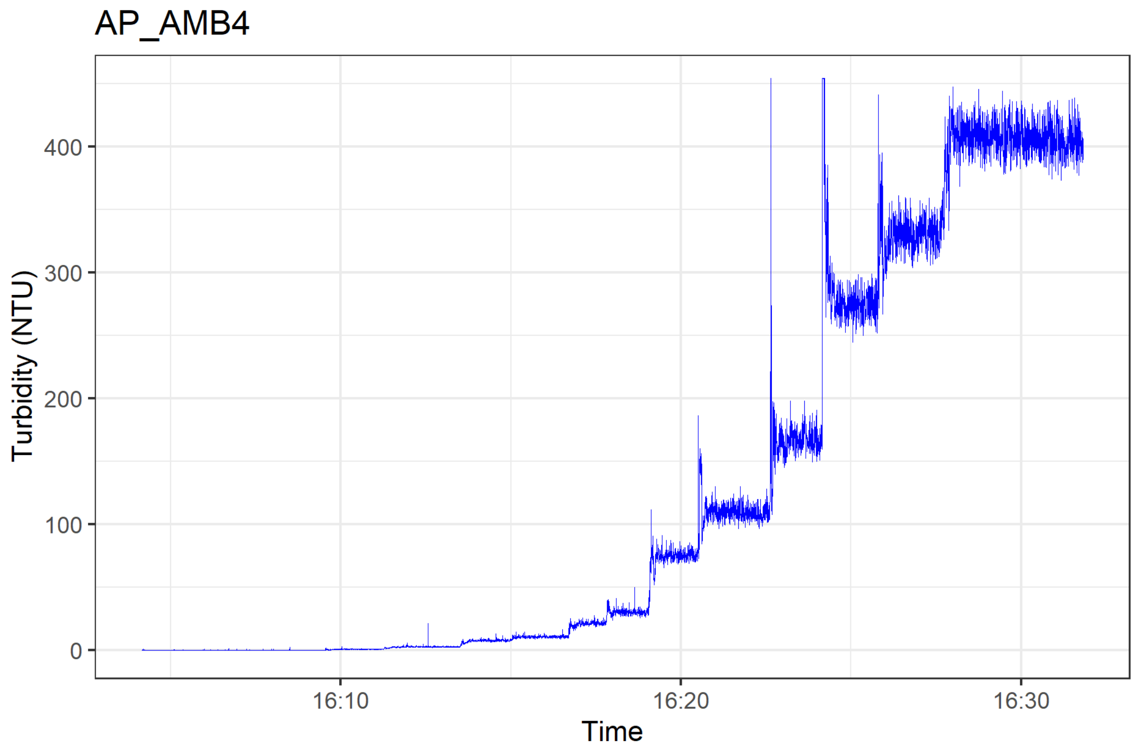

Figure B 3: Time series of NTU logger readings as sediments from Camp Island (AP_AMB4) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

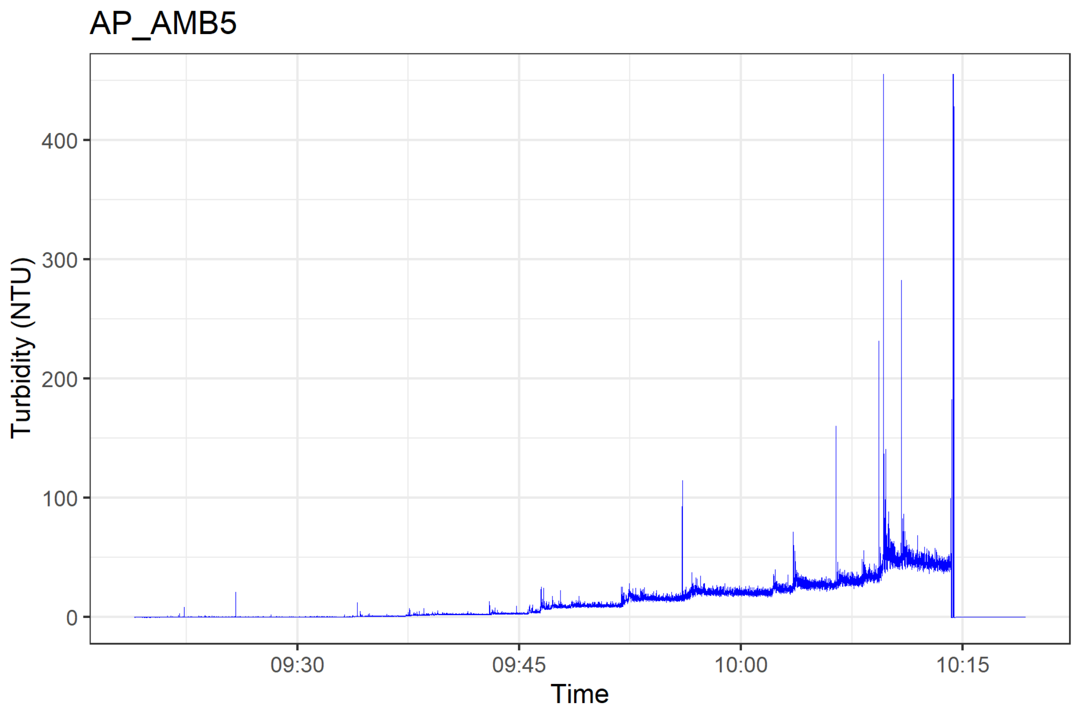

Figure B 4: Time series of NTU logger readings as sediments from Holbourne Island (AP_AMB5) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

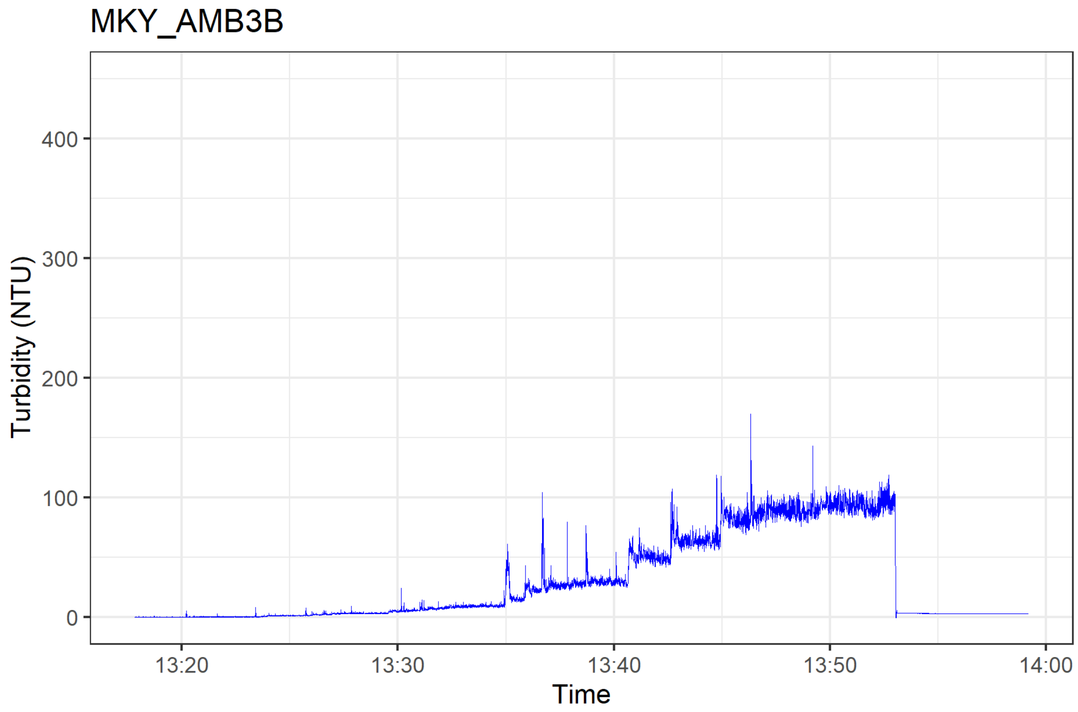

Figure B 5: Time series of NTU logger readings as sediments from Round Top Island (MKY_AMB3B) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

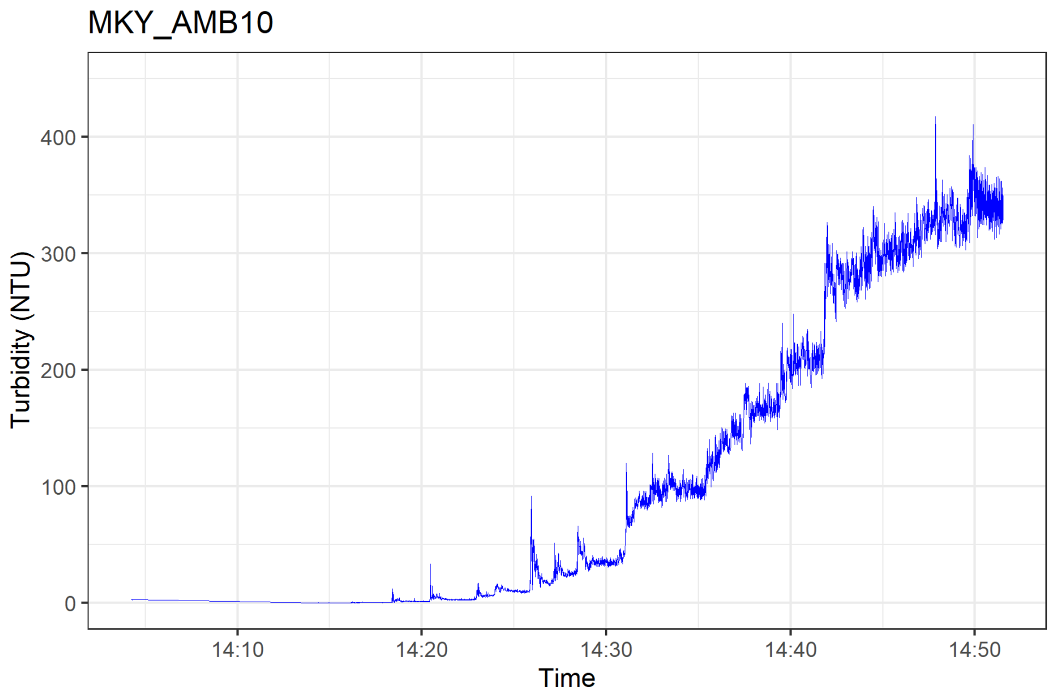

Figure B 6: Time series of NTU logger readings as sediments from Victor Island (MKY_AMB10) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

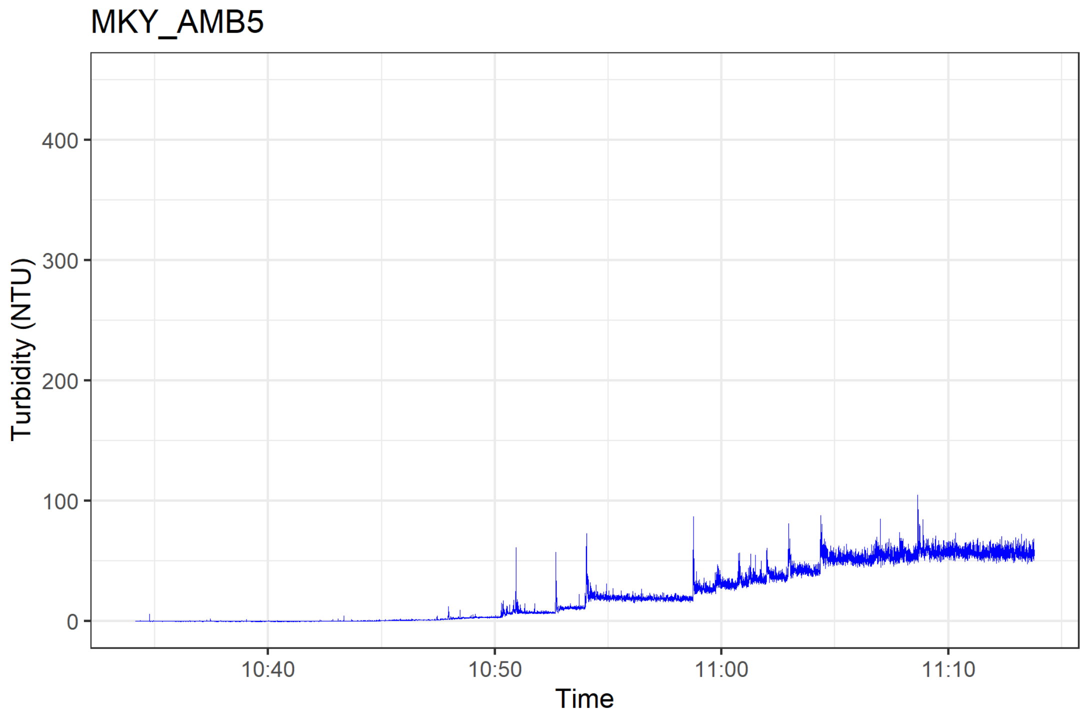

Figure B 7: Time series of NTU logger readings as sediments from Slade Island (MKY_AMB5) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

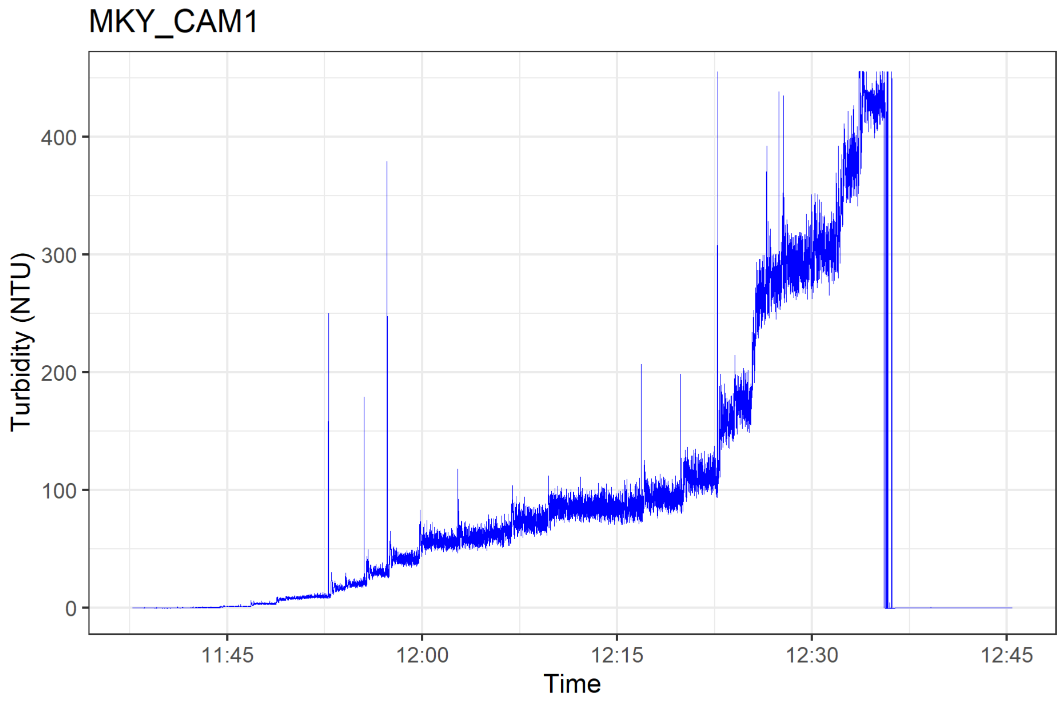

Figure B 8: Time series of NTU logger readings as sediments from Aquila Island (MKY_CAM1) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

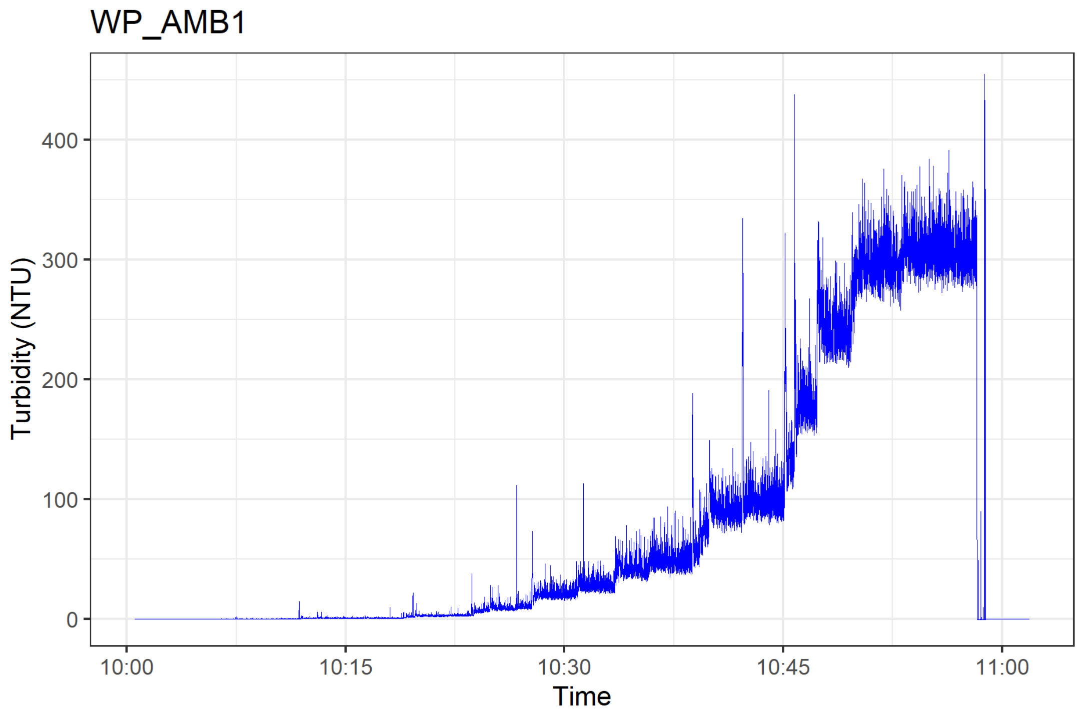

Figure B 9: Time series of NTU logger readings as sediments from Weipa (WP_AMB1) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

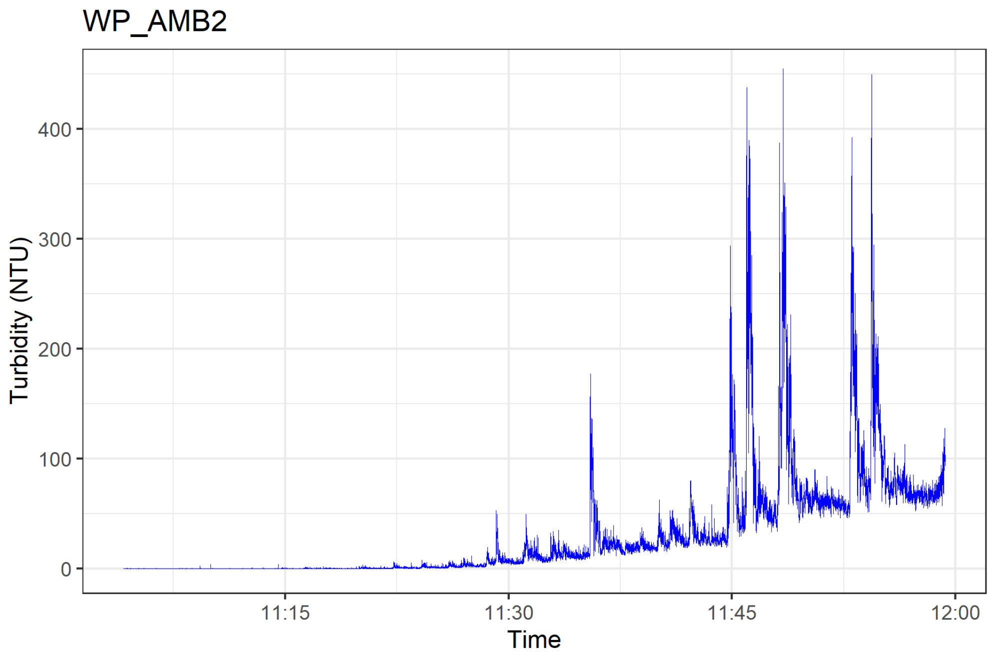

Figure B 10: Time series of NTU logger readings as sediments from Weipa (WP_AMB2) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

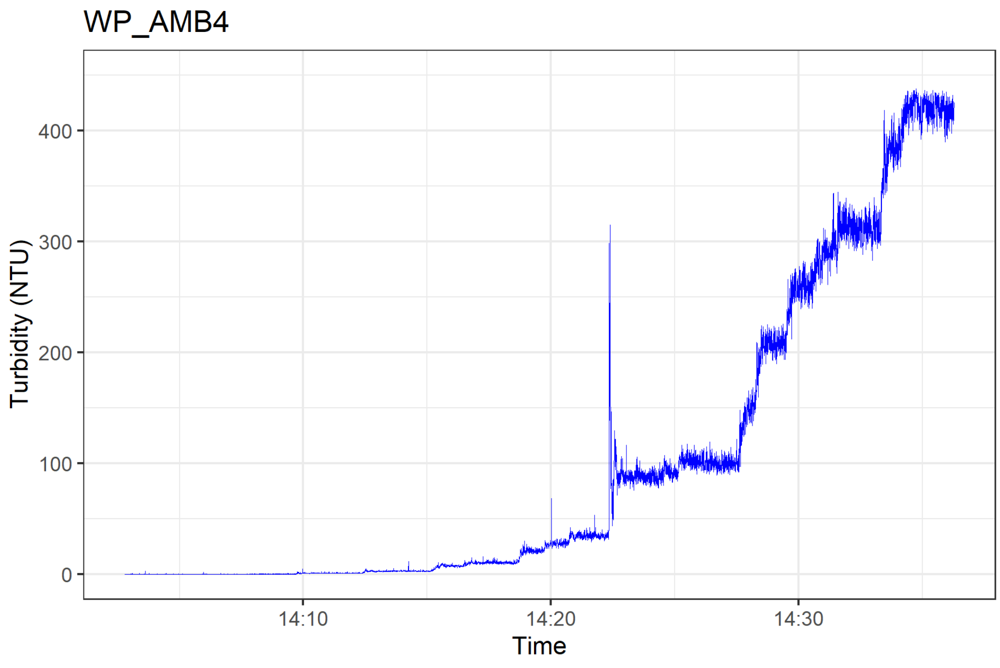

Figure B 11: Time series of NTU logger readings as sediments from Weipa (WP_AMB4) were added in increments for the purpose of calibrating NTU with Suspended Sediment Concentration (SSC).

Appendix C

Regression model results tables

Table C 1: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Euri Creek (AP_AMB1). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm (formula = SSC ~ NTU, data = AP_AMB1)					
Residuals:					
Min 1Q Median 3Q Max					
-20.0047 0.6268 3.4966 3.9975 6.4638					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-3.24078	3.76345	-0.861	0.422	
NTU	1.90049	0.03273	58.06	1.75E-09	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 9.262 on 6 degrees of freedom					
Multiple R-squared: 0.9982,	Adjusted R-squared: 0.9979				
F-statistic: 3371 on 1 and 6 DF, p-value: 1.754e-09					

Table C 2: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Camp Island (AP_AMB4). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = AP_AMB4)					
Residuals:					
1 2 3 4 5 6 7					
3.732 4.288 3.161 2.354 -1.314 -18.295 6.075					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-3.14097	4.07482	-0.771	0.476	
NTU	2.0136	0.03075	65.477	1.57E-08	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 9.178 on 5 degrees of freedom					
Multiple R-squared: 0.9988,	Adjusted R-squared: 0.9986				
F-statistic: 4287 on 1 and 5 DF, p-value: 1.573e-08					

Table C 3: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Holbourne Island (AP_AMB5). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = AP_AMB5)					
Residuals:					
1 2 3 4 5 6 7					
1.7392 1.3102 0.5202 -0.1978 -2.8174 -3.7732 3.2188					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	0.14098	1.31204	0.107	0.919	
NTU	1.60291	0.06371	25.158	1.85E-06	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 2.742 on 5 degrees of freedom					
Multiple R-squared: 0.9922,	Adjusted R-squared: 0.9906				
F-statistic: 632.9 on 1 and 5 DF, p-value: 1.852e-06					

Table C 4: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Freshwater (MK_AMB1). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = MK_AMB1)					
Residuals:					
2.0873 2.4898 1.5828 2.1921 -0.7076 -11.2313 3.5870					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-1.1492	2.4956	-0.46	0.664	
NTU	1.9247	0.0212	90.79	3.07E-09	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 5.61 on 5 degrees of freedom					
Multiple R-squared: 0.9994,	Adjusted R-squared: 0.9993				
F-statistic: 8242 on 1 and 5 DF, p-value: 3.073e-09					

Table C 5: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Roundtop Island (MK_AMB3). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = MK_AMB3)					
Residuals:					
1.0042 1.9170 0.5867 0.6108 -2.9970 -2.0338 0.9120					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-0.25623	0.87654	-0.292	0.782	
NTU	1.67996	0.02322	72.356	9.55E-09	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 1.967 on 5 degrees of freedom					
Multiple R-squared: 0.999,	Adjusted R-squared: 0.9989				
F-statistic: 5235 on 1 and 5 DF, p-value: 9.551e-09					

Table C 6: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Slade Island (MK_AMB5). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = MK_AMB5)					
Residuals:					
Min 1Q Median 3Q Max					
-2.5519 -1.0360 -0.5383 1.0041 2.7797					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	2.10002	0.80269	2.616	0.0346	*
NTU	1.6877	0.02987	56.494	1.43E-10	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 1.762 on 7 degrees of freedom					
Multiple R-squared: 0.9978,	Adjusted R-squared: 0.9975				
F-statistic: 3192 on 1 and 7 DF, p-value: 1.428e-10					

Table C 7: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Victor Island (MK_AMB10). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = MK_AMB10)					
Residuals:					
Min 1Q Median 3Q Max					
-4.531 -1.842 1.019 1.879 2.564					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-1.239683	1.119055	-1.108	0.31	
NTU	1.900074	0.009112	208.53	8.21E-13	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 2.764 on 6 degrees of freedom					
Multiple R-squared: 0.9999,	Adjusted R-squared: 0.9998				
F-statistic: 4.348e+04 on 1 and 6 DF, p-value: 8.206e-13					

Table C 8: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Aquila Island (MKY_CAM1). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = MKY_CAM1)					
Residuals:					
Min 1Q Median 3Q Max					
-11.498 -3.691 1.325 5.424 8.043					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-4.666	2.279	-2.048	0.0631	.
NTU	1.59	0.023	69.131	<2e-16	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 6.516 on 12 degrees of freedom					
Multiple R-squared: 0.9975,	Adjusted R-squared: 0.9973				
F-statistic: 4779 on 1 and 12 DF, p-value: < 2.2e-16					

Table C 9: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Weipa (WP_AMB1). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = WP_AMB1)					
Residuals:					
Min 1Q Median 3Q Max					
-14.311 -1.041 2.899 4.110 4.950					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-3.31806	2.90783	-1.141	0.297	
NTU	1.6058	0.02516	63.823	9.95E-10	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 7.181 on 6 degrees of freedom					
Multiple R-squared: 0.9985,	Adjusted R-squared: 0.9983				
F-statistic: 4073 on 1 and 6 DF, p-value: 9.948e-10					

Table C 10: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Weipa (WP_AMB2). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = WP_AMB2)					
Residuals:					
1 2 3 4 5 6					
-5.484 -4.770 -3.027 6.324 11.828 -4.872					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	7.145	3.9931	1.789	0.148	
NTU	2.5387	0.1376	18.446	5.08E-05	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 8.149 on 4 degrees of freedom					
Multiple R-squared: 0.9884,	Adjusted R-squared: 0.9855				
F-statistic: 340.3 on 1 and 4 DF, p-value: 5.082e-05					

Table C 11: Linear model for suspended sediment concentration (SSC) and turbidity (NTU) at Weipa (WP_AMB4). Highlighted value is slope of line between the two variables, and therefore the conversion factor.

lm(formula = SSC ~ NTU, data = WP_AMB4)					
Residuals:					
Min 1Q Median 3Q Max					
-34.241 -0.590 5.750 7.176 11.357					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-6.29706	6.42955	-0.979	0.365	
NTU	2.11107	0.05545	38.072	2.19E-08	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Residual standard error: 15.79 on 6 degrees of freedom					
Multiple R-squared: 0.9959,	Adjusted R-squared: 0.9952				
F-statistic: 1449 on 1 and 6 DF, p-value: 2.193e-08					

Appendix D

Historical (prior to 2021) NTU: SSC conversions

This section shows the procedures and data used to convert turbidity to suspended sediment concentrations (NTU: SSC) as performed by the Marine Geophysics Lab (MGL) at James Cook University and applied to logger data prior to September 2021.

Sediment calibration

An instrument is placed in a large container (50 l) with black sides and the output is read on a computer attached to the logger. Seawater is used to fill the container. Sediment from one of the study sites is added to a small container of salt water and agitated. The water-sediment slurry is then added to the large container, which is stirred with a small, submerged pump. A water sample is taken and analysed for TSS using standard laboratory techniques in the ACTFR laboratory at JCU which is accredited for these measurements. Approximately 6 different concentrations of sediment are used for each site. TSS is then plotted against the NTU reading from the logger for each of the different sediment concentrations. A linear correlation between NTU and SSC is then calculated. The correlations typically have an r^2 value of equal to or greater than 0.9.

While the correlation between the instruments and the sediment samples is high, it should be noted that an *in-situ* correlation will be much lower, since the sediments in suspension at the site may not be constituted of particles of the same size as those in the sample. For example, the sediments in suspension could be from another location rather than from local resuspension, also the sediments at the site may change over time due to an influx of new sediment. These changes in sediments may cause a factor of two error in the calibration.

Results

Table D- 1: Previous conversion factors calibrated by the Marine Geophysics Lab at James Cook University and applied prior to September 2021.

Project	Region	Site_code	Site_name	m_value (CF)	Calibration Date
NQBP	Bowen	AP_AMB1	Euri Creek	1.319	29/03/2018
NQBP	Bowen	AP_AMB2	Spoil Grounds	1.735	29/03/2018
NQBP	Bowen	AP_AMB3	Elliot River	1.334	29/03/2018

NQBP	Bowen	AP_AMB4	Camp Island	1.577	29/03/2018
NQBP	Bowen	AP_AMB5	Holbourne Island	1.348	29/03/2018
NQBP	Mackay	MKY_AMB1	Freshwater Point	0.803	3/03/2015
NQBP	Mackay	MKY_AMB2	Hay Reef	1.243	3/03/2015
NQBP	Mackay	MKY_AMB3B	Round Top Island	1.315	19/04/2010
NQBP	Mackay	MKY_AMB5	Slade Island	1.197	2/03/2015
NQBP	Mackay	MKY_AMB6B	Dudgeon Point		
NQBP	Mackay	MKY_AMB8	Spoil Grounds	2.031	20/01/2016
NQBP	Mackay	MKY_AMB10	Victor Island	1.459	3/03/2015
NQBP	Mackay	MKY_AMB12	Keswick Island	1.488	31/07/2014
CAM	Mackay	MKY_CAM1	Aquila Island	1	30/01/2013
NQBP	Weipa	WP_AMB1	WQ1	1.295	23/05/2018
NQBP	Weipa	WP_AMB2	WQ2	1.337	23/05/2018
NQBP	Weipa	WP_AMB3	WQ3	1.314	23/05/2018
NQBP	Weipa	WP_AMB4	WQ4	1.77	23/05/2018

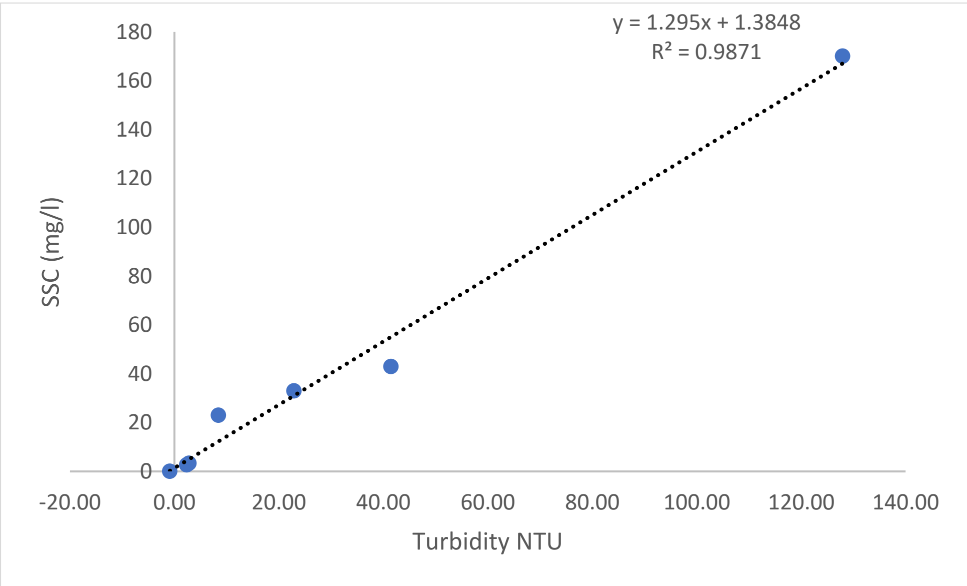

Figure D 1: Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Weipa (WQ1)

Date	17/05/2018	Tech ID	SIMON	Site Name	WQ1
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	9:48:00	-0.87	0.1		
Water bottle 2	10:07:00	2.35	2.7		
Water bottle 3	10:10:00	2.77	3.3		
Water bottle 4	10:14:00	8.42	23		
Water bottle 5	10:56:00	22.87	33		
Water bottle 6	10:35:00	41.46	43		
Water bottle 7	10:44:00	127.95	170		

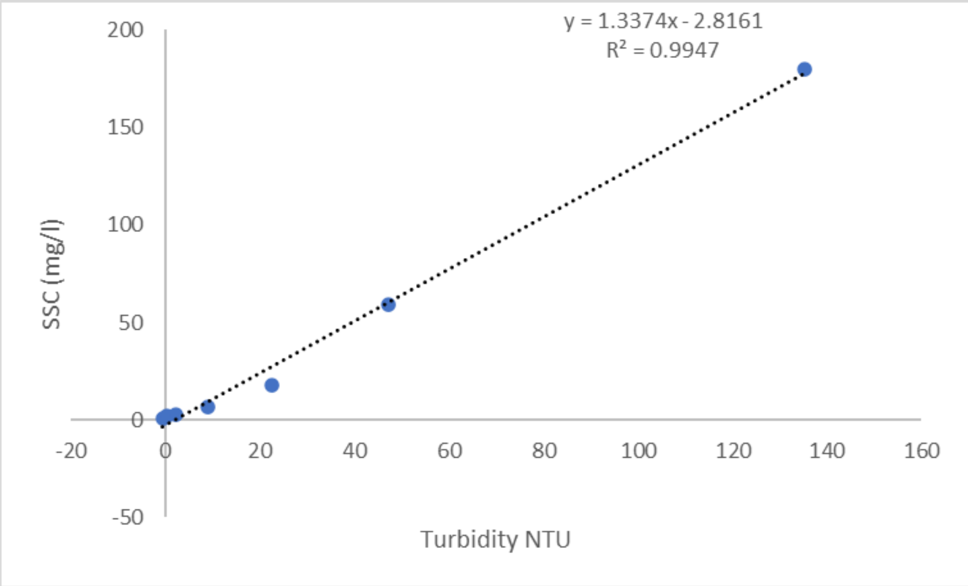

Figure D 2: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Weipa (WQ2)

Table D 1: Raw values for determining the relationship between NTU and SSC at Weipa (WQ2)

Date	17/05/2018	Tech ID	SIMON	Site Name	WQ2
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	11:16:00	-0.49	0.8		
Water bottle 2	11:19:00	0.39	1.9		
Water bottle 3	11:25:00	2.26	2.5		
Water bottle 4	11:31:00	8.97	6.8		
Water bottle 5	11:32:00	22.47	18		

Water bottle 6	11:36:00	47.14	59		
Water bottle 7	11:38:00	135.13	180		

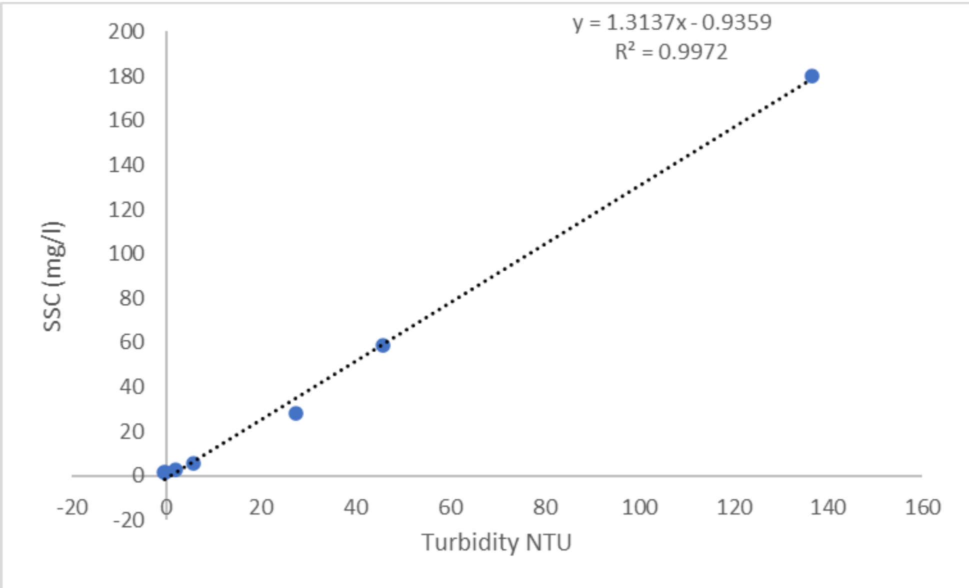

Figure D 3: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Weipa (WQ3)

Table D 2: Raw values for determining the relationship between NTU and SSC at Weipa (WQ3)

Date	17/05/2018	Tech ID	SIMON	Site Name	WQ3
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	11:50:00	-0.22	1.7		
Water bottle 2	11:52:00	-0.38	1.3		

Water bottle 3	11:55:00	2	3		
Water bottle 4	11:58:00	5.68	5.4		
Water bottle 5	12:01:00	27.44	28		
Water bottle 6	12:06:00	45.85	59		
Water bottle 7	12:09:00	136.53	180		

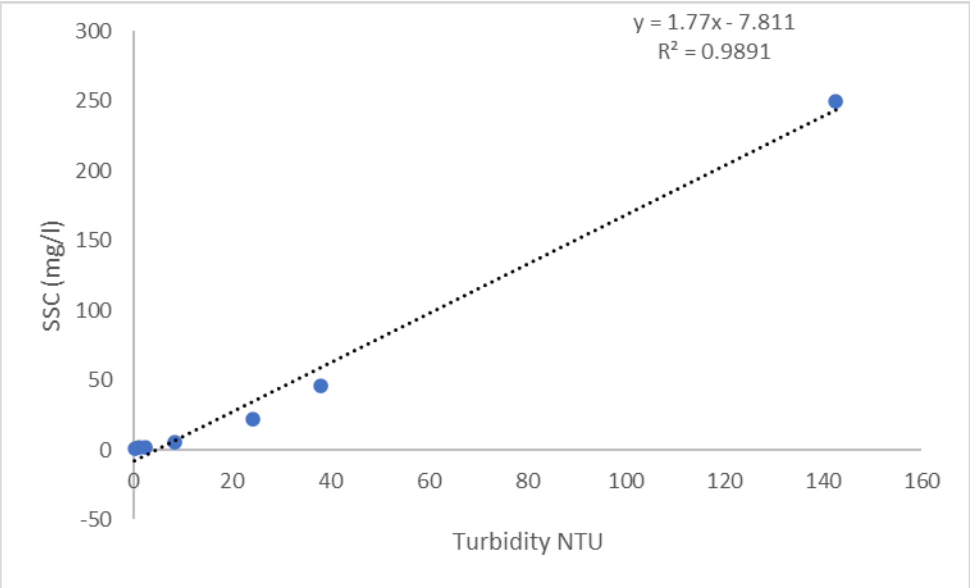

Figure D 4: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Weipa (WQ4)

Table D 3: Raw values for determining the relationship between NTU and SSC at Weipa (WQ4)

Date	17/05/2018	Tech ID	SIMON	Site Name	WQ4

	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	12:29:00	0.23	0.9		
Water bottle 2	12:32:00	1.02	2		
Water bottle 3	12:35:00	2.42	2.1		
Water bottle 4	12:37:00	8.34	5.6		
Water bottle 5	12:40:00	24.17	22		
Water bottle 6	12:46:00	37.89	46		
Water bottle 7	12:50:00	142.47	250		

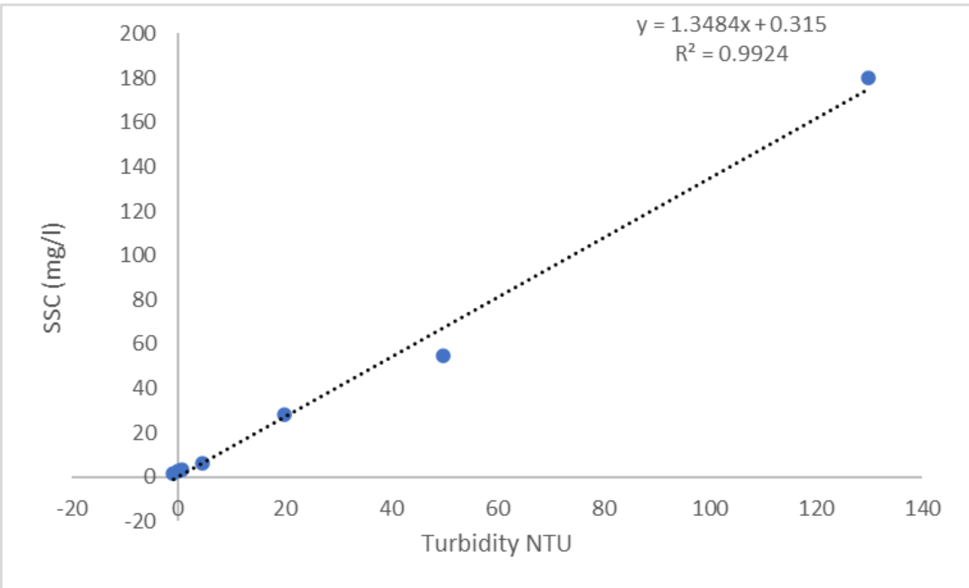

Figure D 5: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Holbourne Island (AP_AMB5)

Table D 4: Raw values for determining the relationship between NTU and SSC at Holbourne Island (AP_AMB5)

Date	29/03/2018	Tech ID	Chancey	Site Name	Holbourne Island
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	12:47:00	-0.91	1.4		
Water bottle 2	12:49:00	-0.04	2.6		
Water bottle 3	12:50:00	0.64	3.6		
Water bottle 4	12:54:00	4.5	6.3		
Water bottle 5	13:05:00	19.97	28		
Water bottle 6	13:20:00	49.74	55		
Water bottle 7	13:31:00	129.82	180		

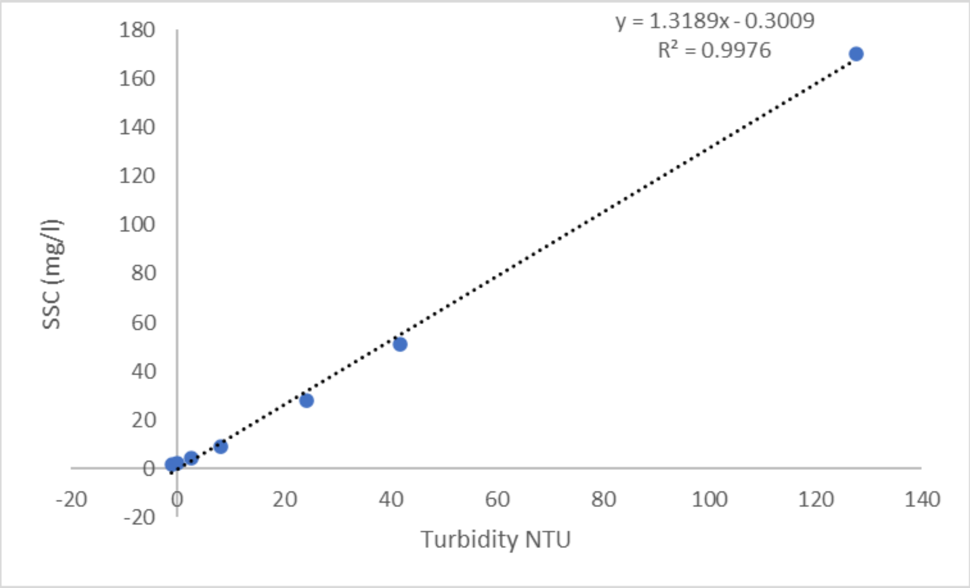

Figure D 6: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Euri Creek (AP_AMB1)

Table D 5: Raw values for determining the relationship between NTU and SSC at Euri Creek (AP_AMB1)

Date	29/03/2018	Tech ID	Chancey	Site Name	Euri Creek
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	14:05:00	-0.98	1.5		
Water bottle 2	14:08:00	0.03	2.3		
Water bottle 3	14:14:00	2.53	4.3		
Water bottle 4	14:20:00	8.06	9		
Water bottle 5	14:27:00	24.26	28		

Water bottle 6	14:31:00	41.92	51		
Water bottle 7	14:38:00	127.53	170		

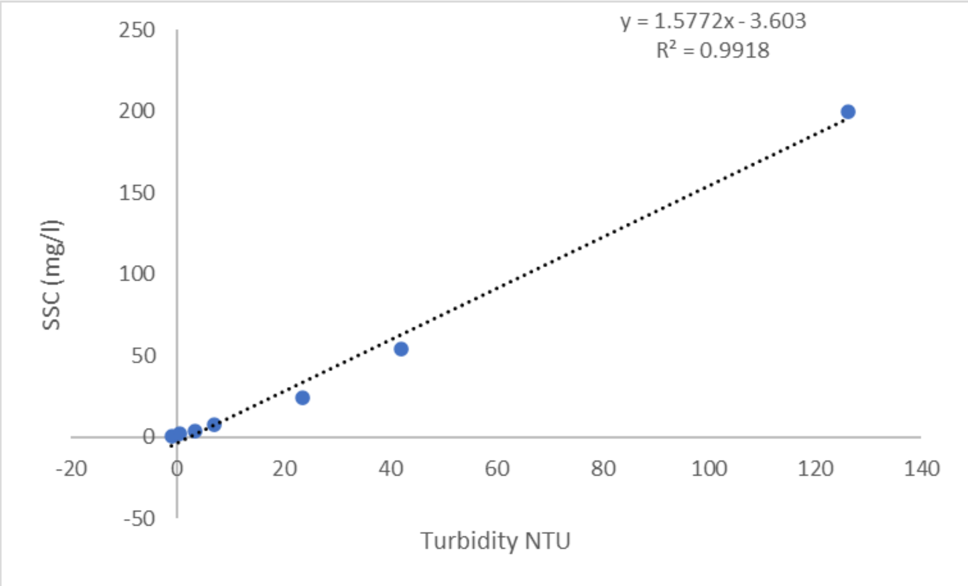

Figure D 7: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Camp Island (AP_AMB4)

Table D 6: Raw values for determining the relationship between NTU and SSC at Camp Island (AP_AMB4)

Date	29/03/2018	Tech ID	Chancey	Site Name	Camp Island
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	15:58:42	-1.02	0.7		
Water bottle 2	16:02:42	0.4	2		

Water bottle 3	16:04:12	3.47	4.2		
Water bottle 4	16:06:12	7.03	8		
Water bottle 5	16:10:12	23.51	24		
Water bottle 6	16:13:12	42.2	54		
Water bottle 7	16:15:42	126.11	200		

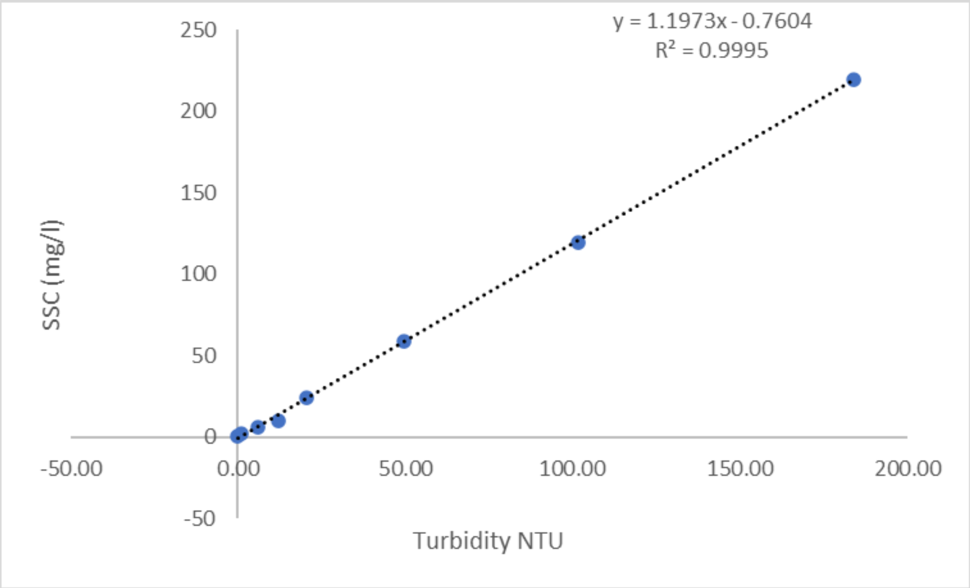

Figure D 8: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Slade Island (MKY_AMB5).

Table D 7: Raw values for determining the relationship between NTU and SSC at Slade Island (MKY_AMB5).

Date	2/03/2015	Tech ID	Kallum	Site Name	Slade Is.

	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	12:57:00	0.00	1		
Water bottle 2	13:03:00	0.95	2		
Water bottle 3	13:14:00	5.76	6		
Water bottle 4	13:26:00	12.10	10		
Water bottle 5	13:45:00	20.42	24		
Water bottle 6	14:05:00	49.52	59		
Water bottle 7	14:25:00	101.57	120		
Water bottle 8	15:11:00	183.92	220		

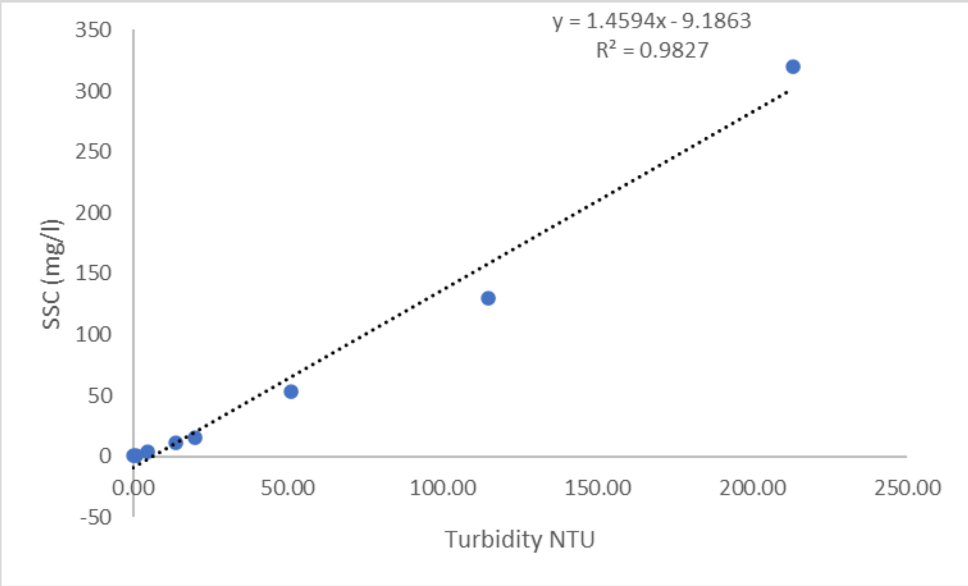

Figure D 9: Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Victor Island (MKY_AMB10)

Table D 8: Raw values for determining the relationship between NTU and SSC at Victor Island (MKY_AMB10)

Date	3/03/2015	Tech ID	Kallum	Site Name	Victor Is.
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	16:16:00	0.00	0.6		
Water bottle 2	16:22:00	0.77	1.3		
Water bottle 3	16:30:00	4.76	4.3		
Water bottle 4	16:35:00	13.84	11		
Water bottle 5	16:38:00	19.80	16		

Water bottle 6	16:46:00	50.85	53		
Water bottle 7	16:50:00	114.60	130		
Water bottle 8	16:55:00	213.14	320		

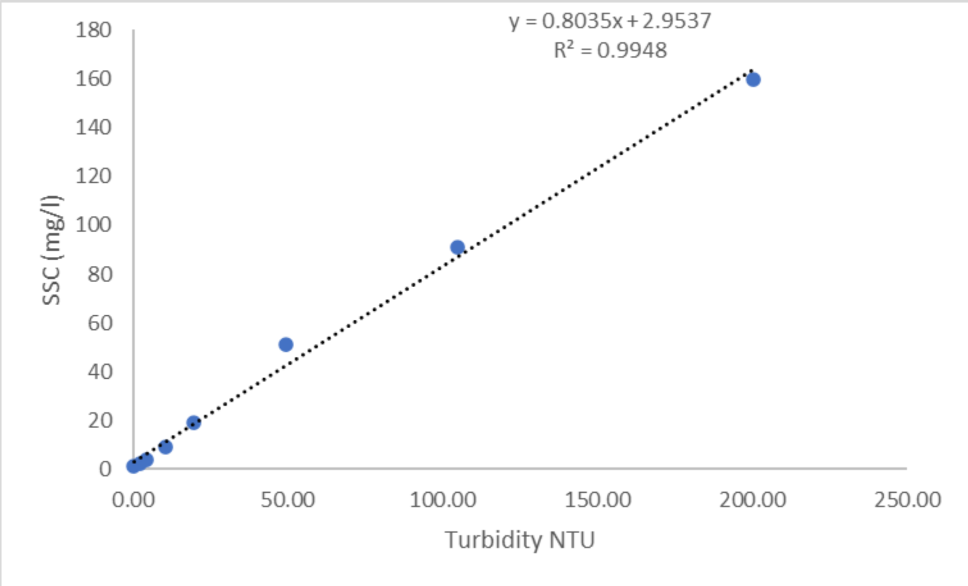

Figure D 10: : Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Freshwater Point (MKY_AMB1)

Table D 9: Raw values for determining the relationship between NTU and SSC at Freshwater Point (MKY_AMB1)

Date	3/03/2015	Tech ID	Kallum	Site Name	Freshwater
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	11:41:00	0.18	1.1		

Water bottle 2	12:02:00	1.89	2.4		
Water bottle 3	12:20:00	4.25	4.1		
Water bottle 4	12:27:00	10.49	9.1		
Water bottle 5	12:33:00	19.57	19		
Water bottle 6	12:39:00	49.39	51		
Water bottle 7	12:46:00	104.78	91		
Water bottle 8	13:13:00	200.34	160		

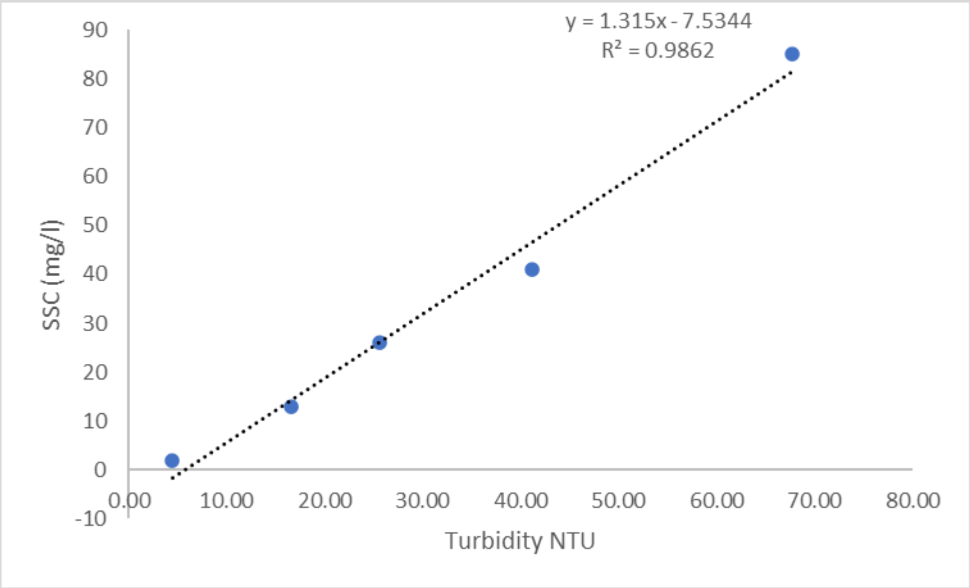

Figure D 11: Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Round Top Island (MKY_AMB3)

Table D 10: Raw values for determining the relationship between NTU and SSC at Round Top Island (MKY_AMB3)

Date	19/04/2010	Tech ID	rob	Site Name	Roundtop
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	14:24:00	4.48	1.8		
Water bottle 2	14:31:30	16.60	13		
Water bottle 3	14:37:00	25.54	26		
Water bottle 4	14:42:00	41.20	41		
Water bottle 5	14:51:30	67.67	85		

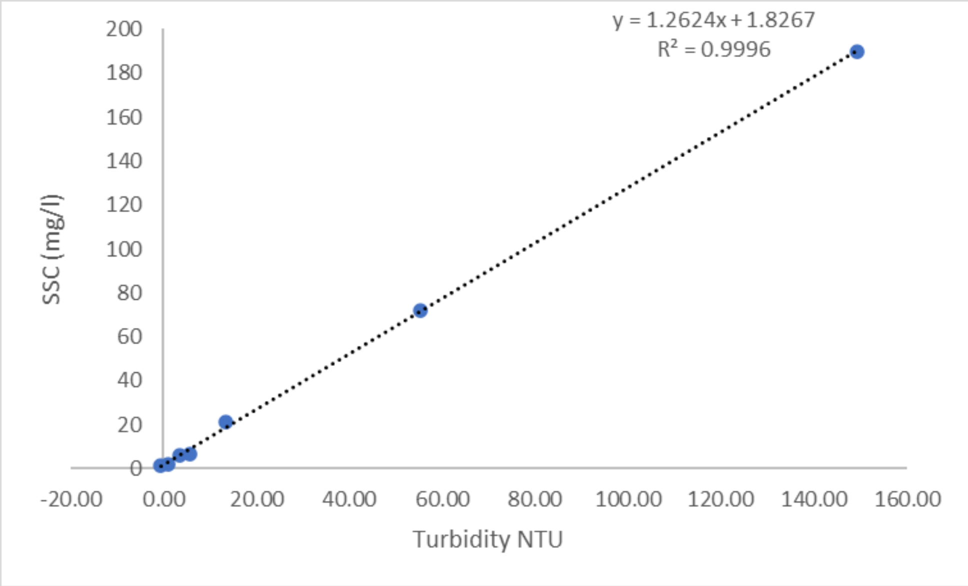

Figure D 12: Relationship between turbidity (NTU) and suspended sediment concentration (SSC) at Aquila Island (MKY_CAM1)

Table D 11: Raw values for determining the relationship between NTU and SSC at Aquila Island (MKY_CAM1)

Date	14/11/2017	Tech ID	Simon	Site Name	Aquila
	Time	Mean Turbidity from Neph	SSC (mg/L) from water sample		
Water bottle 1	10:24:00	-0.61	1.3		
Water bottle 2	10:30:00	0.95	2		
Water bottle 3	10:34:00	3.38	6.3		
Water bottle 4	10:37:00	5.54	6.9		
Water bottle 5	10:41:00	13.31	21		

Water bottle 6	10:45:00	55.26	72		
Water bottle 7	10:48:00	149.28	190		