Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2022-2023

Authored by: Jordan Iles, Paula Cartwright, Jamie Johns, and Nathan Waltham

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A Report for North Queensland Bulk Ports Corporation

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Prepared by Jordan Iles, Paula Cartwright, Jamie Johns, and Nathan Waltham

Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER)
James Cook University, Townsville, Queensland, Australia
Phone: (07) 4781 4262
Email: TropWATER@jcu.edu.au
Web: www.jcu.edu.au/tropwater/
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Contacts

For more information contact: Nathan Waltham, nathan.waltham@jcu.edu.au

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Executive summary

Background

1. North Queensland Bulk Ports (NQBP) in partnership with The Centre for Tropical Water and Aquatic Ecosystems (TropWATER) at James Cook University implemented an ambient marine water quality monitoring program in the region surrounding the Port of Weipa in January 2018. By incorporating a combination of approaches including spot measurements, acquisition of data via deployment of high frequency continuous loggers, water sample collection, and laboratory analysis of samples for a range of nutrients and heavy metals, the objective of the program is to collect a long-term water quality dataset that characterises the ambient water quality conditions within the Weipa region.
2. The Port of Weipa currently has three active sites for ambient water quality monitoring. Sites include two estuary sites (Evans Landing and Leithen Point) and one coastal site (South Channel). Seagrass receptor habitat assessments for Weipa are available in companion reports on the TropWATER website (www.tropwater.com).
3. In September 2021, a major investment by NQBP saw the roll out of new state-of-the-art water quality loggers that has allowed for more reliable data logging, a broader range of data acquisition across the region (e.g., multispectral PAR), and therefore an increased capacity to answer important scientific questions. This report covers the period from July 2022 to June 2023.

Climatic conditions

1. This reporting year saw the third wettest year in Weipa (2470 mm) since the Bureau of Meteorology data began here in 1992.
2. There was a large rainfall event and associated stream discharge from the Embley River in late December 2022/ early January 2023. This event moved a large amount of sediment into the estuary and resulted in the burial of water quality loggers at Evans Landing and Leithen Point.
3. January and February 2023 saw very high wave activity, with more waves measured over 1.2 m than any other months, and maximum waves of up to 4 m.
4. In March, a low-pressure system caused extreme wave energy, and resulted in the wave buoy station becoming out-of-action for several weeks.

Water chemistry

1. Water quality conditions were measured at all sites on a ~8 weekly basis. Parameters collected were water temperature, electrical conductivity, pH, dissolved oxygen, and photosynthetically active radiation at three depths (surface, mid-water, and bottom), along with Secchi disk depth.

2. The water column is mostly well mixed with water temperature, electrical conductivity, dissolved oxygen, and pH generally similar throughout the water column on each sampling event and within normal range for coastal / estuarine environment. There was a large decrease in salinity in February 2023, and April 2023 (to a lesser extent), caused by wet season rainfall.

3. Nitrogen: Total nitrogen (TN) and total dissolved nitrogen (TDN) showed a decline in concentration over the reporting period with higher nitrogen concentrations measured in the 2022 dry season compared to the 2023 dry season.

4. Phosphorous: Total phosphorous (TP) and total dissolved phosphorous (TDP) showed lower concentrations present during the wet season compared to the dry season.

5. Chlorophyll-*a* concentrations were generally higher in the wet season compared to the dry season, following long-term trends.

6. Dissolved trace metals were undetected (below limit of detection) throughout the reporting year apart from arsenic which was reported in low concentrations on both sampling events.

Turbidity

1. Turbidity logger data supports the pattern found more broadly in north Queensland coastal marine environments, that during dry periods with minimal rainfall, elevated turbidity is likely experienced in relation to re-suspension of sediment by wind/wave activity.
2. Turbidity was highly variable at the coastal site South Channel during June to September and showed a strong correlation to wave activity overall. Evans Landing showed high variability throughout the year but only a weak correlation to wave activity, while Leithen Point was the most turbid of all the sites with periods of high variability during January, April to July, and December.
3. Highest turbidity occurred at South Channel during the March 2023 low-pressure system that affected the region.

Benthic photosynthetically active radiation (bPAR)

1. bPAR was highest at the coastal South Channel site compared to both estuarine sites in the Embley River, with Leithen Point showing the lowest light levels (bPAR) of the entire year.

2. Patterns of light were similar among all sites, with lower light associated with periods of higher rainfall and significant climate events.

3. During periods of high turbidity when water clarity was lowest, the more photosynthetically useful shorter blue wavelengths were much more attenuated than the longer red wavelengths. The spectral peak also shifts from the blue-green part of the spectrum to longer yellow wavelengths.

Recommendations

This monitoring program has been underway for six years (2018 to present) and should remain in place to continue to characterise, and build, a detailed understanding of the water quality dynamics in and around this port facility. The data is invaluable for use in plume modelling and determination of regionally specific trigger values for enhanced management of maintenance dredging campaigns. And will continue to assist NQBP to manage current activities, as well as assist with future strategic planning and management. With an emerging long-term dataset, there is also potential for answering important research questions around coastal processes affecting water quality in this remote region of northern Australia.

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1 Introduction

1.1 Program outline

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 initiatives surrounding the Port of Weipa (Figure 1.1). As part of the agreement, an ambient water quality monitoring program has been implemented that incorporates discreet field measurements, acquisition of data via deployment of continuous dataloggers, and water sample collection for laboratory analysis of a range of nutrients, pesticides, and heavy metals. The program aims to characterise variability in water quality by monitoring a suite of key parameters to better define the potential impacts associated with port operations adjacent to sensitive seagrass and other coastal habitats. Along with regular monitoring of water quality parameters, an overview of the meteorological and oceanographic (metocean) conditions that affect the regions coastal ecosystems is presented to increase understanding of factors driving seasonal and interannual variability in water quality.

1.2 Program objectives

The goal of the program is to characterise the ambient marine water quality by monitoring within the port limits of Port of Weipa. This report provides a review and analysis of data collected between 1st July 2022 and 30th June 2023. These data are part of a longer-term commitment to monitor and characterise receiving water quality conditions, to support future planned asset management and protection of this coastal port. The partnership objective also moves beyond basic environmental stewardship and incorporates robust science research initiatives undertaken by leading researchers and specialists in marine water quality, coastal habitat, seagrass ecology, and natural resource management. The long-term acquisition of data under the partnership presents an invaluable resource for understanding the interannual variability and climatic influences that drive water quality and ecological processes along coastal Queensland.

Figure 1.1. James Cook University research vessel underway to conduct water quality monitoring on the Embley River estuary (Weipa).

2 Methods

2.1 Regional description

Weipa is located in Albatross Bay (12°45'S, 141°40'E), a tropical coastal embayment on the western side of Cape York Peninsula, within the Gulf of Carpentaria in northern Queensland (Figure 2.1). Four main estuaries (Pine, Mission, Embley and Hey) each with extensive mangrove-lined inlets, drain into Albatross Bay, delivering wet season freshwater, nutrients, and sediments ranging from mud through sand (Larcombe & Taylor, 1997). A diverse range of habitats including coral reefs, seagrass meadows, mangrove forests, estuarine waters, intertidal banks, saltpans, marshes, and marine and freshwater wetlands are present, and provide important nursery habitats for juvenile fish and crustaceans, of which more than 360 species have been found in the region (Baker & Sheppard, 2006). Coastal processes at Weipa are influenced by features of the Gulf of Carpentaria that include shallow bathymetry (<60 m) and low near-shore gradient; a monsoonal climate with seasonal reversals in wind and wave direction; a semi-diurnal meso-tidal regime with a mean spring tide range of 2.2 m; low to moderate wave energy with occasional tropical cyclones delivering strong winds, high waves, storm surge and heavy rainfall leading to coastal inundation events (Short, 2020). During the wet season, significant coastal discharge leads to the trapping of nutrient-rich water along the coast, with minimal mixing occurring between estuarine and offshore waters (Somers & Long, 1994).

2.2 Port description

The Port of Weipa is situated within the township of Weipa, where the Embley, Mission and Pine River's converge and discharge into the Gulf of Carpentaria (Figure 2.1). North Queensland Bulk Ports Corporation (NQBP) act as Port Authority, with Rio Tinto managing the Port facilities that consist of a series of operational and associated loading/unloading facilities. Along with other ports

in Queensland, Port of Weipa requires routine maintenance dredging to maintain declared navigational depths within the swing basin and berth areas, departure path and aprons. Dredging activities necessary in the operating ports in the region are undertaken in accordance with Commonwealth and State approvals.

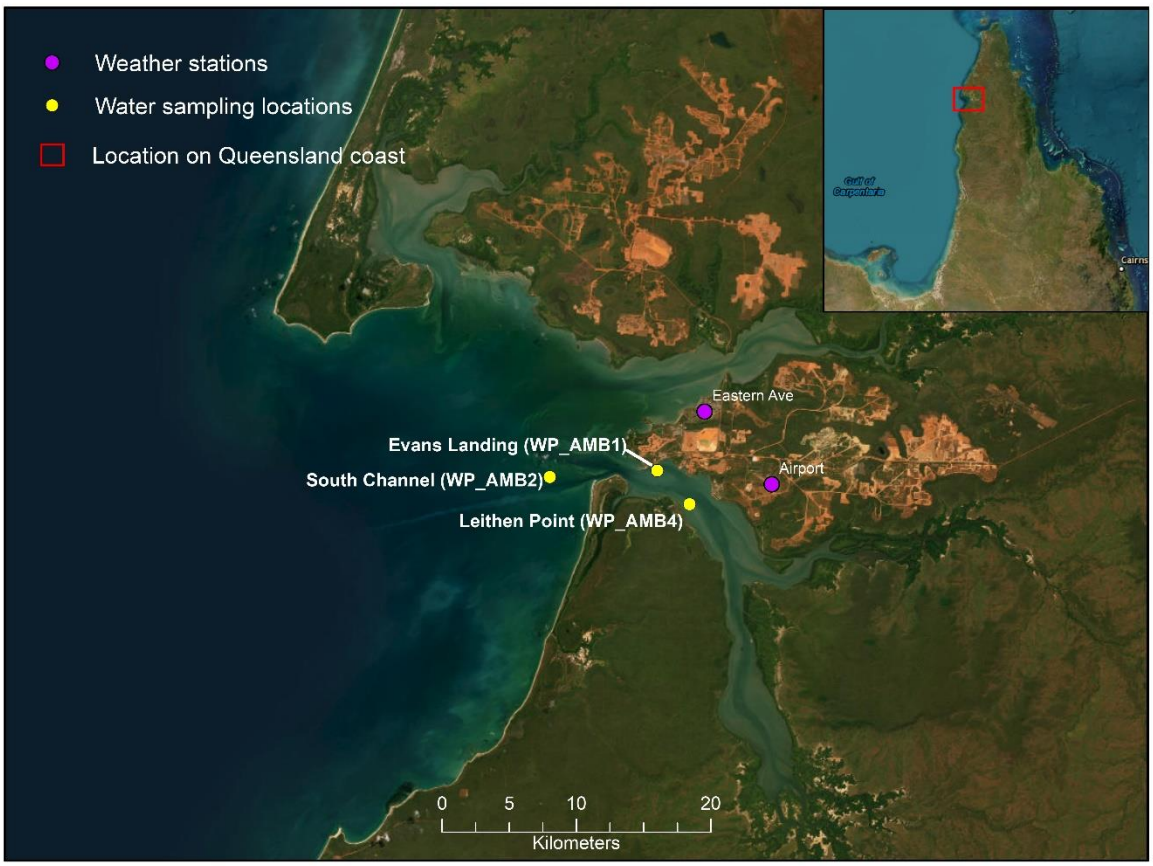

Figure 2.1. Map of Weipa showing location of water quality monitoring sites (yellow) and meteorological stations (purple), utilised in the 2022-2023 reporting period. Inset map shows location on Queensland coast.

2.3 Characterisation of weather, hydrological status, and oceanographic conditions

Climate data for the region was extracted from the Australian Bureau of Meteorology climate data online tool (http://www.bom.gov.au/climate/data/). Total rainfall, rainfall onset date, along with wet season rainfall totals were calculated. The nominal wet season is defined as 1st November to 30th April. The rainfall onset is calculated as the date when the rainfall total reaches 50 mm since 1st September. Stream discharge data for streams discharging into the coastal waters of the region was extracted from the Queensland Government water monitoring information portal (https://water-monitoring.information.qld.gov.au/). Total discharge and date of first significant discharge event were calculated. The water year reported throughout is defined as 1st July to 30th June. Wave data for the region was extracted from Queensland Government open data portal (https://www.data.qld.gov.au/) comprising of the significant wave height (Hs), calculated as the

average of the highest third of the waves in a recorded period (26.6 minutes), and the Peak Direction (which the waves are coming from), as recorded by the Albatross Bay Wave Buoy located 6 nautical miles offshore from South Channel (WP_AMB2, Figure 2.1).

2.4 Monitoring and sampling design

The Weipa region has three active ambient marine water quality monitoring sites (Figure 2.1, Table 2-1). Two sites, Evans Landing (WP_AMB1) and Leithen Point (WP_AMB4) are located in the Embley River estuary, with another site, South Channel (WP_AMB2) located in Albatross Bay to the south-west of the river mouth. Each site has a pair of dataloggers deployed on the seafloor to continuously record environmental data. The sites are revisited on an 8 weekly schedule to conduct water sampling, record physiochemical measurements, and exchange dataloggers (Table 2-2).

Table 2-1. Site locations and main features

Site name	Site code	Latitude	Longitude	Depth (m)	Site features
Evans Landing	WP_AMB1	-12.669467	141.848283	5	Seagrass
South Channel	WP_AMB2	-12.673683	141.77625	4.2	Seagrass
Leithen Point	WP_AMB4	-12.691983	141.869833	4.6	Seagrass

2.5 Water quality sampling

Each monitoring site was visited by our research vessel for sampling on an ~8-week basis. Sampling dates throughout the reporting period are provided in Table 2-2.

Water samples were collected from 0.2 m below water surface by hand. Samples were collected for analytical determination of total nitrogen, total phosphorus, total dissolved nitrogen, total dissolved phosphorus, pH, salinity, electrical conductivity, total suspended solids, chlorophyll-*a* and phaeophytin-*a* (Table 2-3). Dissolved nutrient samples were filtered onsite with a 0.45 µm syringe filter (Sartorius minisart PES 0.45). TSS samples were collected in a 1 L bottle, Chlorophyll-*a* was collected in a dark 1 L bottle, pH and salinity were collected in a 60 mL vial. Water samples were stored on ice and immediately transported to laboratory for analysis.

Water for chlorophyll determination was filtered through a Whatman 0.45 µm GF/F glass-fiber 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, following the methodology described in 'Standard Methods for the Examination of Water and Wastewater, 10200 H. Chlorophyll'.

Physiochemical parameters were measured at three depths in the water column with a multiparameter water quality meter (Hydrolab Quanta, Hydrolab CO, USA). The water quality meter records water temperature, electrical conductivity, pH, % saturation oxygen, and dissolved oxygen (Table 2-4). The three measurement depths were surface (0.25 m below surface), mid-water, and bottom (1 m above seafloor). Photosynthetically active radiation (PAR) was measured at the three depths, and above water with an underwater quantum sensor (LI-192) and light meter (LI-250A)

(Licor Biosciences, Nebraska USA). Care was taken to measure PAR without interference of sporadic cloud cover or boat shadow, though occasionally this was unavoidable.

Water clarity as measured with a Secchi disk was recorded at each site at the time of water sampling. A Secchi disk was lowered to a depth where it is no longer visible then raised back to depth where it becomes visible again. The mean depth between those two points was then recorded as Secchi disk depth.

Water samples were collected for dissolved metals analysis on two occasions - August 2022 (end of dry season) and February 2023 (wet season). Dissolved metals samples were immediately filtered onsite with a 0.45 µm syringe filter (Sartorius minisart PES 0.45) and stored on ice (Table 2-5).

Where appropriate, results of water samples and logger data were compared to water quality objectives (WQO) outlined in the Environmental Protection (Water and Wetland Biodiversity) Policy 2019 (EPP, 2019) or guideline values (GV) outlined in the Australian and New Zealand guidelines for fresh and marine water quality (ANZG, 2018).

Table 2-2. *Field dates for water sampling, logger maintenance, and dissolved metal sampling at the three monitoring locations.*

Date	Water sampling	Logger maintenance	Metals sampling	Pesticides
2022-08-24	Yes	Yes	Yes	No
2022-10-11	Yes	Yes	No	No
2022-11-28	Yes	Yes	No	No
2023-02-02	Yes (WP_AMB1, WP_AMB4 only)	Yes	Yes (WP_AMB1, WP_AMB4 only)	Yes (WP_AMB1, WP_AMB4 only)
2023-02-23	Yes (WP_AMB2 only)	Yes	Yes (WP_AMB2 only)	Yes (WP_AMB2 only)
2023-04-20	Yes	Yes	No	No
2023-06-22	Yes	Yes	No	No

Table 2-3. Water quality parameters that were analysed using water samples collected at the water quality monitoring locations, along with the methods and reporting limits of the laboratory analysis.

Parameter	APHA method number	Reporting limit
Routine water quality analysis		
pH	4500-H+ B	-
Salinity	2520 B	0.1 PSU
Electrical conductivity (EC)	2510 B	5 µS cm^{-1}
Total Suspended Solids (TSS)	2540 D @ 103 - 105°C	0.2 mg L^{-1}
Nutrients		
Total nitrogen (TN)	Simultaneous 4500-NO3- F and 4500-P F analyses after alkaline persulphate digestion	10 µg N L^{-1}
Total dissolved nitrogen (TDN)		
Total phosphorus (TP)		1 µg P L^{-1}
Total Dissolved phosphorus (TDP)		
Particulate nitrogen (PN)	Calculated as PN = TN - TDN	-
Particulate phosphorus (PP)	Calculated as PP = TP - TDP	-
Chlorophyll		
Chlorophyll-*a*	10200-H	0.2 µg L^{-1}
Phaeophytin-*a*		

Table 2-4. Physiochemical measurements recorded in the field with handheld water quality meters and Secchi disk.

Parameter	Units
Multiparameter water quality meter	
Water temperature	Degrees Celsius (°C)
Electrical conductivity (SpC)	mS cm^{-1}
pH	
Dissolved Oxygen	%sat
Dissolved Oxygen	mg L^{-1}
Light meter	
Photosynthetically active radiation (PAR)	µmol m^{-2} s^{-1}
Water clarity	
Secchi disk depth	Meters (m)

Table 2-5. Dissolved metals/ pesticides and herbicides that were analysed using water samples collected at three locations in the Weipa region, and the methods and reporting limits of the laboratory analysis.

Parameter	APHA method number	Reporting limit
Dissolved metals		
Arsenic (As)	3125B ORC/ICP/MS	-
Cadmium (Ca)		0.2 µg L^{-1}
Copper (Cu)		1 µg L^{-1}
Zinc (Zn)		5 µg L^{-1}
Lead (Pb)		0.2 µg L^{-1}
Nickel (Ni)		0.5 µg L^{-1}
Silver (Ag)		0.1 µg L^{-1}
Mercury (Hg)		0.1 / 0.04 µg L^{-1}
Pesticides/herbicides		
Organophosphate pesticides	In house LC/MS method: EP234A	0.0002-0.001 µg L^{-1}
Thiocarbamates and Carbamates - Thiobencarb	In house LC/MS method: EP234B	0.0002 µg L^{-1}
Dinitroanilines - Pendimethalin	In house LC/MS method: EP234C	0.001 µg L^{-1}
Triazinone Herbicides - Hexazinone	In house LC/MS method: EP234D	0.0002 µg L^{-1}
Conazole and Aminopyrimidine Fungicides - Propiconazole, Hexaconazole, Difenoconazole, Flusilazole, Penconazole	In house LC/MS method: EP234E	0.0002 µg L^{-1}
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^{-1}

2.6 Seafloor mounted continuous dataloggers

A pair of water quality loggers were deployed at each site to measure water temperature, water depth, turbidity, and light. At each site a pair of loggers were attached to stainless steel frame and placed on the seafloor (Figure 2.2). The loggers used are NTU-LPT and MS9-LPT loggers manufactured by In-situ Marine Optics, Perth WA (https://insitumarineoptics.com). The loggers record a burst of 50 measurements of water temperature (°C), water depth (m), turbidity (NTU), and light (PAR, µmol m^{-2} s^{-1}) at a frequency of 5 Hz every 10-minutes.

Figure 2.2. Water quality loggers attached to instrument frames ready for deployment to the seabed. The horizontally orientated logger is an NTU-LPT turbidity logger, and the vertically orientated logger is a MS9-LPT multispectral light logger manufactured by Insitu Marine Optics.

Table 2-6. Specifications of NTU-LPT turbidity logger and MS9-LPT multispectral light loggers.

Parameter	Units	Sensor range	Accuracy / Resolution
Water temperature	Degrees Celsius (°C)	-55 to 125 °C	+/- 1.0 °C
Water depth	Meters (m)	0 – 90 m	+/- 1.0 %
Turbidity	Nephelometric turbidity units (NTU)	0 – 400/1000 NTU	0.05 NTU
Irradiance	µW cm^{-2} nm^{-1}	0 – 400 µW cm^{-2} nm^{-1}	2.5 x 10^{-3} W cm^{-2} nm^{-1}

Logger data processing and quality control

After each deployment, dataloggers are returned to the laboratory and the raw logfiles pre-processed. The median values for water temperature, water depth, turbidity and irradiance are calculated for each 10-minute burst interval. The data are then subjected to an automated rule-based quality control (QC) process as outlined in Iles et al. (2023). Following the automated QC process, a final manual QC is conducted before the data is ingested into the water quality database for further analysis and reporting. A description of QC rules for flagging data is in Appendix 1 and further detailed in Iles et al. (2023).

RMS Depth

A pressure sensor is located on the MS9-LPT water quality logging instrument. The pressure sensor is used to determine changes in water depth due to tide and to produce a proxy for wave action. The average water depth and Root Mean Square (RMS) water depth can be used to analyse the influence that tide and water depth may have on turbidity, deposition, and light levels at an instrument location. The RMS water height is a measure of short-term variation in pressure at the sensor. Changes in pressure over a 10 second time-period at the sensor are caused by wave energy. RMS water height can be used to analyse the link between wave re-suspension and SSC. It is important to

clearly establish that RMS water height is not a measurement of wave height at the sea surface. What it does provide is a relative indication of wave shear stress at the sea floor that is directly comparable between sites of different depths. For example, where two sites both have the same surface wave height, if site one is 10 m 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.

Each time a pressure measurement is made the pressure sensor takes 50 measurements over a period of 10 seconds. From these 50 measurements, average water depth (m) and Root Mean Square (RMS) water height are calculated.

RMS water height, D_{rms}, is calculated as follows:

$$RMS_{depth} = \sqrt{\frac{\sum_{n=1}^{N}(D_n - \bar{D})^2}{N}} \qquad \text{[Equation 1]}$$

Where D_n is the n_{th} of the 50 readings and $\bar{D}$ is the mean water depth of the n readings.

Benthic photosynthetically active radiation (bPAR)

Benthic light limitation is often attributed to turbidity (Erftemeijer et al., 2012) however, the relationship between turbidity and benthic photosynthetically active radiation (bPAR) is not always strong (Sofonia & Unsworth, 2010). As bPAR 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 healthy growth for these habitats (e.g. Chartrand et al., 2012). For this reason, it is important to include bPAR in the suite of water quality variables when capturing local baseline conditions of ambient water quality.

Benthic photosynthetically active radiation (bPAR) was calculated from the response of the nine individual irradiance channels on the MS9 logger. Light data between 400 and 700 nm was interpolated and integrated internally. The mean value for bPAR was calculated for each 10-minute burst interval.

Daily light integral (DLI) describes the number of photosynthetically active photons that are delivered to a specific area over a 24-hour period.

Daily light integral (DLI) was calculated as follows:

$$DLI = \sum_i PAR_i * \frac{600}{1000000} \qquad \text{[Equation 2]}$$

Where:

DLI is the daily light integral in mol photons m^{-2} d^{-1}

i is each bPAR reading during the day

bPAR is the benthic photosynthetically active radiation in µmol photons m^{-2} s^{-1}

600 is the time interval between readings over the 24 hours

1,000,000 is the unit conversion of µmol photons m^{-2} s^{-1} to mol photons m^{-2} d^{-1}

Benthic multispectral irradiance

Increasingly, scientists and managers are looking at spectral light as the most important parameter for water quality monitoring. This is because photosynthesising biota, such as corals and seagrasses have preferential light requirements (e.g., blue light) and are unable to use light along the full visible spectrum (Jones et al., 2021). With the optical properties of marine waters highly changeable dependent on adjacent river catchments, sediment transport pathways and autochthonous processes, wavelengths of light reaching benthic habitats cannot be determined by measurement of turbidity or PAR alone. The IMO-LPT MS9 multispectral light loggers contain nine light sensors measuring light (irradiance) at specific wavelengths that correspond to colours across the visible light spectrum (Table 2-7).

Values of individual irradiance channels were selected over a one-hour period centred at midday each day. Data were normalised to peak irradiance for comparison of spectral distributions across different times throughout the reporting period. Normalising the data removes interference by cloud allowing direct comparison between light intensity across the channels regardless of overall PAR. Multispectral profiles were then classified according to corresponding turbidity values (2-hour mean), with turbidity values binned into low (<1 NTU), mid-range (1-5 NTU) and high-range (>5 NTU). The spectra were then displayed to visualise how turbidity affected individual irradiance channels.

Table 2-7. Wavelength specifications of the InSitu Marine Optics MS9 nine wavelength multispectral light sensor. Each channel has a 10 nm full-width-half-maximum spectral response.

Irradiance channel	1	2	3	4	5	6	7	8	9
Wavelength (nm)	410	440	490	520	550	570	610	660	700
Colour	Violet	Blue	Cyan	Green	Green	Yellow	Orange	Red	Red

Suspended sediment concentration

Suspended sediment concentration was calculated from turbidity data after establishing a relationship with each site. Full methods are provided in (Cartwright et al., 2022). While there is no published protocol for re-evaluation of this relationship, it should ideally be re-established every few years, or after major events that could affect particle size distribution among the benthic sediments.

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

$$SSC = Turb * Cf \pm e \qquad \text{[Equation 3]}$$

Where:

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

Turb is the measured turbidity value in NTU

C_f is the conversion factor (unique for each site)

e is the root mean square error value

Note that error values are not presented in the converted data values.

2.7 Long term trend analysis

The Weipa region ambient water quality program has now been running since January 2018. There is now 6 years of data collected which we can begin to use to explore temporal aspects of coastal water quality. Generalized Additive Mixed Models (GAMMs) are a flexible statistical approach used for analysing irregular time series data, including water quality data. GAMMs extend the capabilities of Generalized Additive Models (GAMs) by incorporating random effects, which account for the hierarchical structure often present in longitudinal or repeated measures data.

Multi-year data for parameters measured in discrete water samples was analysed for long-term trends using generalized additive mixed effects models (GAMM). GAMM analysis was conducted using the 'mgcv' package in R, as developed by Wood (2017). The model formula used was "response ~ month + time" where "response" is the dependent variable, and "month" and "time" are the independent variables. The water quality site was included as a random effect in the model.

Splines were employed to capture the non-linear relationships between the variables. Specifically, a cyclic cubic regression spline was used for the "month" variable, and a thin plate regression spline was used for the "time" variable. The number of knots (points where the spline changes direction) was fixed at 5 for the "month" variable and 20 for the "time" variable.

A gamma distribution with a log linking function was chosen for the model. This choice was based on the performance of gamma distribution being generally better for irregular time series data compared to fitting the data to a Gaussian (normal) distribution.

3 Results and Discussion

3.1 Rainfall and river flows

Daily rainfall for the Weipa region is shown in Figure 3.1. The 2022-2023 wet season rainfall total was 2446 mm, while total rainfall for the water year was 2469.8 mm (Figure 3.2). The 2022-2023 year showed above average rainfall equivalent to approximately 90th percentile of annual rainfall since 1992. Most of the rainfall fell throughout the wet season. An extreme weather event in early January 2023 saw 237.2 mm rain fall in Weipa in a single day. The first rainfall greater than 5 mm for the water year occurred on 24th September 2022, with the rainfall onset occurring on 9th November 2022. While the northern wet season is defined as between 1st November and 30th April, the rainfall onset is calculated as the date when the rainfall total reaches 50 mm since 1st September, and hence is a better indication of the start of the wet season.

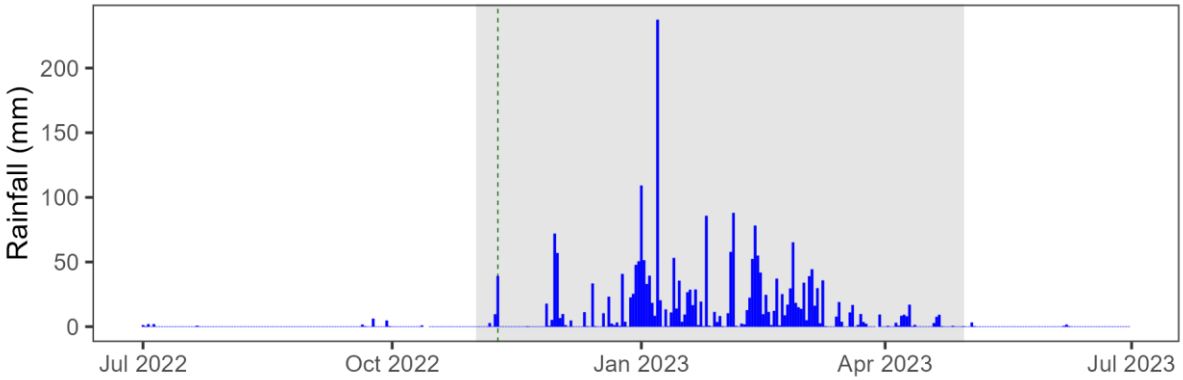

Figure 3.1. Rainfall recorded at Weipa Aero (station 027045) for the 2022-2023 water year. The nominal wet season period is shaded grey. Green vertical dash indicates northern rainfall onset. Data source: http://www.bom.gov.au/climate/data/

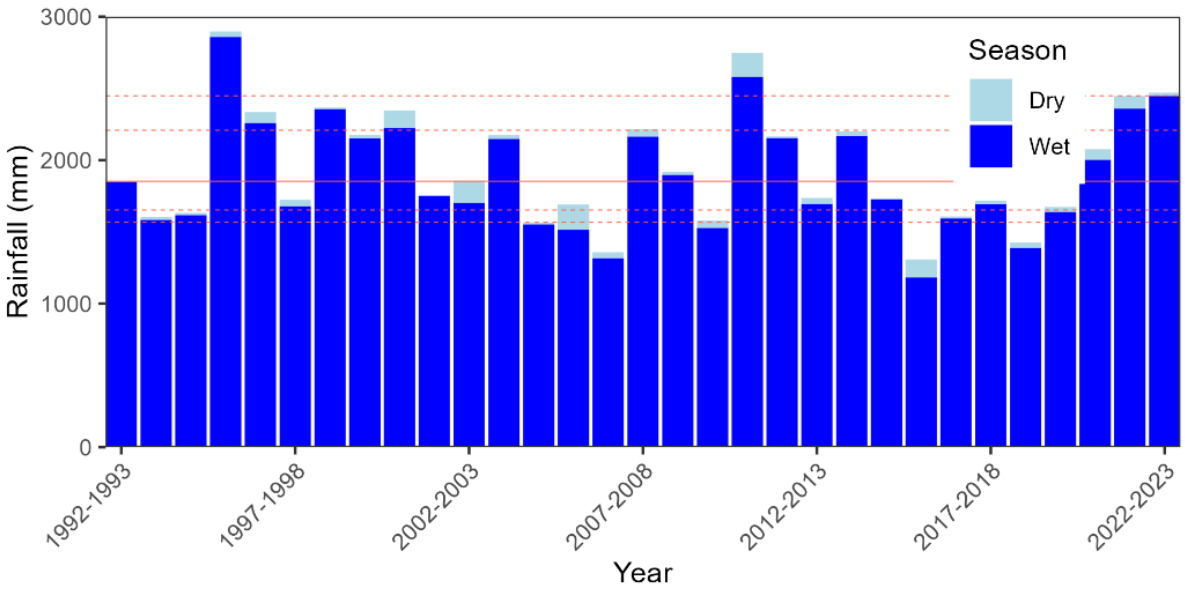

Figure 3.2. Annual rainfall by water year for the Weipa region during wet season (blue) and dry season (light blue). Totals were calculated for the wet season period 1st November to 30th April for each water year. Water year runs from 1st July to 30th June. Solid red line represents median annual rainfall by water year, dashed lines represent 10th, 25th, 75th, and 90th percentiles. Daily rainfall data was obtained from the Weipa Aero (station 027045) weather station. Data source: http://www.bom.gov.au/climate/data/

The only local river gauging station near to Weipa is on the Watson River, which is located ~75 km south and does not discharge into the Embley/Hey/Mission River systems where the Port is located. Therefore, although Watson River discharge has been used throughout this report to provide context for Port water quality conditions, results regarding the influence of water discharge on water quality variability should be interpreted with caution. The hydrograph for Watson River shows onset of stream discharge on 29/12/2022, with consecutive large pulses every 1-2 weeks following throughout the wet season (Figure 3.3). Total discharge for the 2022-2023 water year was 1088 GL. There were no major meteorological events impacting the Weipa region in 2022-2023. There was evidence of a significant discharge event occurring in the Embley River sometime between December 2022 and January 2023, possibly related to the extreme rainfall event on January 7. Instrument frames and dataloggers were discovered buried in sediment and debris when undertaking routine maintenance in early February 2023. There was a tropical low (16U) in the southern gulf throughout early March 2023.

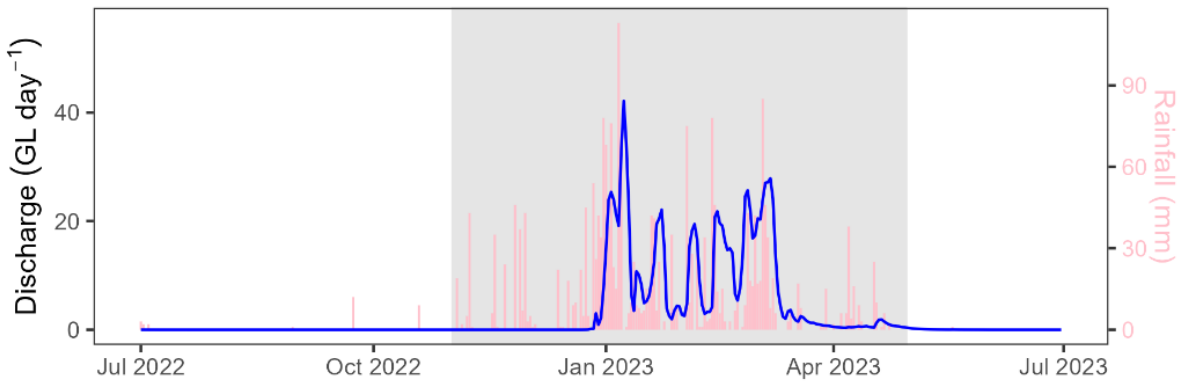

Figure 3.3. Stream discharge (GL d^{-1}) from the Watson River at Jackin Creek (station 923001A) during the 2022-2023 reporting period. Daily rainfall totals from each corresponding stream gauge shown in pink. The nominal wet season period is shaded grey. Data source: https://water-monitoring.information.qld.gov.au/

3.2 Oceanographic conditions

Waves detected at Albatross Bay in Weipa were predominantly 0.3 to 0.8 m in height and from a south-westerly direction (Figure 3.4). October 2022 showed the lowest wave activity, while January and February 2023 had the largest significant wave heights for the monitoring period (Figure 3.5; Figure 3.6). Note that a tropical low in early March coincided with (possibly led to) the Albatross Bay wave buoy station being out of commission for several weeks and therefore not recording what were potentially the largest swells of the reporting period (as confirmed by the South Channel logger RMS depth data, section 3.4.3 of this report). Wave peak period shows longer periods during times of higher wave activity (Figure 3.7). Wave direction timeseries shows the dominance of westerly swells during periods of high wave activity (Figure 3.8).

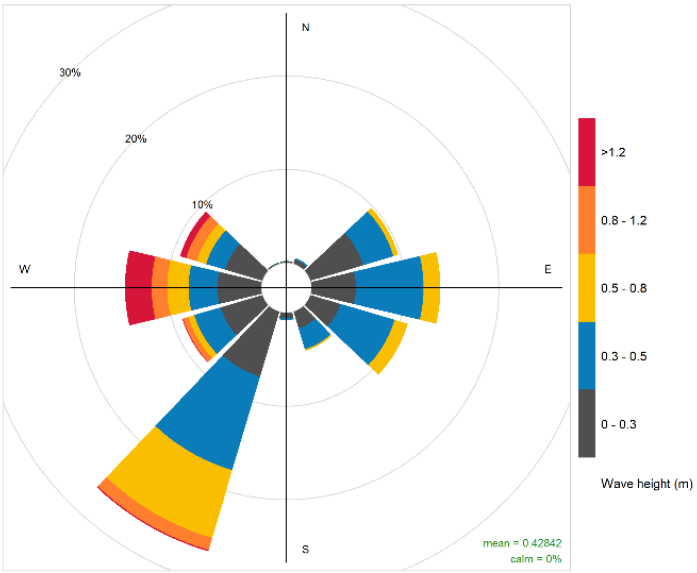

Figure 3.4. Frequency of counts by wave direction (%), and significant wave height (m) at the Albatross Bay wave buoy station between July 1, 2022, and June 30, 2023. Data source: https://www.qld.gov.au/environment/coasts-waterways/beach/monitoring

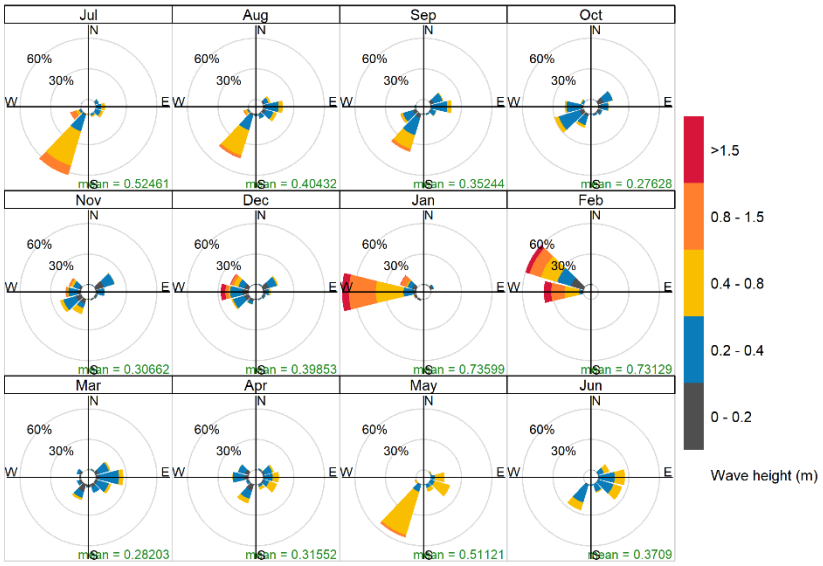

Figure 3.5. Frequency of counts by wave direction (%), and significant wave height (m) at the Albatross Bay wave buoy station between July 1, 2022, and June 30, 2023. Data source: https://www.qld.gov.au/environment/coasts-waterways/beach/monitoring

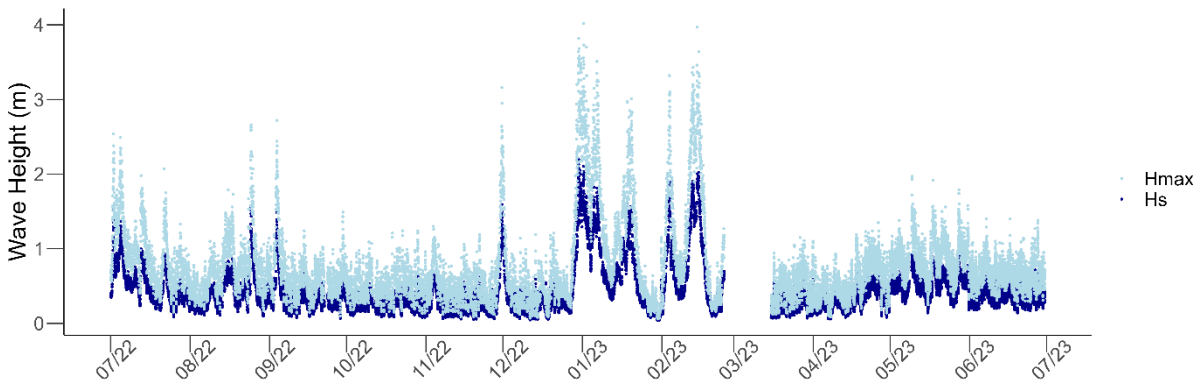

Figure 3.6. Time series of significant wave height (Hs) and maximum wave height (Hmax) at the Albatross Bay Wave buoy station between July 1, 2022, and June 30, 2023. Note that wave data was missing from this station for several weeks following a low-pressure system that affected the region in February/March 2023. Data source: https://www.qld.gov.au/environment/coasts-waterways/beach/monitoring

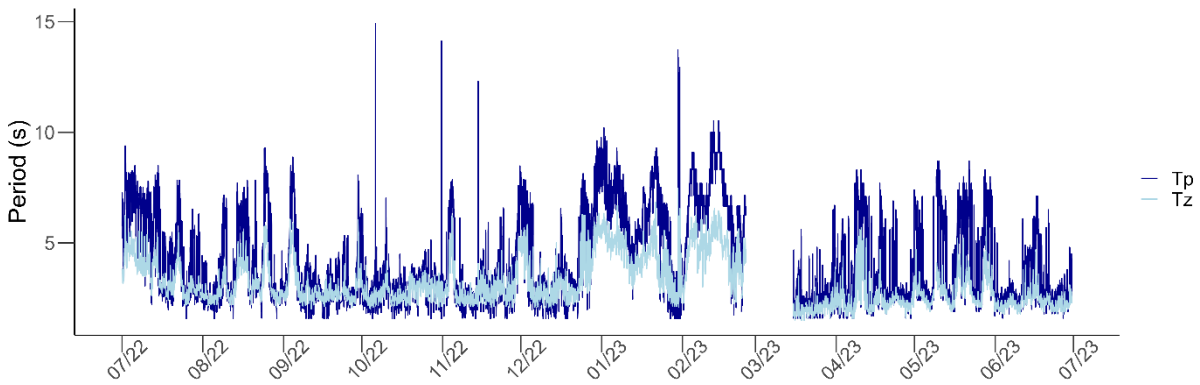

Figure 3.7. Time series of wave period at the Albatross Bay Wave buoy station between July 1, 2022, and June 30, 2023. Peak energy wave (Tp: light blue) and zero upcrossing wave (Tz: dark blue). Note that wave data was missing from this station for several weeks following a low-pressure system that affected the region in February/March 2023. Data source: https://www.qld.gov.au/environment/coasts-waterways/beach/monitoring

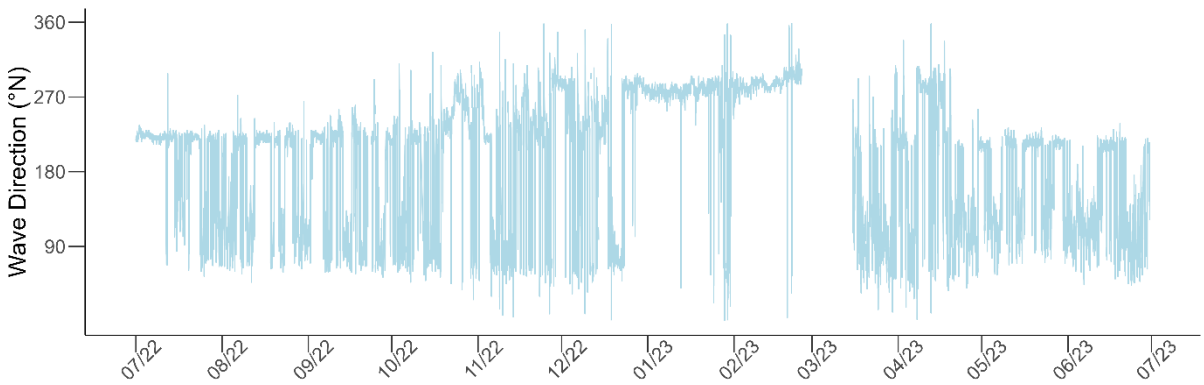

Figure 3.8. Wave direction (relative to true north) from which the peak period waves are coming from. Data source: https://www.qld.gov.au/environment/coasts-waterways/beach/monitoring

3.3 Water quality

3.3.1 Physiochemical

Dissolved oxygen ranged from 4.64 to 9.89 mg L^{-1} with a mean of 6.08 mg L^{-1} across the three sites, indicating generally well oxygenated waters (Figure 3.9). Electrical conductivity ranged from 28.2 to 55.3 mS cm^{-1} with a mean of 51.8 mS cm^{-1} and was in the range typical of seawater (Figure 3.10). Conductivity values followed expected seasonality with lower values occurring during wet season when rainfall and freshwater inputs diluted seawater in the estuary and coastal ocean and higher values during the dry season. There was a halocline present in February 2022 with surface brackish water overlying more dense and saline waters. Water temperature ranged from 21.8 to 31.8 °C with a mean of 27.3 °C (Figure 3.11). As expected, there is a strong seasonal effect on water temperatures in the region, with the highest water temperatures observed during surveys in the summer months, and cool water temperatures observed during the winter months. pH ranged from 6.69 to 8.48 with a mean pH of 8.29 (Figure 3.12). The water column at all sites was generally well mixed with only minor differences in values through the three depths.

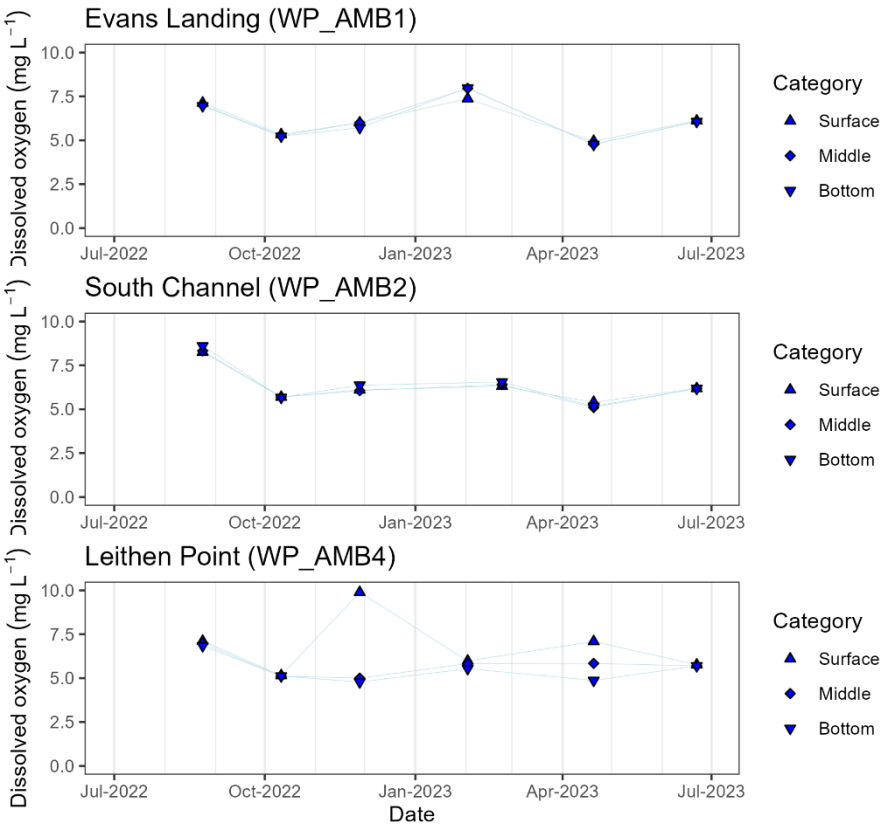

Figure 3.9. Dissolved oxygen concentration (mg L^{-1}) at three water quality monitoring sites showing results for the surface, middle, and bottom water.

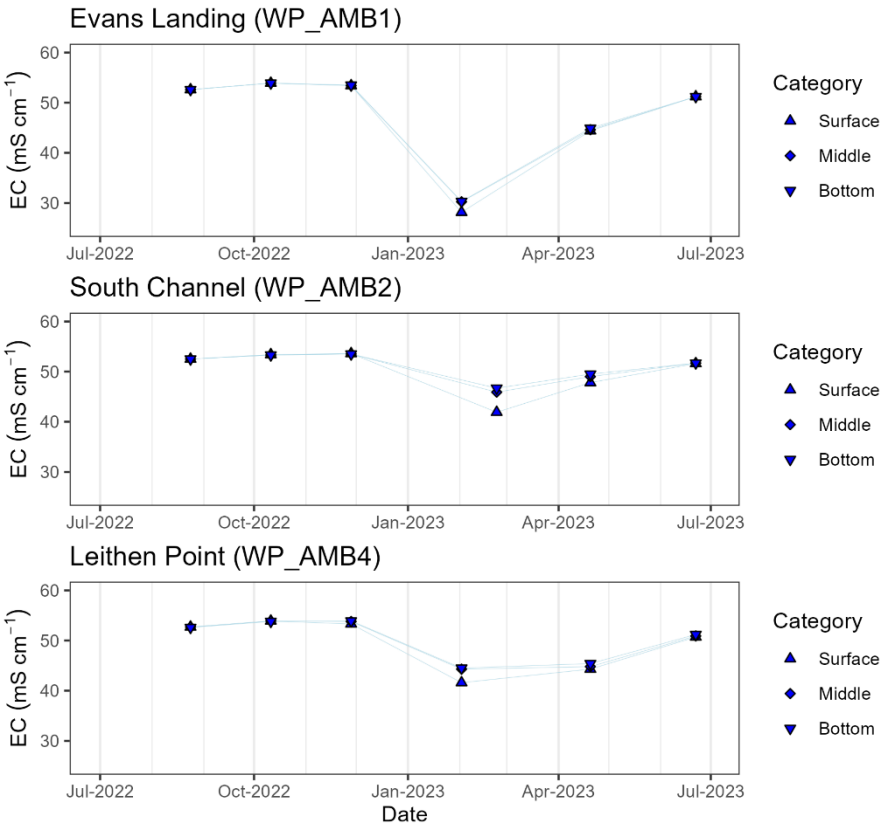

Figure 3.10. Electrical conductivity recorded at three depths at the three water quality sites throughout the reporting period.

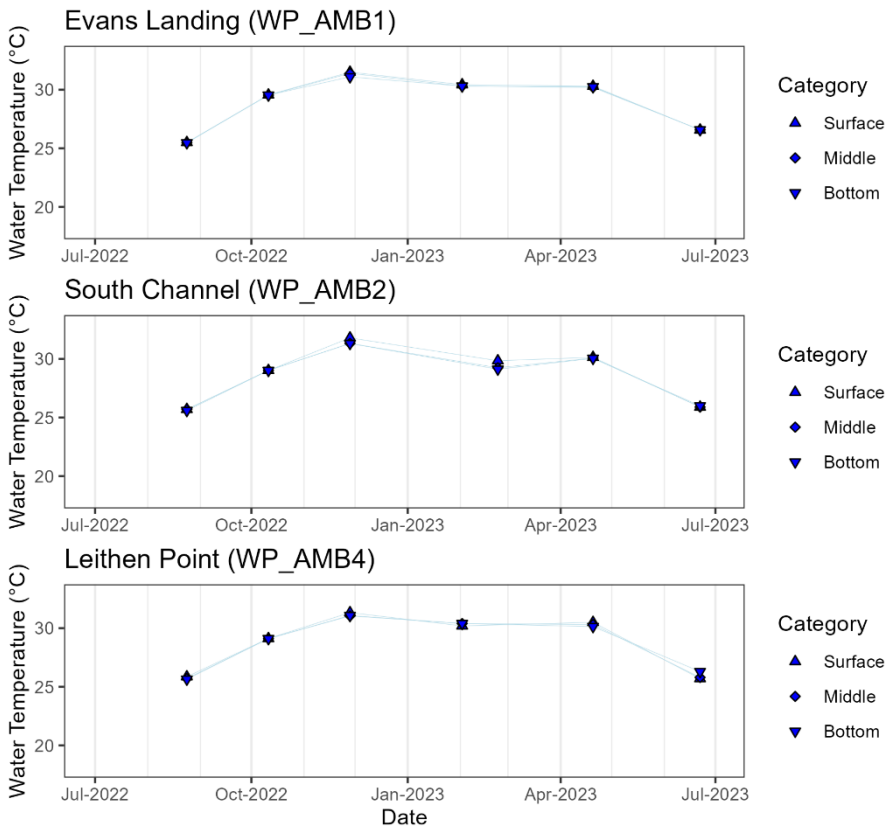

Figure 3.11. Water temperature recorded at three depths at the five water quality sites throughout the reporting period.

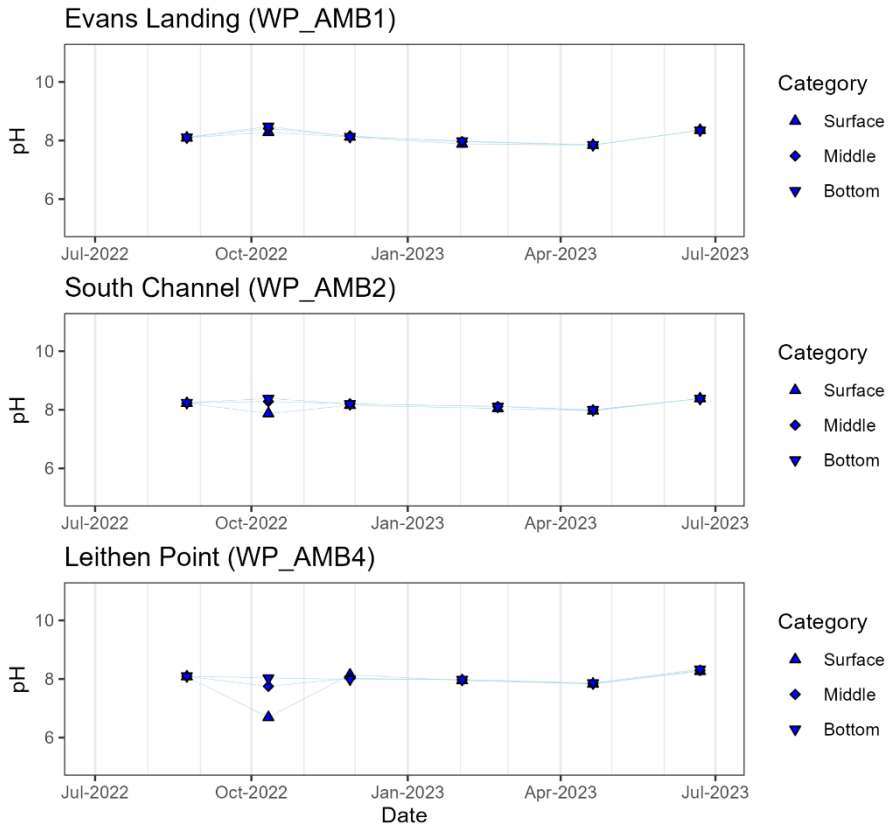

Figure 3.12. pH recorded at three depths at the three water quality sites throughout the reporting period.

3.3.2 Nutrients

Nitrogen concentrations measured in water samples from the three Weipa water quality monitoring sits is shown in Figure 3.13. Total nitrogen (TN) concentrations ranged from 108 to 210 µg L^{-1} with a mean of 157 µg L^{-1} across sites over the reporting period. Total dissolved nitrogen (TDN) ranged from 92 to 163 µg L^{-1} with a mean of 121 µg L^{-1}. Particulate nitrogen (PN) ranged from 3 to 107 µg L^{-1} with a mean of 36 µg L^{-1}. TN and TDN showed a decline in nitrogen concentration over the reporting period with higher nitrogen concentrations measured in the 2022 dry season compared to the 2023 dry season.

Phosphorus concentrations measured in water samples from the three Weipa water quality monitoring sits is shown in Figure 3.14. Total phosphorus (TP) concentrations ranged from 8 to 25 µg L^{-1} with a mean of 16 µg L^{-1} across sites over the reporting period. Total dissolved phosphorus (TDP) ranged from 4 to 16 µg L^{-1} with a mean of 10 µg L^{-1}. Particulate phosphorus (PP) ranged from 0 to 18 µg L^{-1} with a mean of 6 µg L^{-1}. TP and TDP showed lower phosphorus concentrations during the wet season compared to the dry season.

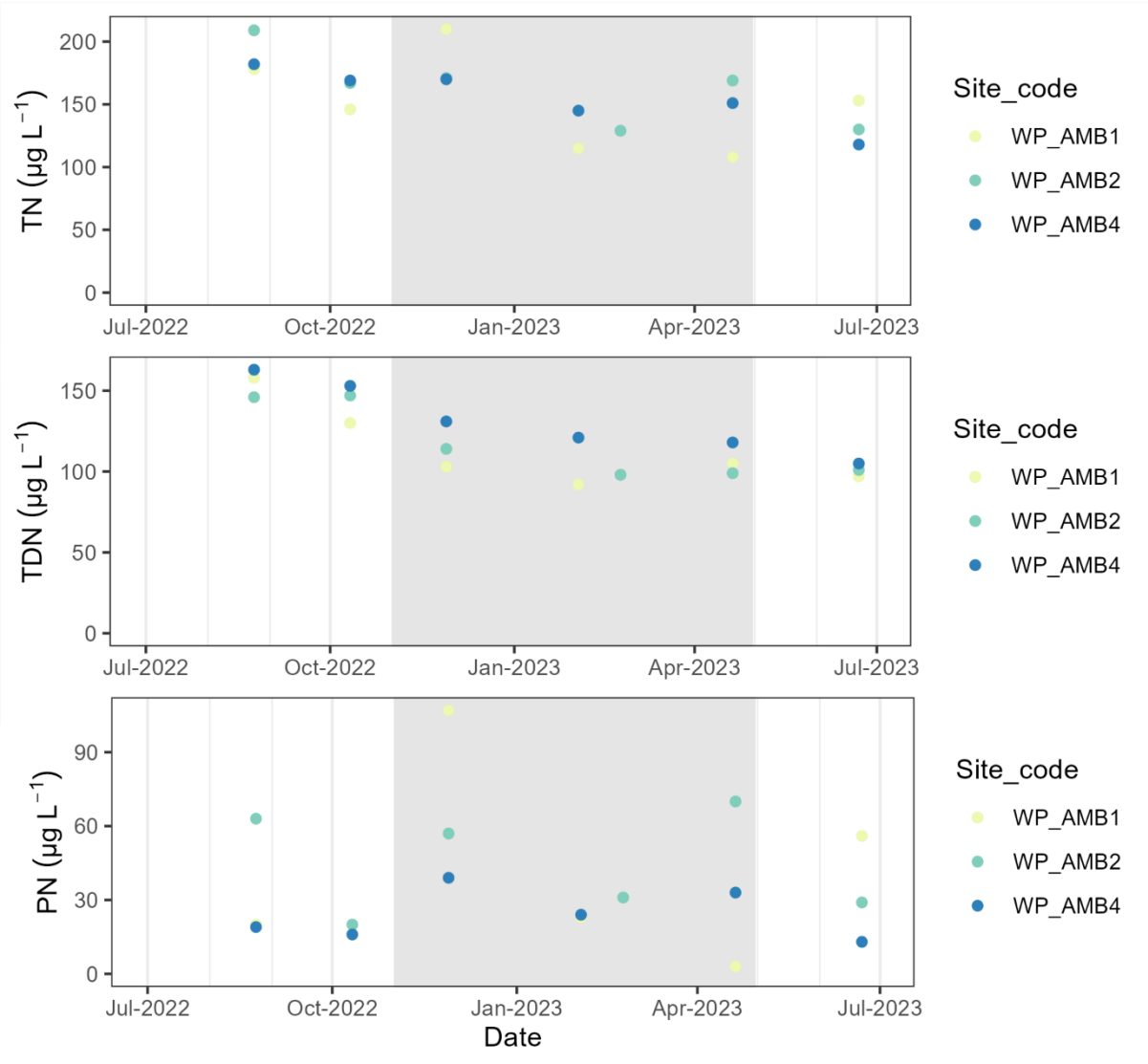

Figure 3.13. Total nitrogen (TN), total dissolved nitrogen (TDN), and particulate nitrogen (PN) concentrations measured in water samples collected from the three water quality sites over the reporting period.

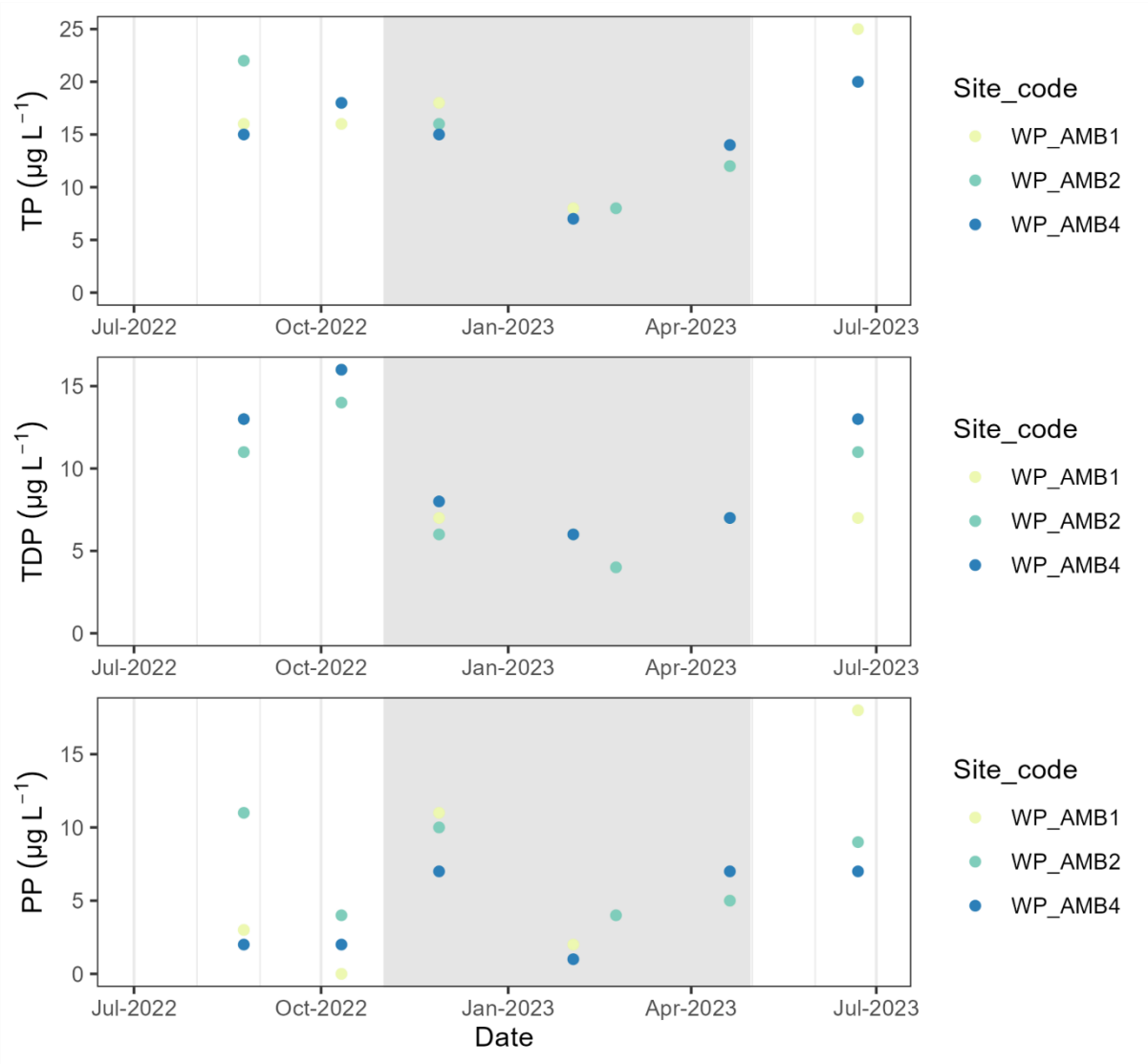

Figure 3.14. Total phosphorus (TP), total dissolved phosphorus (TDN), and particulate phosphorus (PN) concentrations measured in water samples collected from the three water quality sites over the reporting period.

3.3.3 Water clarity

Secchi depth ranged from 1.0 m to 3.0 m with a mean of 1.86 m over the reporting period (Figure 3.15). Water clarity as measured by Secchi depth was similar between sites throughout the reporting period. Shallow Secchi depths correspond with the turbid nature of the Embley River estuary and coastal ocean. Total suspended solids ranged from 1.3 to 22 mg L^{-1} with a mean of 5.2 mg L^{-1} over the reporting period (Figure 3.16).

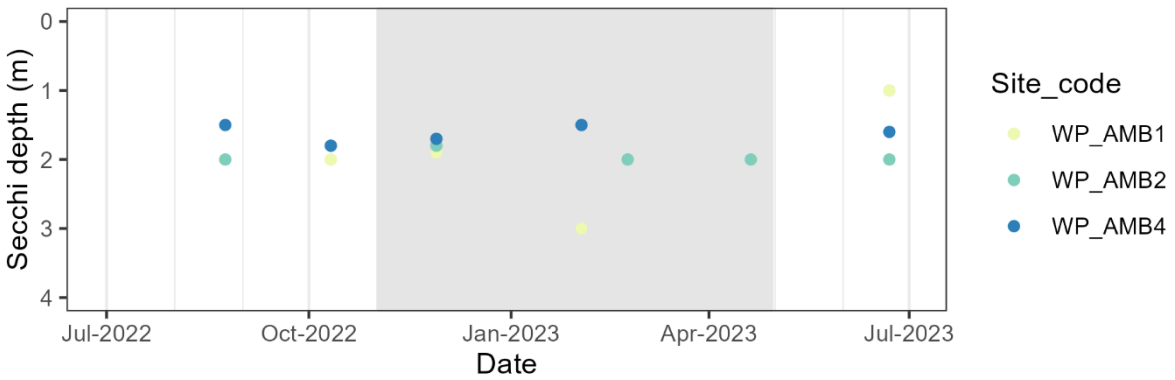

Figure 3.15. Secchi disk depth recorded at the three water quality sites throughout the reporting period.

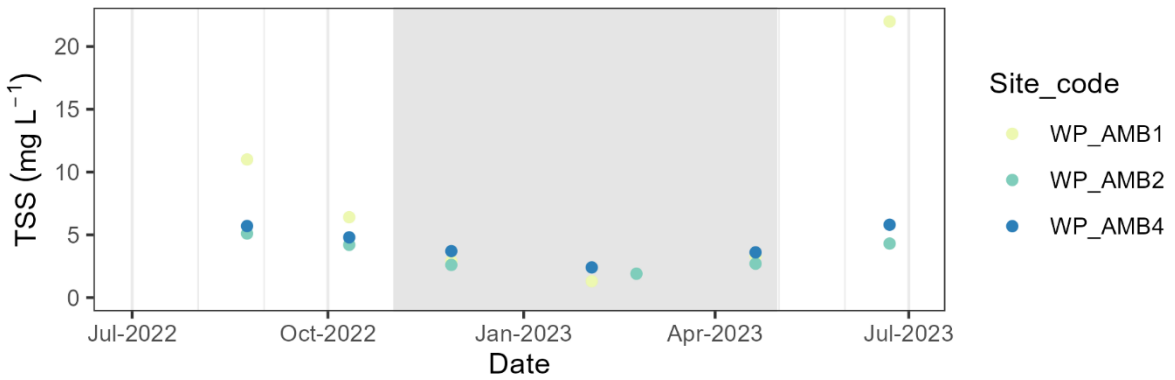

Figure 3.16. Total suspended solids (TSS) concentrations measured from water samples collected from the three water quality sites throughout the reporting period.

3.3.4 Chlorophyll a

Chlorophyll *a* concentration ranged from 0.21 to 3.41 µg L^{-1} with a mean of 1.7 µg L^{-1} across sites over the reporting period (Figure 3.17). Chlorophyll *a* concentrations were generally higher in the summer / wet season and lower in the winter / dry season.

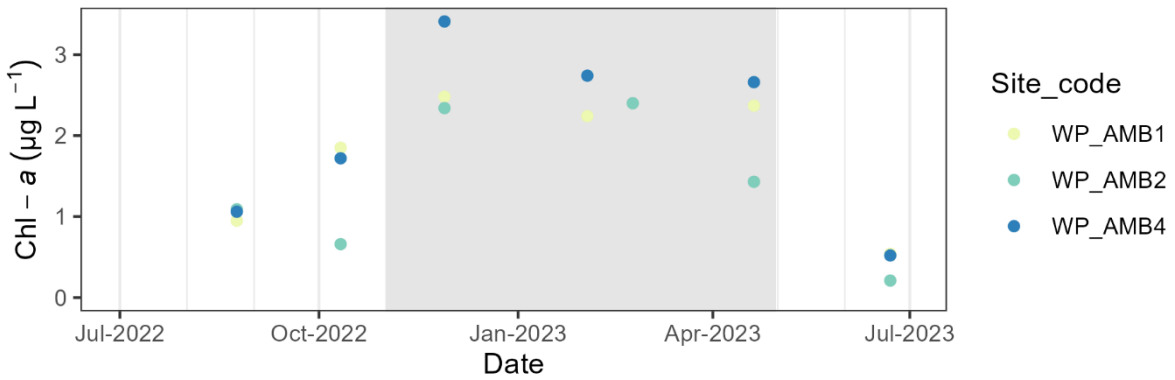

Figure 3.17. Chlorophyll-a concentrations (µg L^{-1}) measured in water samples collected from the three ambient water quality monitoring sites in the Weipa region throughout the reporting period.

3.3.5 Dissolved metals

Heavy metal concentrations are presented in Table 3-1. Metal concentrations measured in these waters during the 2022-2023 monitoring period were below the laboratory limit of detection (LOD) for all monitoring sites in both the dry and wet season sampling. Arsenic was detected at low concentrations at all sites in both the dry and wet season sampling. Metal concentrations were compared to default guideline values (DGV) from the Australian and New Zealand guidelines for fresh and marine water quality (ANZG, 2018). Metals did not exceed DVG's at any monitoring sites when sampled in either the dry or wet season.

Table 3-1. Heavy metal concentrations measured in water samples collected from three water quality sites in the Weipa region throughout the reporting period. Silver (Ag), Arsenic (As), Cadmium (Cd), Copper (Cu), Mercury (Hg), Nickel (Ni), and Lead (Pb). The ANZG water quality default guideline value 99% and 95% level of protection trigger values for marine waters are shown for comparison.

Site name	Site code	Ag	As	Cd	Cu	Hg	Ni	Pb
Dry season (24/08/2022)		µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}
Evans Landing	WP_AMB1	<0.1	1.3	<0.5	<1	<0.04	<0.5	<0.2
South Channel	WP_AMB2	<0.1	1.6	<0.5	<1	<0.04	<0.5	<0.2
Leithen Point	WP_AMB4	<0.1	1.9	<0.5	<1	<0.04	<0.5	<0.2
Wet season (02/02/2023 WP_AMB1 and WP_AMB4, 23/02/2023 WP_AMB2)								
Evans Landing	WP_AMB1	<0.1	1.2	<0.2	<1	<0.1	<0.5	<0.2
South Channel	WP_AMB2	<0.1	1	<0.2	<1	<0.1	<0.5	<0.2
Leithen Point	WP_AMB4	<0.1	1.3	<0.2	<1	<0.1	<0.5	<0.2
Limit of detection (LOD)#		0.1	-	0.2/0.5	1	0.1/ 0.04	0.5	0.2
ANZG 99% level of species protection		0.8	-	0.7	0.3	0.1	7	2.2
ANZG 95% level of species protection		1.4	-	5.5	1.3	0.4	70	4.4

#Note: External laboratory provided different LOD for mercury between the two sampling events

3.3.6 Pesticides

Pesticides used for ms-PAF calculations are presented in Table 3-2. No pesticides were detected in the early wet season. The herbicides Chlorpyrifos, Diazinon, Hexazinone, and Ametryn were also not detected (< LOD). There was no pesticide analysis conducted in the late wet season.

Table 3-2. Pesticide results from water samples taken in the early wet season from three locations in the Weipa region.

Analyte (µg/L)	WP_AMB1 Evans Landing	WP_AMB2 South Channel	WP_AMB4 Leithen Point
Chlorpyrifos	<0.001	<0.001	<0.001
Malathion	<0.001	<0.001	<0.001
Diazinon	<0.0002	<0.0002	<0.0002
Pirimiphos-methyl	<0.0002	<0.0002	<0.0002
Thiobencarb	<0.0002	<0.0002	<0.0002
Pendimethalin	<0.001	<0.001	<0.001
Hexazinone	<0.0002	<0.0002	<0.0002
Propiconazole	<0.0002	<0.0002	<0.0002
Hexaconazole	<0.0002	<0.0002	<0.0002
Difenoconazole	<0.0002	<0.0002	<0.0002
Tebuconazole	<0.0002	<0.0002	<0.0002
Flusilazole	<0.0002	<0.0002	<0.0002
Penconazole	<0.0002	<0.0002	<0.0002
Diuron	<0.0002	<0.0002	<0.0002
Ametryn	<0.0002	<0.0002	<0.0002
Atrazine	<0.0002	<0.0002	<0.0002
Cyanazine	<0.0002	<0.0002	<0.0002
Prometryn	<0.0002	<0.0002	<0.0002
Propazine	<0.0002	<0.0002	<0.0002
Simazine	<0.0002	<0.0002	<0.0002
Terbuthylazine	<0.0002	<0.0002	<0.0002
Terbutryn	<0.0002	<0.0002	<0.0002

3.4 In-situ loggers

3.4.1 Water temperature

Water temperature recorded near the seafloor by the in-situ water quality loggers at each of the three Weipa region water quality monitoring sites is presented in Figure 3.18. Water temperature

ranged from 23.86 to 33.16 °C with the coolest water temperatures recorded in July 2022 and the warmest month being November 2022. Water temperature is primarily driven by season, with warmer temperatures throughout the wet season / summer. This overall trend is made variable by several factors including - tidal influences (spring/neap tides driving tidal currents and depth changes that affect local sea temperatures); synoptic events (winds, low pressure systems, troughs, and fronts impact water temperature through advection, mixing, and solar radiation limitations); and oceanographic influences (ocean currents and interaction with the coastline/ the mixing of water masses that redistribute heat). Rainfall and freshwater inflows throughout the wet season also lowered water temperature during those events. Examples of this can be seen in late December/early January, when an extreme weather event saw a sharp drop in water temperatures. Monthly, seasonal, and overall temperatures for each site are presented in in Table 3-3, Table 3-4, and Table 3-5.

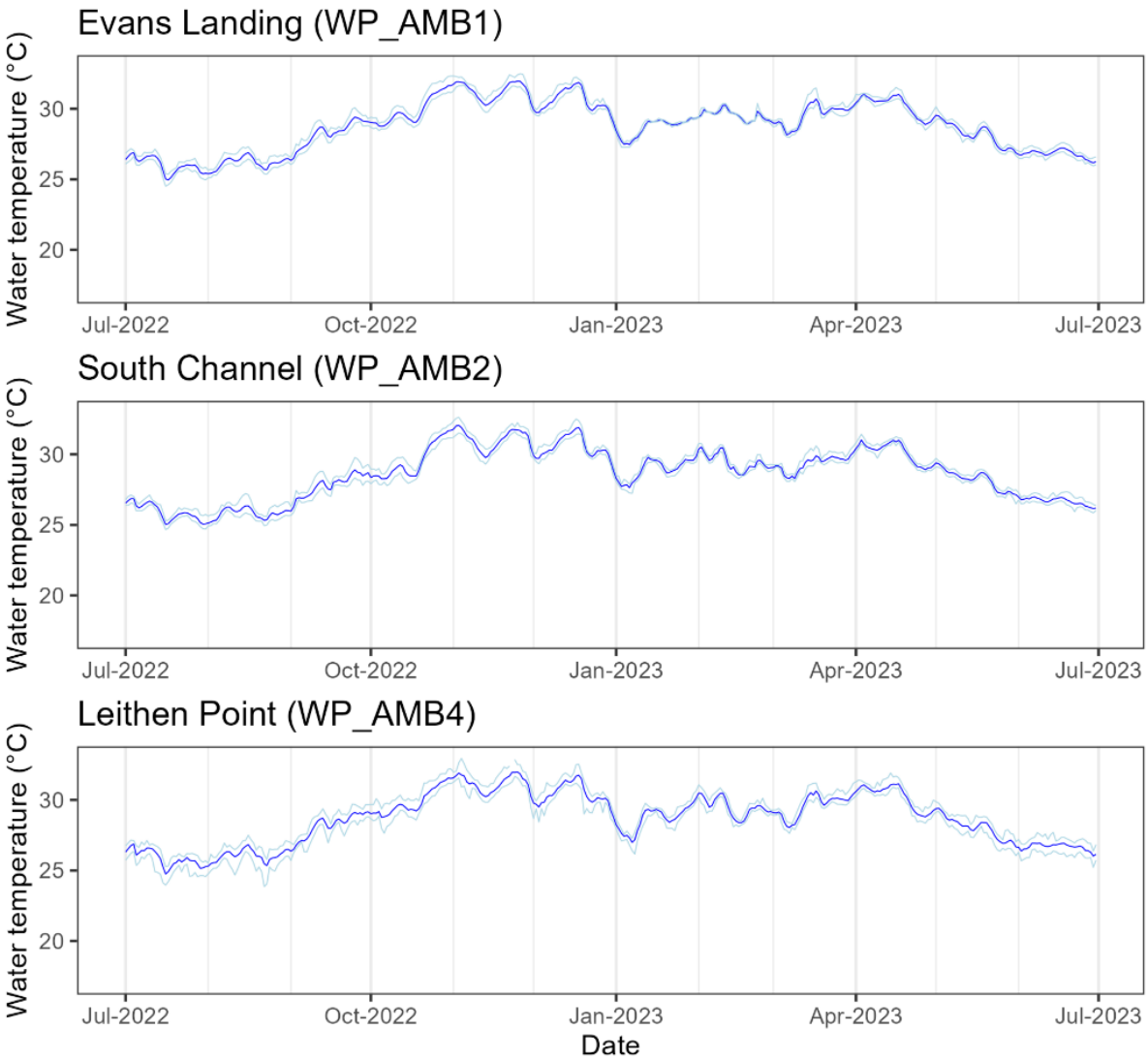

Figure 3.18. Daily mean water temperature (blue) and daily minimum and maximum (light blue) measured at water quality monitoring sites in the Weipa region. Periods of missing data are indicated by the orange bar.

Measured water temperatures at the three Weipa region water quality monitoring sites were compared to NOAA daily global 5km satellite sea surface temperature (a.k.a. CoralTemp) for the Gulf

of Carpentaria region virtual station (Figure 3.19). Water temperature at all three monitoring sites was similar to the regional daily average sea surface temperature (SST) measured from satellite. Water temperature was warmer than the monthly mean climatology during the 2022 and 2023 dry seasons, but similar to monthly mean climatology over the 2022-2023 wet season. Water temperature was generally 2 °C warmer than the monthly mean climatology from July to November 2022, with water temperature up to 3 °C warmer than the monthly mean climatology during September 2022. Water temperature was generally 0.5 to 1 °C cooler than the monthly mean climatology from January to March 2023.

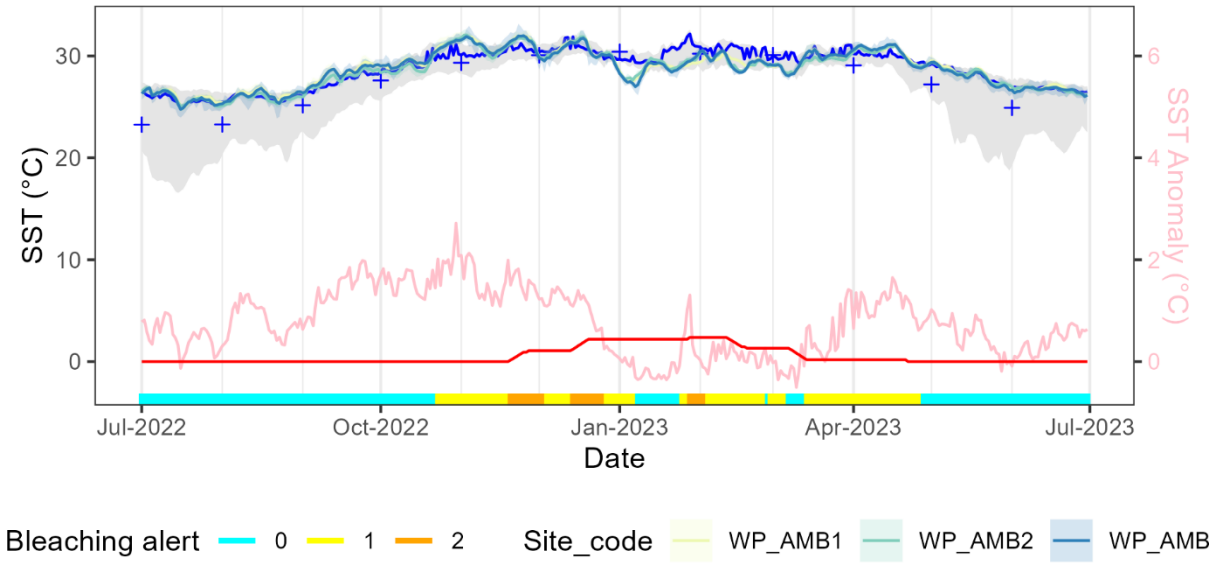

Figure 3.19. Water temperature measured at the three Weipa water quality monitoring sites compared to NOAA Daily Global 5km Satellite Sea Surface Temperature (a.k.a. CoralTemp) (blue), sea surface temperature (SST) anomaly (pink), degree heating weeks (red), monthly mean climatology (blue cross), and coral bleaching alert levels (0 = no stress, 1 = Bleaching watch, 2 = Bleaching warning, 3 = Alert level 1, 4 = Alert level 2). NOAA data and plot adapted from: https://coralreefwatch.noaa.gov/product/5km/index_5km_sst.php

Table 3-3. Monthly summary statistics for water temperature (°C) measured by continuous dataloggers at the Evans Landing (WP_AMB1) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	26.04	26.09	0.57	24.51	27.17	25.63	26.51	4464
Aug-2022	26.18	26.2	0.44	25.11	27.3	25.9	26.49	4458
Sep-2022	28.24	28.37	0.87	26.04	30.07	27.66	28.95	4320
Oct-2022	29.9	29.52	1.01	28.46	32.32	29.05	30.9	4461
Nov-2022	31.29	31.37	0.62	29.76	32.48	30.81	31.77	4313
Dec-2022	30.54	30.3	0.78	28.69	32.25	29.96	31.3	4464
Jan-2023	28.66	28.95	0.61	27.26	29.43	28.15	29.09	4464
Feb-2023	29.55	29.59	0.36	28.9	30.38	29.22	29.77	3858
Mar-2023	29.55	29.77	0.75	27.97	31.48	28.94	30.1	4464
Apr-2023	30.23	30.52	0.72	28.49	31.52	29.57	30.76	4318
May-2023	28.2	28.22	0.79	26.67	30.15	27.44	28.84	4464
Jun-2023	26.79	26.82	0.32	25.95	27.6	26.62	27	4316
Dry season	27.56	27.05	1.54	24.51	32.32	26.38	28.78	26483
Wet season	29.97	29.95	1.07	27.26	32.48	29.15	30.7	25881
Overall	28.75	29.04	1.8	24.51	32.48	27.03	30.09	52364

Table 3-4. Monthly summary statistics for water temperature (°C) measured by continuous dataloggers at the South Channel (WP_AMB2) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	25.93	25.89	0.6	24.66	27.12	25.44	26.45	4464
Aug-2022	25.81	25.8	0.43	24.92	27.22	25.51	26.12	4454
Sep-2022	27.78	27.91	0.82	25.66	29.78	27.12	28.35	4320
Oct-2022	29.51	29.01	1.25	27.79	32.14	28.45	30.75	4462
Nov-2022	31.1	31.25	0.71	29.3	32.63	30.52	31.66	4317
Dec-2022	30.5	30.3	0.78	28.46	32.51	29.99	31.2	4464
Jan-2023	28.92	29.02	0.71	27.23	30.36	28.34	29.54	4464
Feb-2023	29.46	29.38	0.63	28.29	30.78	28.96	30.01	3851
Mar-2023	29.34	29.47	0.56	28.07	30.61	29.01	29.73	4464
Apr-2023	30.15	30.41	0.72	28.74	31.42	29.36	30.71	4310
May-2023	28.21	28.34	0.68	26.49	29.72	27.48	28.7	4464
Jun-2023	26.68	26.72	0.3	25.85	27.35	26.46	26.91	4319
Dry season	27.32	26.98	1.52	24.66	32.14	26.17	28.38	26483
Wet season	29.91	29.84	1.02	27.23	32.63	29.19	30.58	25870
Overall	28.6	28.81	1.83	24.66	32.63	26.96	29.98	52353

Table 3-5. Monthly summary statistics for water temperature (°C) measured by continuous dataloggers at the Leithen Point (WP_AMB4) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	25.87	25.88	0.66	23.96	27.15	25.39	26.43	4464
Aug-2022	26.06	26.11	0.51	23.86	27.5	25.71	26.41	4457
Sep-2022	28.16	28.41	0.86	25.7	29.7	27.51	28.82	4320
Oct-2022	29.87	29.61	0.95	27.64	32.2	29.13	30.73	4461
Nov-2022	31.22	31.28	0.63	29.49	33.16	30.76	31.73	4314
Dec-2022	30.4	30.23	0.79	28.43	32.53	29.88	31.11	4464
Jan-2023	28.66	28.8	0.85	26.16	30.64	28.05	29.31	4464
Feb-2023	29.49	29.43	0.67	28.09	31.07	29.05	30.08	4028
Mar-2023	29.57	29.84	0.8	27.63	31.2	29.04	30.17	4464
Apr-2023	30.24	30.59	0.86	28.35	31.91	29.3	30.88	4317
May-2023	28.04	28.09	0.79	26.05	29.88	27.35	28.61	4464
Jun-2023	26.67	26.71	0.38	25.23	27.7	26.41	26.95	4317
Dry season	27.45	26.99	1.58	23.86	32.2	26.27	28.68	26483
Wet season	29.93	29.99	1.12	26.16	33.16	29.16	30.75	26051
Overall	28.68	28.95	1.85	23.86	33.16	26.96	30.13	52534

3.4.2 Water depth

The daily tidal range for each site is presented in Figure 3.20. The Weipa region is mixed semi-diurnal with a very pronounced diurnal inequality. At certain times the inequality results in only one tidal cycle per day. Daily tidal range was measured to be from 0.54 to 2.75 m during the reporting period. The water depth which the water quality loggers were positioned was 4.5 - 5.0 m for all sites.

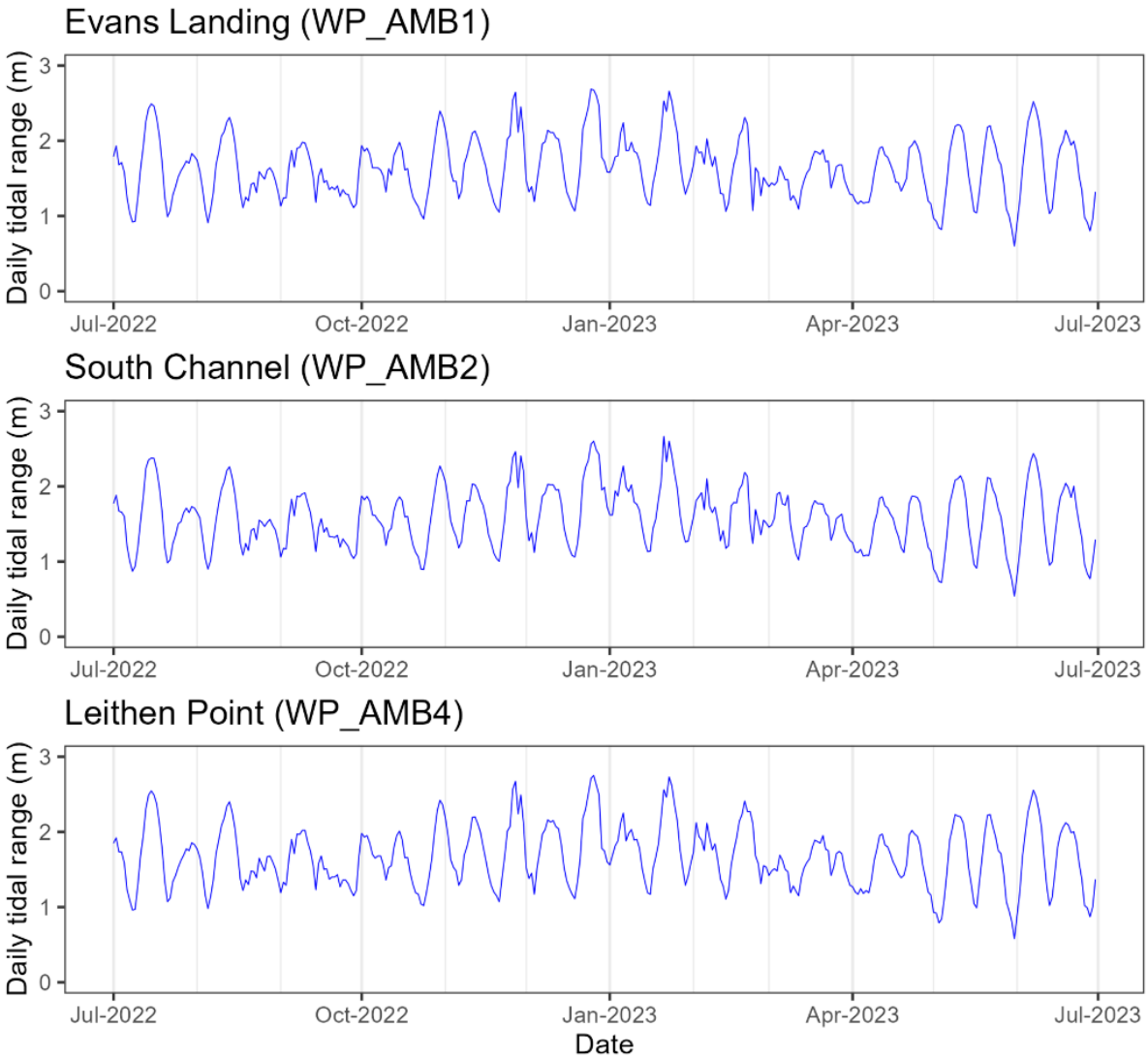

Figure 3.20. Daily tidal range measured at Weipa monitoring sites.

Table 3-6. Monthly summary statistics for water depth (m) measured by continuous dataloggers at the Evans Landing (WP_AMB1) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	4.37	4.49	0.53	2.65	5.28	4.07	4.76	4464
Aug-2022	4.36	4.44	0.51	2.73	5.4	4.07	4.73	4460
Sep-2022	4.47	4.55	0.47	3.25	5.28	4.14	4.84	4320
Oct-2022	4.75	4.84	0.53	3.43	5.84	4.41	5.15	4461
Nov-2022	4.94	5.06	0.55	3.17	6.08	4.62	5.35	4317
Dec-2022	4.67	4.74	0.59	3.03	5.92	4.27	5.11	4464
Jan-2023	4.81	4.92	0.58	3.08	6.15	4.42	5.21	4464
Feb-2023	4.73	4.86	0.59	3.14	5.74	4.31	5.18	3861
Mar-2023	4.24	4.3	0.52	2.93	5.3	3.86	4.65	4464
Apr-2023	4.07	4.18	0.52	2.49	4.97	3.71	4.45	4318
May-2023	3.72	3.86	0.5	2.15	4.58	3.42	4.07	4464
Jun-2023	3.87	3.97	0.58	2.12	4.91	3.59	4.31	4319
Dry season	4.26	4.32	0.63	2.12	5.84	3.86	4.73	26488
Wet season	4.57	4.62	0.64	2.49	6.15	4.13	5.06	25888
Overall	4.41	4.45	0.65	2.12	6.15	3.98	4.91	52376

Table 3-7. Monthly summary statistics for water depth (m) measured by continuous dataloggers at the South Channel (WP_AMB2) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	4.08	4.18	0.51	2.43	4.98	3.8	4.46	4464
Aug-2022	4.13	4.22	0.48	2.64	5.1	3.84	4.46	4459
Sep-2022	4.35	4.42	0.45	3.16	5.13	4.04	4.71	4320
Oct-2022	4.48	4.6	0.49	3.14	5.41	4.19	4.84	4462
Nov-2022	4.58	4.66	0.54	3.19	5.71	4.26	4.97	4317
Dec-2022	4.79	4.85	0.57	3.24	6.13	4.42	5.2	4464
Jan-2023	4.98	5.06	0.57	3.28	6.33	4.61	5.38	4464
Feb-2023	5.04	5.14	0.53	3.59	6.1	4.69	5.43	3855
Mar-2023	4.92	4.96	0.49	3.69	6.11	4.58	5.32	4464
Apr-2023	4.68	4.77	0.51	3.06	5.61	4.34	5.06	4317
May-2023	4.41	4.51	0.47	2.94	5.3	4.15	4.73	4464
Jun-2023	4.39	4.47	0.53	2.97	5.44	4.05	4.78	4319
Dry season	4.31	4.38	0.51	2.43	5.44	3.99	4.68	26488
Wet season	4.83	4.89	0.56	3.06	6.33	4.47	5.23	25881
Overall	4.56	4.59	0.6	2.43	6.33	4.19	4.98	52369

Table 3-8. Monthly summary statistics for water depth (m) measured by continuous dataloggers at the Leithen Point (WP_AMB4) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	4.57	4.7	0.54	2.8	5.49	4.25	4.97	4464
Aug-2022	4.55	4.62	0.53	2.89	5.63	4.24	4.93	4460
Sep-2022	4.72	4.8	0.49	3.37	5.59	4.36	5.13	4320
Oct-2022	4.8	4.91	0.52	3.33	5.75	4.46	5.2	4463
Nov-2022	4.87	4.98	0.57	3.28	5.95	4.5	5.3	4317
Dec-2022	5	5.07	0.61	3.38	6.32	4.6	5.45	4464
Jan-2023	5.24	5.35	0.59	3.47	6.55	4.87	5.65	4464
Feb-2023	5.38	5.5	0.56	3.81	6.28	5.06	5.81	4029
Mar-2023	5.22	5.24	0.56	3.81	6.4	4.84	5.62	4464
Apr-2023	4.79	4.82	0.64	2.82	5.88	4.36	5.33	4317
May-2023	4.22	4.34	0.5	2.65	5.15	3.96	4.58	4464
Jun-2023	4.19	4.28	0.56	2.68	5.24	3.85	4.6	4317
Dry season	4.51	4.58	0.57	2.65	5.75	4.15	4.94	26488
Wet season	5.08	5.17	0.62	2.82	6.55	4.68	5.53	26055
Overall	4.79	4.83	0.66	2.65	6.55	4.36	5.28	52543

3.4.3 Wave activity

South Channel (WP_AMB2) is located along the exposed coastline and had the most wave exposure of the three Weipa sites, while Evans Landing (WP_AMB1) and Leithen Point (WP_AMB4) are sheltered within the Embley River estuary and wave activity was minimal (Figure 3.21). Wave energy at the South Channel monitoring site was generally low throughout the 2022 and 2023 dry season, whereas there were notable high energy periods from November 2022 through to March 2023.

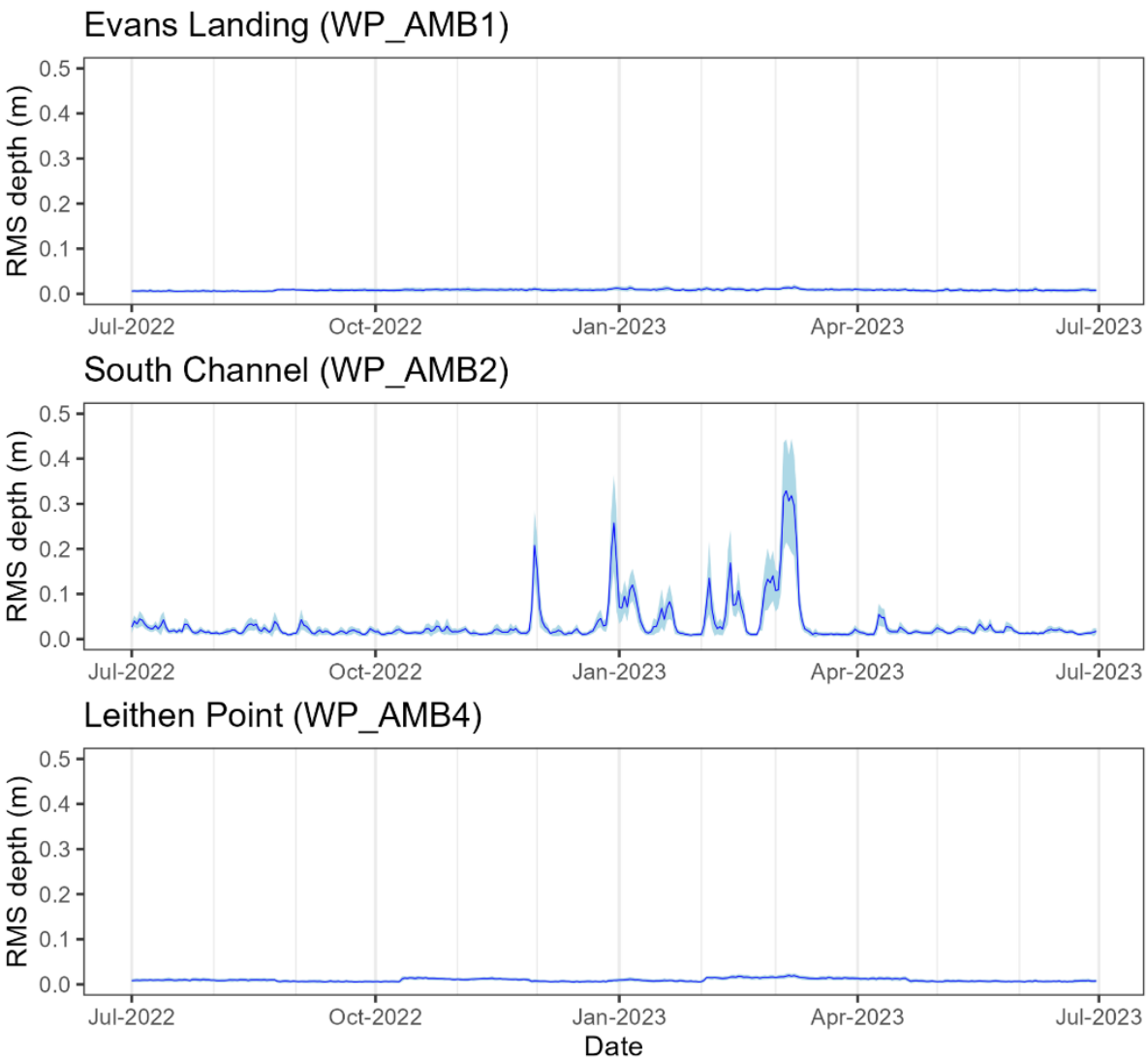

Figure 3.21. RMS depth measured at Weipa monitoring sites. Values presented are daily mean (blue line) +/- standard deviation (light blue ribbon).

Table 3-9. Monthly summary statistics for wave activity (Depth RMS) measured by continuous dataloggers at the Evans Landing (WP_AMB1) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	0.006	0.006	0.003	0	0.025	0.004	0.008	4464
Aug-2022	0.007	0.007	0.003	0	0.026	0.004	0.009	4460
Sep-2022	0.008	0.008	0.004	0	0.03	0.005	0.011	4320
Oct-2022	0.009	0.009	0.004	0	0.029	0.005	0.012	4461
Nov-2022	0.009	0.01	0.004	0	0.058	0.006	0.013	4317
Dec-2022	0.009	0.01	0.004	0	0.028	0.005	0.012	4464
Jan-2023	0.01	0.01	0.005	0	0.044	0.007	0.013	4464
Feb-2023	0.01	0.01	0.004	0	0.031	0.007	0.013	3861
Mar-2023	0.01	0.011	0.004	0	0.048	0.007	0.013	4464
Apr-2023	0.008	0.008	0.004	0	0.026	0.005	0.011	4318
May-2023	0.008	0.008	0.004	0	0.028	0.005	0.01	4464
Jun-2023	0.008	0.008	0.004	0	0.029	0.005	0.011	4319
Dry season	0.008	0.007	0.004	0	0.03	0.005	0.01	26488
Wet season	0.009	0.01	0.004	0	0.058	0.006	0.013	25888
Overall	0.008	0.008	0.004	0	0.058	0.005	0.012	52376

Table 3-10. Monthly summary statistics for wave activity (Depth RMS) measured by continuous dataloggers at the South Channel (WP_AMB2) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	0.025	0.021	0.013	0.001	0.131	0.015	0.03	4464
Aug-2022	0.019	0.016	0.012	0	0.117	0.012	0.024	4459
Sep-2022	0.018	0.015	0.011	0	0.134	0.011	0.022	4320
Oct-2022	0.017	0.015	0.01	0	0.097	0.012	0.02	4462
Nov-2022	0.024	0.014	0.04	0	0.404	0.011	0.021	4317
Dec-2022	0.046	0.02	0.071	0	0.594	0.012	0.041	4464
Jan-2023	0.044	0.026	0.041	0	0.212	0.013	0.068	4464
Feb-2023	0.067	0.049	0.062	0	0.415	0.016	0.095	3855
Mar-2023	0.082	0.016	0.125	0	0.671	0.01	0.104	4464
Apr-2023	0.019	0.015	0.014	0	0.138	0.012	0.021	4317
May-2023	0.02	0.019	0.009	0	0.093	0.014	0.024	4464
Jun-2023	0.015	0.014	0.006	0	0.074	0.011	0.018	4319
Dry season	0.019	0.016	0.011	0	0.134	0.012	0.023	26488
Wet season	0.047	0.018	0.072	0	0.671	0.012	0.047	25881
Overall	0.033	0.017	0.053	0	0.671	0.012	0.028	52369

Table 3-11. Monthly summary statistics for wave activity (Depth RMS) measured by continuous dataloggers at the Leithen Point (WP_AMB4) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	0.01	0.01	0.004	0	0.03	0.006	0.013	4464
Aug-2022	0.009	0.009	0.004	0	0.024	0.006	0.012	4460
Sep-2022	0.006	0.006	0.003	0	0.019	0.004	0.009	4320
Oct-2022	0.011	0.011	0.005	0	0.027	0.007	0.015	4463
Nov-2022	0.011	0.011	0.004	0	0.025	0.009	0.014	4317
Dec-2022	0.007	0.006	0.004	0	0.026	0.004	0.009	4464
Jan-2023	0.008	0.008	0.004	0	0.022	0.005	0.011	4464
Feb-2023	0.015	0.015	0.005	0	0.029	0.012	0.018	4029
Mar-2023	0.015	0.015	0.005	0	0.032	0.012	0.018	4464
Apr-2023	0.011	0.011	0.005	0	0.03	0.007	0.014	4317
May-2023	0.007	0.007	0.003	0	0.028	0.004	0.009	4464
Jun-2023	0.007	0.007	0.004	0	0.023	0.004	0.009	4318
Dry season	0.008	0.008	0.004	0	0.03	0.005	0.011	26489
Wet season	0.011	0.011	0.005	0	0.032	0.007	0.015	26055
Overall	0.01	0.009	0.005	0	0.032	0.006	0.013	52544

3.4.4 Turbidity

Turbidity measured at water quality monitoring sites in the Weipa region is presented in Figure 3.22. Annual mean turbidity values were 17.15 NTU at Evans Landing, 29.4 NTU at South Channel, and 54.65 NTU at Leithen Point. Turbidity was approximately two times higher in the wet season compared to the dry season at Evans Landing (Table 3-12), and ten-fold higher at the South Channel monitoring site (Table 3-13). Meanwhile, there was no major difference in turbidity between seasons for the inner-estuary site at Leithen Point (Table 3-14). Turbidity was highly variable at Evans Landing from July to September 2022, and at all sites in June 2023.

There was a significant relationship ($p<0.001$) between turbidity and wave activity (RMS depth) at South Channel, with a Pearsons R correlation of 0.54 between the variables. Waves were a very minor contributor to turbidity at Evans Landing and did not affect turbidity at Leithen Point.

There was a period of missing data from the Evans Landing site from 26th December 2022 to 23rd February 2023 due to damage to instruments. The instrument frame and water quality loggers were buried and stuck in sediment following an extreme weather event. When maintenance was performed in early February it was not possible to retrieve the logger frames and a follow-up recovery trip was arranged in late February.

There were numerous prolonged periods when turbidity was recorded as maximum value on the loggers (either approx. 400 or 1000 NTU depending on the specific logger unit in use). This can be seen best on the 10-minute interval plots where data appears to be 'clipped' at 400 or 1000 NTU (Appendix 2). Hence, turbidity is most likely under-estimated during these periods. Note that since these occurrences were noticed, efforts have been made to ensure all loggers deployed in Weipa are the high range (1000 NTU) loggers.

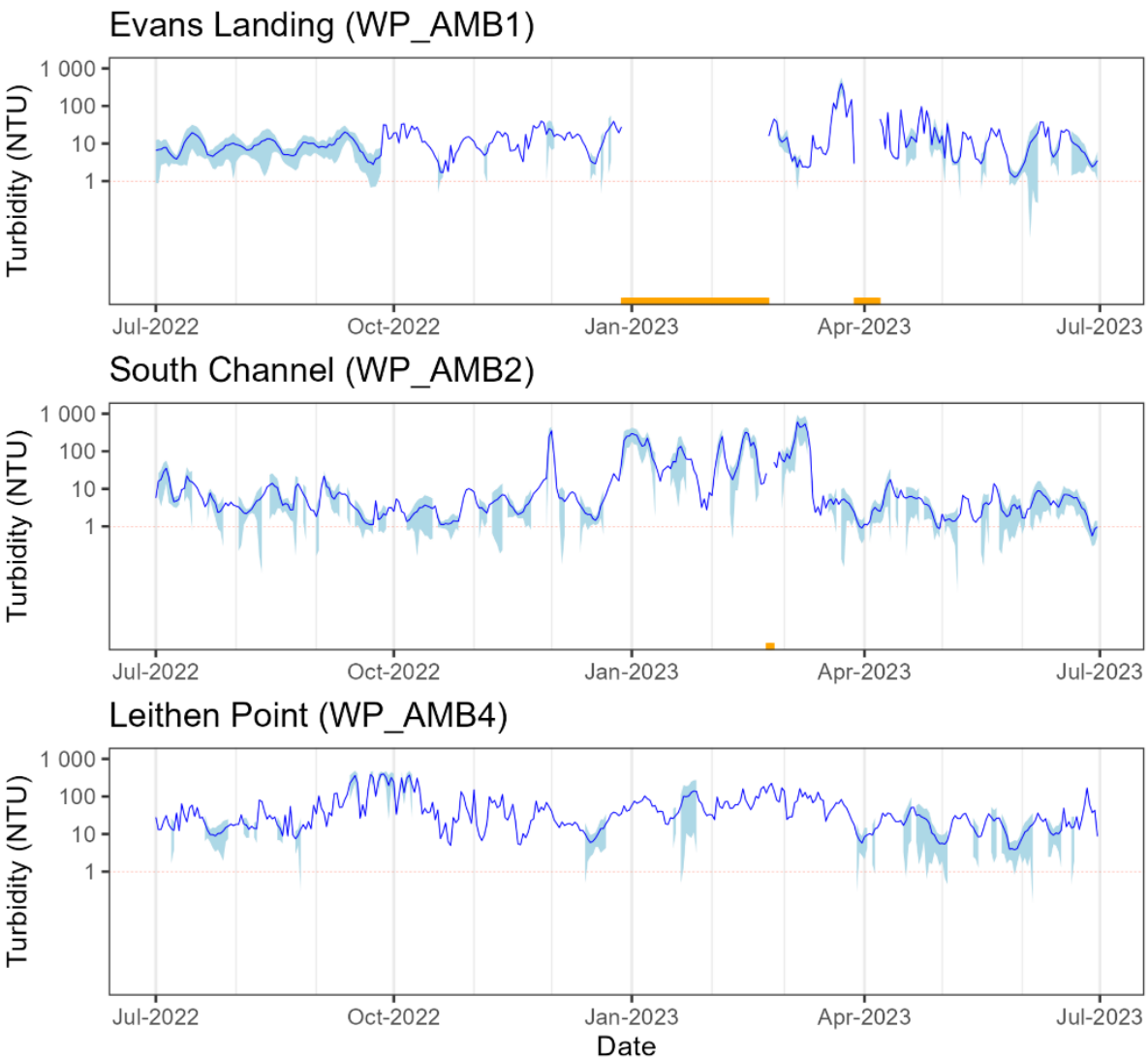

Figure 3.22. Turbidity measured at the three water quality monitoring sites in Weipa. Results presented are daily mean (blue line) and standard deviation (light blue). Y-axis is in log scale. Periods of missing data are indicated by the orange bar.

Table 3-12. Monthly summary statistics for turbidity (NTU) measured by continuous dataloggers at the Evans Landing (WP_AMB1) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	8.7	5.66	7.65	0.88	88.98	3.72	11.04	4464
Aug-2022	8.73	6.86	6.13	1.45	44.89	4.29	11.34	4458
Sep-2022	10.98	7.06	24.56	0.42	407.54	3.66	12.85	4320
Oct-2022	12.93	2.89	45.93	0.43	1002	1.56	9.1	4461
Nov-2022	14.88	4.74	50.69	0.95	1003.02	2.65	13.01	4313
Dec-2022	15.6	7.38	29.09	0.95	451.86	3.28	17.95	3931
Jan-2023	-	-	-	-	-	-	-	0
Feb-2023	26.02	15.55	58.7	2.16	1115.55	9.66	26.01	776
Mar-2023	54.69	4.66	130.15	0.12	1115.45	2.51	21.71	3972
Apr-2023	27.24	9.33	80.42	1.22	1114.94	4.8	18.69	3430
May-2023	10	3.43	32.69	0.6	1044.95	1.77	10.16	4464
Jun-2023	12.07	4.16	38.34	0.83	1047.49	2.74	10.5	4316
Dry season	10.56	5.11	29.87	0.42	1047.49	2.82	11.18	26483
Wet season	27.79	6.7	82.1	0.12	1115.55	3.28	18.08	16422
Overall	17.15	5.59	56.58	0.12	1115.55	2.96	13.18	42905

Table 3-13. Monthly summary statistics for turbidity (NTU) measured by continuous dataloggers at the South Channel (WP_AMB2) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	9.78	5.28	13.58	0.88	406.09	2.76	11.12	4464
Aug-2022	5.98	3.3	7.62	0.27	204.09	2.23	6.93	4454
Sep-2022	4.89	2.32	9.8	0.34	491.04	1.31	5.33	4320
Oct-2022	3.18	1.61	6.33	0.39	259.66	1.17	2.54	4462
Nov-2022	13.74	3.07	51.6	0.83	419.74	2.22	5.82	4317
Dec-2022	42.85	3.47	100.02	0.82	419.98	2.03	18.91	4455
Jan-2023	78.49	36.62	102.19	0.84	420	10.69	101.34	4266
Feb-2023	93.9	40.75	116.49	0.62	679.64	16	125.52	3644
Mar-2023	97.99	4.17	216.37	0.28	1005.27	2.08	71.5	4464
Apr-2023	5.09	3.12	7.23	0.33	166.99	1.85	5.33	4310
May-2023	3.52	1.7	6.42	0.44	115.62	1.11	3.3	4464
Jun-2023	4.36	3.42	4.72	0.26	137.3	1.81	5.32	4319
Dry season	5.29	2.68	8.87	0.26	491.04	1.46	5.61	26483
Wet season	54.47	5.46	124.42	0.28	1005.27	2.34	39.02	25456
Overall	29.4	3.49	90.73	0.26	1005.27	1.83	11.36	51939

Table 3-14. Monthly summary statistics for turbidity (NTU) measured by continuous dataloggers at the Leithen Point (WP_AMB4) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	23.12	11.23	58.67	1.64	596.02	7.34	18.66	4464
Aug-2022	24.66	12.1	62.48	2.11	595.93	7.71	19.36	4457
Sep-2022	162.23	56.24	173.13	-0.28	422.99	10.4	369.96	4320
Oct-2022	97.73	11.76	160.34	-0.26	1098.32	3.94	113.85	4461
Nov-2022	42.23	8.08	128.49	1.31	1097.45	4.6	23.35	4314
Dec-2022	22.07	10.67	34.01	1.76	406.01	6.19	23.88	4464
Jan-2023	64.82	29.32	87	2.43	406.7	13.73	74.83	4464
Feb-2023	93.59	38.92	161.87	2.93	1099.35	18.22	97.63	4028
Mar-2023	63.19	20.88	134.83	0.48	1101.03	10.43	55.81	4464
Apr-2023	22.75	12.14	36.43	1.39	1096.53	7.31	24.75	4317
May-2023	17.01	8.5	24.08	1	445.86	4.53	19.23	4464
Jun-2023	27.29	10.27	89.86	1.07	1087.96	6.19	17.31	4317
Dry season	58.29	11.9	121.39	-0.28	1098.32	6.4	27.68	26483
Wet season	50.95	17.05	110.63	0.48	1101.03	8.15	45.65	26051
Overall	54.65	14	116.24	-0.28	1101.03	7.15	37.65	52534

3.4.5 Benthic photosynthetically active radiation (bPAR)

Fine-scale patterns of benthic bPAR are primarily driven by tidal cycles, with fortnightly increases in bPAR coinciding with neap tides and lower tidal flows. Larger episodic events, such as low-pressure systems and storms, can lead to extended periods of low light conditions due to a combination of strong winds, increases in wave height and resuspension of particles (Fabricius et al., 2013).

Benthic photosynthetically active radiation (bPAR) was highly variable at all sites throughout the reporting period. The daily light integral (DLI) of bPAR was highest at South Channel (annual mean = 4.74 mol m^{-2} d^{-1}) and lowest at Leithen Point (annual mean = 0.92 mol m^{-2} d^{-1}) (Figure 3.23). The temporal pattern in DLI was similar between the two estuary sites (Evans Landing and Leithen Point), with DLI being approximately double at Evans Landing (annual mean = 2.4 mol m^{-2} d^{-1}) than at Leithen Point.

Raw bPAR values (recorded at 10-minute intervals) are presented in Appendix 2. Missing bPAR data from 26th December 2022 to 23rd February 2023 at Evans Landing was due to damage to instruments after loggers were buried by sediment in an extreme weather event and unable to be retrieved for several weeks. Missing bPAR data from 26th May 2023 to 22nd June 2023 at Evans Landing was due to an internal instrument failure. Missing bPAR data from 2nd February 2023 to 20th April 2023 at Leithen Point was due to the light sensor failing its orientation test (the frame was tipped over on its side). Any missing data is taken seriously, and workflows are always updated following any instance to avoid data loss going forward, e.g., updated maintenance procedures for loggers, improved mooring design for logger frame stability. In some cases, data loss is unavoidable, e.g., extreme weather events, interference with moorings by the public, which were the case in two of these three data loss occasions.

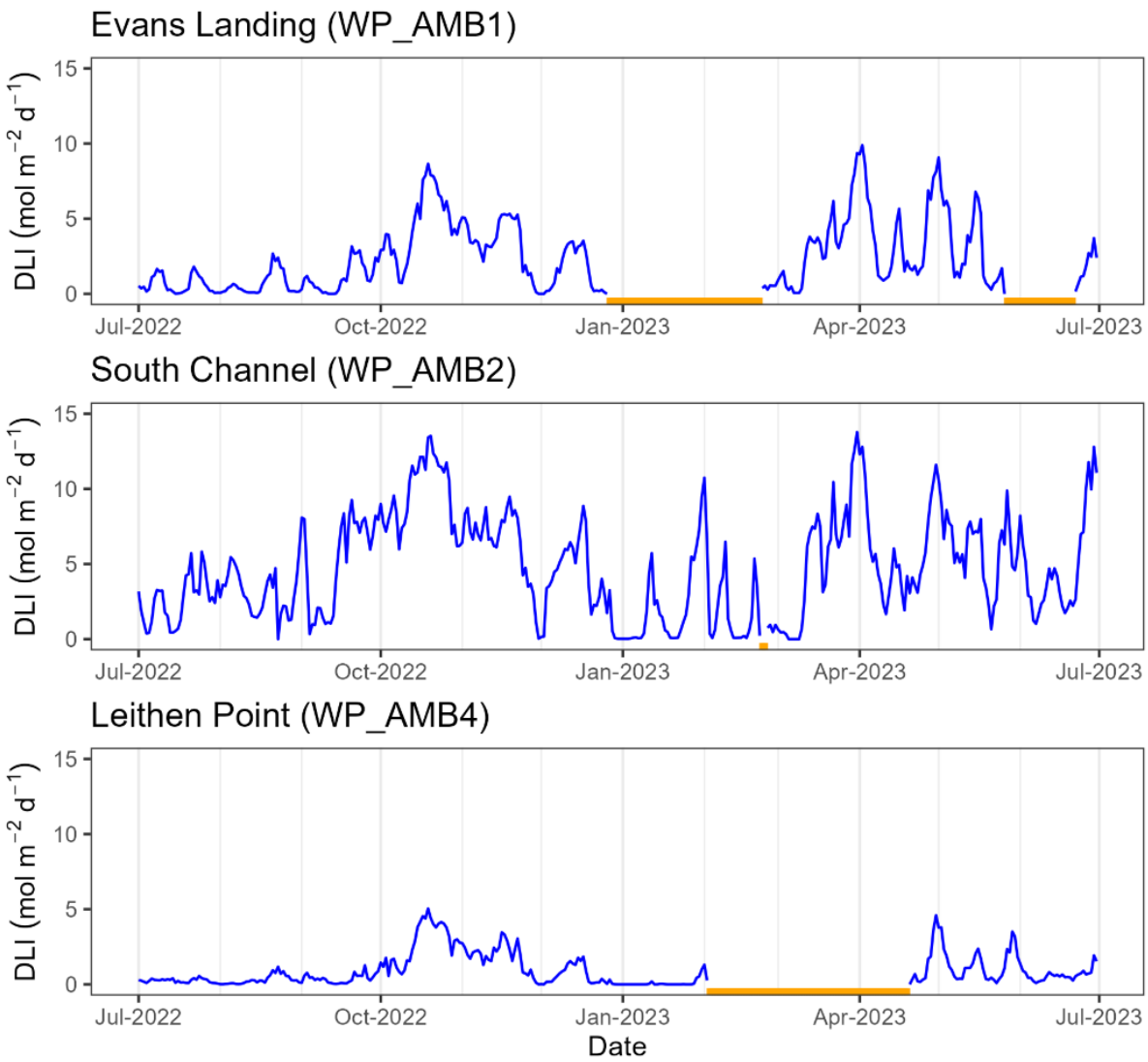

Figure 3.23. Daily light integral (mol photons m^{-2} d^{-1}) of benthic photosynthetically active radiation measured at water quality monitoring sites in the Weipa region. Periods of missing data are indicated by the orange bar.

Table 3-15. Monthly summary statistics for the daily light integral (DLI) (mol m^{-2} d^{-1}) of benthic photosynthetically active radiation (bPAR) measured by continuous dataloggers at the Evans Landing (WP_AMB1) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	0.63	0.36	0.57	0.01	1.8	0.17	1.14	31
Aug-2022	0.65	0.31	0.75	0.05	2.67	0.13	0.83	31
Sep-2022	1.1	0.87	0.98	0	3.15	0.27	1.89	30
Oct-2022	4.63	4.31	2.23	0.71	8.65	2.92	6.29	31
Nov-2022	3.41	3.42	1.66	0	5.32	2.3	5.02	30
Dec-2022	1.48	1.07	1.38	0	3.53	0.2	2.87	26
Jan-2023	-	-	-	-	-	-	-	0
Feb-2023	0.47	0.53	0.11	0.28	0.57	0.42	0.54	6
Mar-2023	3.15	3.37	2.41	0.06	9.36	1.07	4.4	31
Apr-2023	3.92	3.11	2.84	0.88	9.89	1.58	6.17	30
May-2023	3.15	1.97	2.61	0	9.08	1.08	5.59	26
Jun-2023	1.8	1.83	1.13	0.15	3.7	1.13	2.47	9
Dry season	1.99	1.15	2.22	0	9.08	0.31	2.85	158
Wet season	2.92	2.92	2.34	0	9.89	0.96	4.23	123
Overall	2.4	1.65	2.31	0	9.89	0.48	3.57	281

Table 3-16. Monthly summary statistics for the daily light integral (DLI) (mol m^{-2} d^{-1}) of benthic photosynthetically active radiation (bPAR) measured by continuous dataloggers at the south Channel (WP_AMB2) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	2.57	2.78	1.55	0.38	5.81	1.24	3.26	31
Aug-2022	3.03	2.88	1.43	0	5.81	1.88	4.1	31
Sep-2022	5.19	6.42	3.07	0.33	9.25	1.66	7.91	30
Oct-2022	9.75	10.57	2.27	5.97	13.52	7.67	11.52	31
Nov-2022	6.44	6.83	2.3	0.03	9.47	6.13	8.01	30
Dec-2022	3.75	3.69	2.5	0.02	8.86	1.97	5.71	31
Jan-2023	2	0.59	2.58	0.02	9.46	0.09	2.76	31
Feb-2023	1.97	0.69	2.69	0.07	10.74	0.21	3.12	26
Mar-2023	5.17	6.15	4.15	0	13.77	0.55	7.49	31
Apr-2023	5.77	4.84	3.2	1.66	12.79	3.6	7.34	30
May-2023	6.05	6.34	2.33	0.66	10.58	4.7	7.43	31
Jun-2023	4.88	3.76	3.38	1.02	12.79	2.4	6.81	30
Dry season	5.25	4.7	3.37	0	13.52	2.49	7.71	184
Wet season	4.22	4.02	3.41	0	13.77	0.66	6.63	179
Overall	4.74	4.29	3.43	0	13.77	1.75	7.21	363

Table 3-17. Monthly summary statistics for the daily light integral (DLI) (mol m^{-2} d^{-1}) of benthic photosynthetically active radiation (bPAR) measured by continuous dataloggers at the Leithen Point (AP_AMB4) ambient water quality monitoring site. SD = standard deviation, Min = minimum, Max = maximum, Q1 = 1st quartile (25th percentile), Q3 = 3rd quartile (75th percentile), n = sample size (number of measurements). Wet season 1st November to 30th April.

Period	Mean	Median	SD	Min	Max	Q1	Q3	n
Jul-2022	0.25	0.28	0.12	0.05	0.55	0.13	0.32	31
Aug-2022	0.31	0.24	0.31	0.01	1.17	0.07	0.49	31
Sep-2022	0.39	0.36	0.3	0.03	1.26	0.11	0.56	30
Oct-2022	2.71	2.87	1.37	0.56	5.04	1.57	4.02	31
Nov-2022	1.85	2.03	0.91	0	3.46	1.36	2.41	30
Dec-2022	0.56	0.2	0.61	0	1.84	0.08	0.93	31
Jan-2023	0.07	0	0.21	0	0.99	0	0.02	31
Feb-2023	0.78	0.78	0.74	0.25	1.31	0.52	1.04	2
Mar-2023	-	-	-	-	-	-	-	0
Apr-2023	1.26	0.41	1.55	0	4.59	0.26	1.77	11
May-2023	1.41	1.09	1.09	0.09	3.8	0.42	2.08	31
Jun-2023	0.65	0.6	0.4	0.09	1.92	0.44	0.77	30
Dry season	0.96	0.47	1.16	0.01	5.04	0.25	1.11	184
Wet season	0.86	0.34	1.05	0	4.59	0.01	1.56	105
Overall	0.92	0.44	1.12	0	5.04	0.13	1.36	289

3.4.6 Benthic multispectral irradiance

Multispectral light profiles from the three monitoring sites showed that under higher turbidity levels, there was a shift in the peak benthic irradiance from the photosynthetically useful blue light wavelengths (410 – 490 nm) to the less photosynthetically useful green-yellow wavelengths (550-570 nm) (Figure 3.24, Figure 3.25, Figure 3.26). The shape of the multispectral profile within the photosynthetically active radiation range (400 – 700 nm) changes with water clarity. The profile has a broad peak spanning 490 to 550 nm during periods of good water clarity (<1 NTU), shifting to a narrower peak spanning 550 to 570 nm when water clarity is poor (> 5 NTU). There was a general tendency towards higher peaks in the blue light spectra in the dry season compared to wet season across all sites. South channel received more blue light to its benthic habitats than the other sites, with Leithen Point receiving the least amount of blue light.

There was a clear difference in the benthic light environment under different turbidity levels at South Channel (Figure 3.25). During periods of high turbidity when water clarity was lowest, the more photosynthetically useful shorter blue wavelengths were much more attenuated than the longer red wavelengths. The spectral peak shifting from the blue-green part of the spectrum to longer yellow wavelengths. A similar response can be seen at Evans Landing (Figure 3.24) and Leithen Point (Figure 3.26), although at these estuary sites there were only very limited periods when turbidity was low (<1 NTU).

The strongest light attenuation due to turbidity is observed at 490 nm (cyan). Hence, the intensity of the normalised 490 nm irradiance channel and the range of the profile peak may be two useful parameters to monitor and characterise the benthic light environment. Further analysis of the multispectral irradiance data may identify light wavelengths or ratios between different wavelengths which may help to further tease out the cause of lower water clarity such as suspended sediment,

autochthonous production (algal blooms), or allochthonous sources such as catchment derived organic matter. Continuous collection of irradiance spectra may likely make it possible to specifically monitor more closely the photosynthetically usable radiation (PUR) for target benthic primary producers (i.e. individual seagrass and coral species).

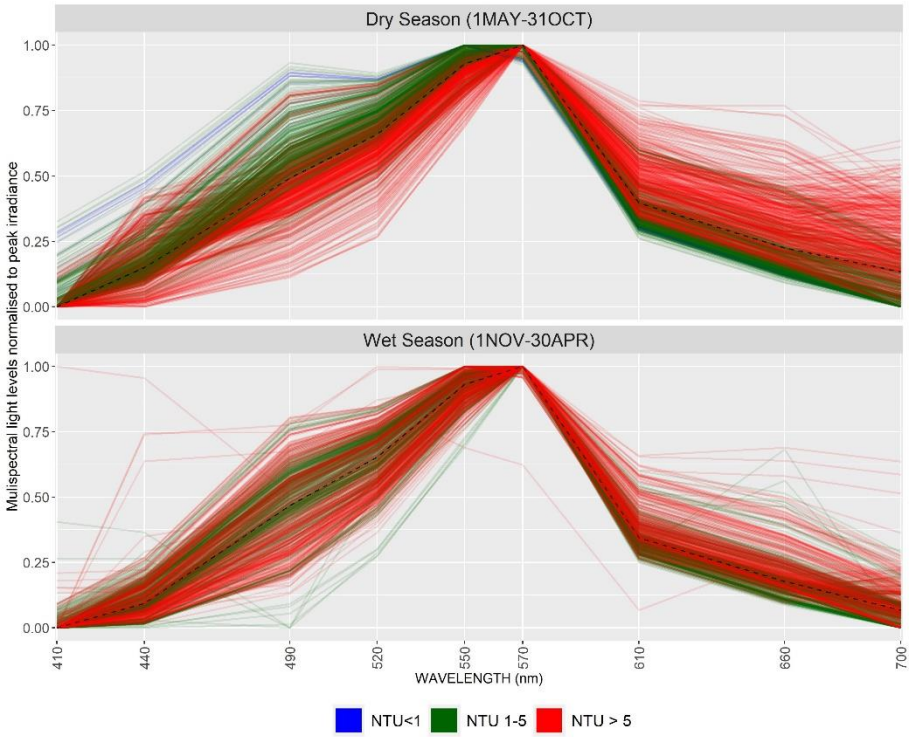

Figure 3.24. Multispectral light ratios at Evans Landing (WP_AMB1) during the wet and dry seasons of 2022-2023.

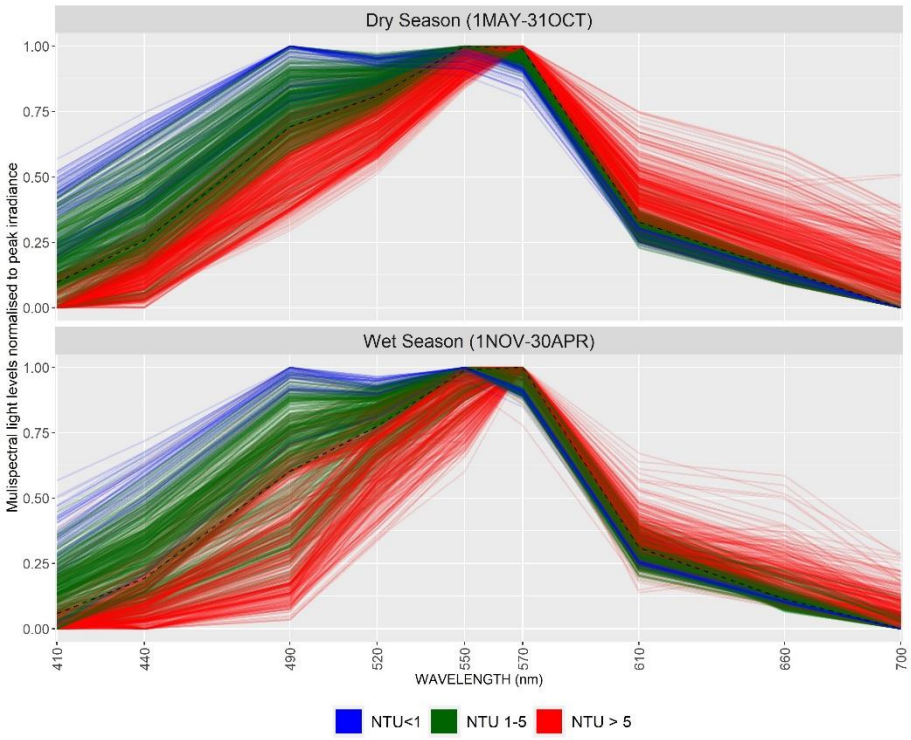

Figure 3.25. Multispectral light ratios at South Channel (WP_AMB2) during the wet and dry seasons of 2022-2023.

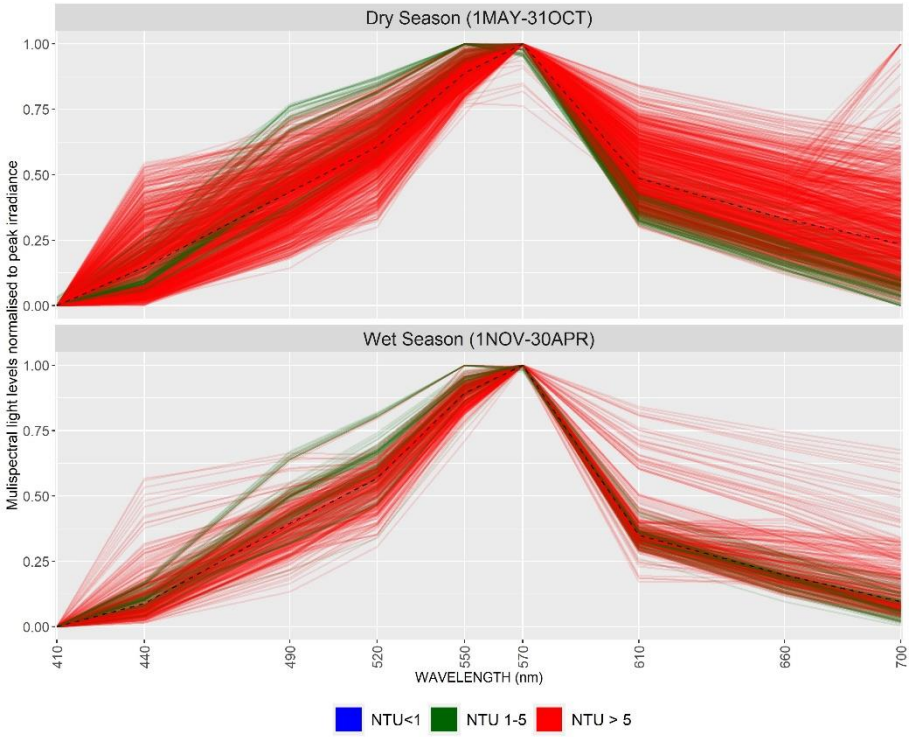

Figure 3.26. Multispectral light levels at Leithen Point (WP_AMB4) during the wet and dry seasons of 2022-2023. There were fewer wet season datapoints at this site due to a period of QC removed data (due to logger tilt) during this time.

3.5 Long term trend analysis

3.5.1 Rainfall and river discharge

First revisit rainfall and river discharge data for the monitoring programs entire period. Generally, rainfall occurred almost exclusively in the wet season of each year as we would expect in the tropical monsoonal climate (Figure 3.27). River flows occurred following rainfall with the largest discharge volumes recorded in January to March of each year. There is some variability in the timing of the wet season rainfall onset each year, with >50 mm rain occurring by mid-November most years (Table 3-18).

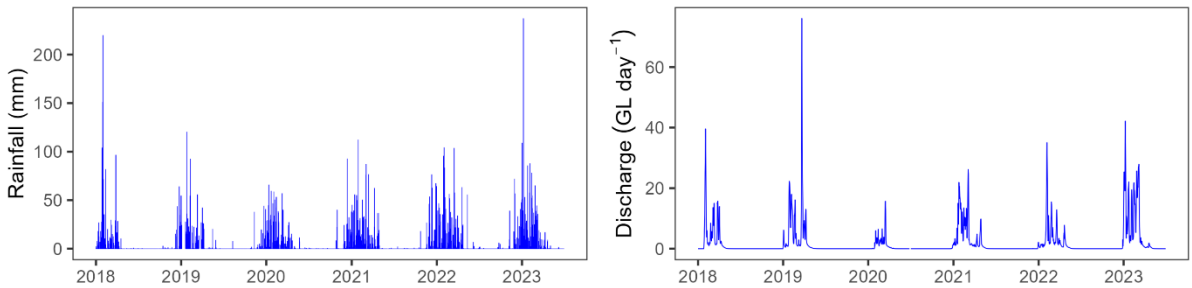

Figure 3.27. Rainfall and river discharge in the Weipa region. a) Rainfall recorded at Weipa Aero (station 027045) for the duration of the ambient water quality monitoring program (Nov 2017 – June 2023). Data source: http://www.bom.gov.au/climate/data/. b) Stream discharge (GL d^{-1}) from the Watson River at Jackin Creek (station 923001A) for the duration of the ambient water quality monitoring program (Jan 2018 – June 2023). Data source: https://water-monitoring.information.qld.gov.au/

Table 3-18. Northern rainfall onset date over the past 6 years

Reporting year	Rainfall onset
2017-2018	30/11/2017
2018-2019	13/12/2018
2019-2020	26/11/2019
2020-2021	31/10/2020
2021-2022	18/11/2021
2022-2023	09/11/2022

3.5.2 Generalized additive mixed effects models (GAMM)

Results of the generalized additive mixed effects models (GAMM) are presented in Figure 3.28 and Figure 3.29. Note that GAMM's have a tendency of overfitting (excessive wiggliness) when sample population size is small (< 1000 samples). For example, there were 140 water samples collected from water quality monitoring sites in the Weipa region over the 5 years of the program. We sought to minimise overfitting of the models by keeping the number of knots low. Outliers deemed to be erroneous were removed from the dataset prior to GAMM analysis.

Nitrogen: Total nitrogen (TN) is showing a slight trend of decreasing concentrations over time. There is a seasonal component to TN with concentration peaks in September and troughs in February each year. Total dissolved nitrogen (TDN) is stable but variable, showing a similar seasonal component observed in TN. Particulate nitrogen (PN) shows a trend of decreasing concentration with no seasonality.

Phosphorus: Total phosphorus (TP) appears stable across years but presents a strong seasonal signal with concentration peaks in August and troughs in March each year. Total dissolved phosphorus (TDP) shows possibly a slight trend of decreasing concentration over time, showing a similar seasonal component observed in TP. Particulate phosphorus (PP) appears stable over time, with a muted seasonal signal compared to TP and TDP.

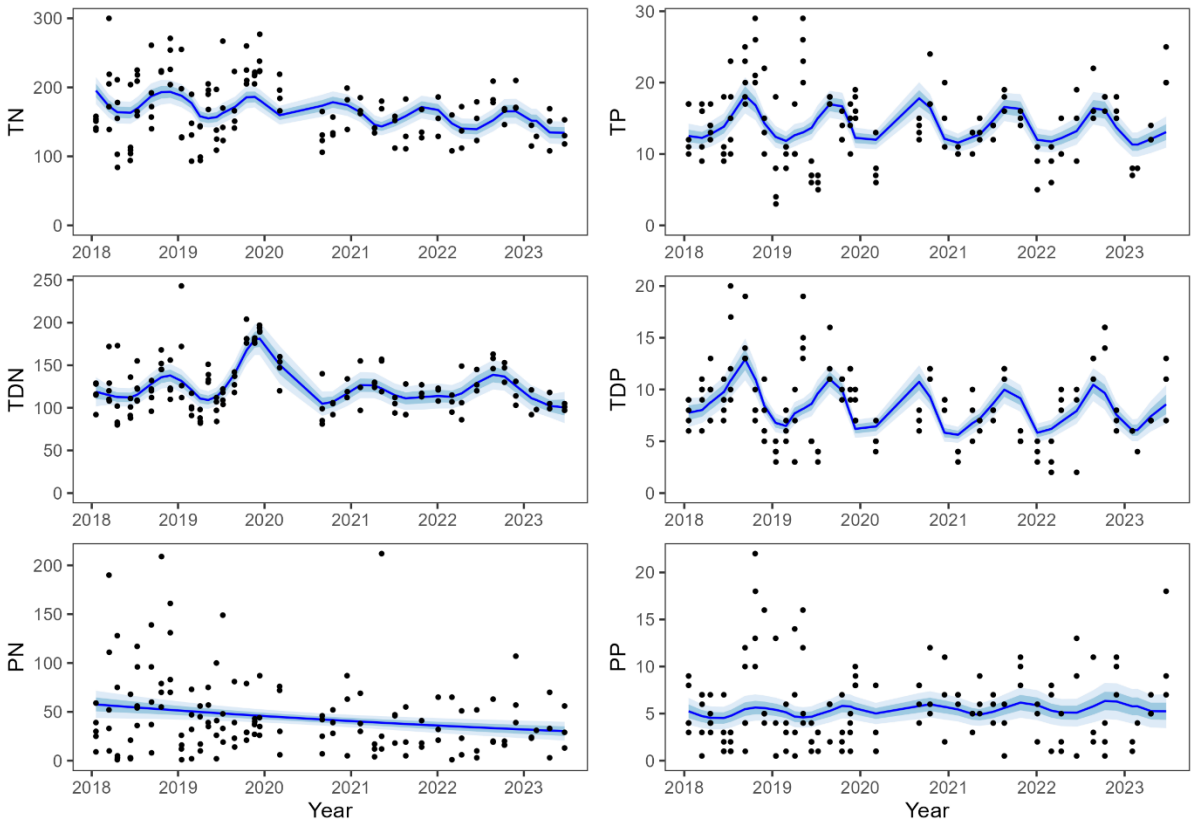

Figure 3.28. Nutrient data from water samples collected between 2018 and 2023. TN = total nitrogen, TP = total phosphorus, TDN = total dissolved nitrogen, TDP = total dissolved phosphorus, PN = particulate nitrogen, PP = particulate phosphorus. Units = µg L^{-1}. General additive mixed effects model (GAMM) showing standard error (blue ribbon) and 95% confidence intervals (light blue).

Chlorophyll-a: Chlorophyll *a* concentration appears stable across years but presents a strong seasonal signal with concentration peaks in September and troughs in March each year.

Electrical Conductivity: The tropical coastal ocean typically shows a seasonal cycle in sea surface salinity (Yu et al., 2021). Around Weipa electrical conductivity is higher during the winter dry season (peaking in August), and lower during the summer wet season (March). Lowest values generally follow rainfall and river discharge events (i.e. compare Figure 3.27) and are due to dilution of seawater with rainfall and freshwater inputs.

Total suspended solids: TSS show a seasonal signal with concentration peaks in winter / dry season and trough in summer / wet season each year. There is no apparent long-term trend with TSS concentrations appearing stable over time.

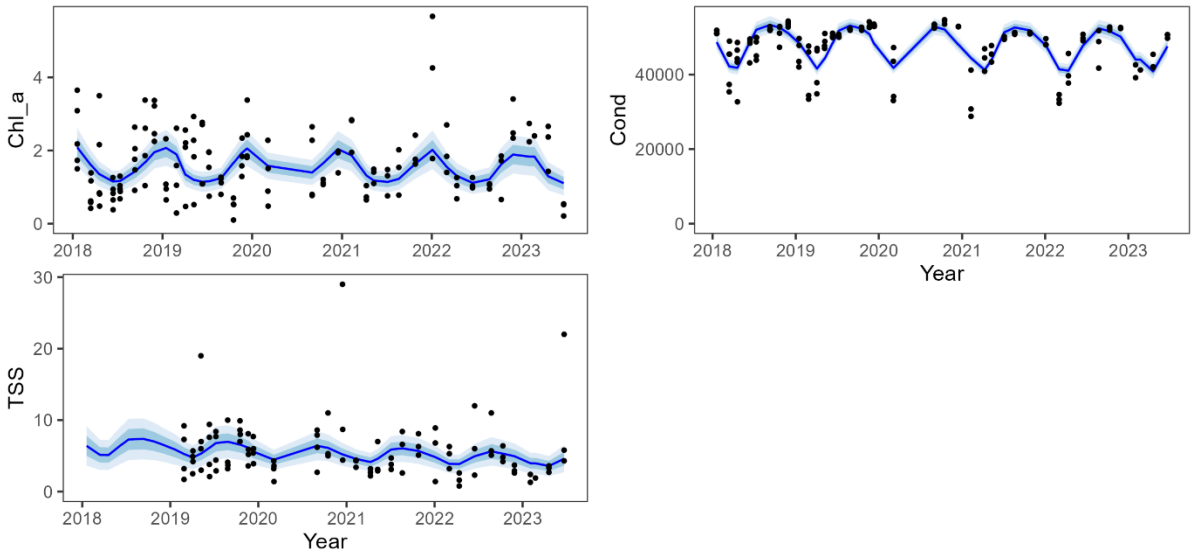

Figure 3.29. Chlorophyll-a (Chl_a: µg L^{-1}), total suspended solids (TSS: mg L^{-1}) and electrical conductivity (Cond: µS cm^{-1}) data from water samples collected between 2018 and 2023. The general additive mixed effects model (GAMM) for each parameter showing standard error (blue ribbon) and 95% confidence intervals (light blue). Note: TSS was not routinely measured prior to February 2019.

3.5.3 Annual and overall summary statistics

Summary statistics for nitrogen (total nitrogen, total dissolved nitrogen, and particulate nitrogen) are presented in Table 3-19. Total nitrogen (TN) ranged from 84 to 300 µg L^{-1} with a mean concentration of 168 µg L^{-1} over the course of the ambient marine water quality program to date. Total dissolved nitrogen (TDN) ranged from 80 to 293 µg L^{-1} with a mean concentration of 125 µg L^{-1}. Particulate nitrogen (PN) ranged from 1 to 212 µg L^{-1} with a mean concentration of 45 µg L^{-1}.

Summary statistics for phosphorus (total phosphorus, total dissolved phosphorus, and particulate phosphorus) are presented in Table 3-20. Total phosphorus (TP) ranged from 3 to 29 µg L^{-1} with a mean concentration of 14 µg L^{-1} over the course of the ambient marine water quality program to date. Total dissolved phosphorus (TDP) ranged from 2 to 20 µg L^{-1} with a mean concentration of 8 µg L^{-1}. Particulate phosphorus (PP) ranged from <1 to 26 µg L^{-1} with a mean concentration of 6 µg L^{-1}.

Summary statistics for chlorophyll *a*, electrical conductivity, total suspended solids, and pH are presented in Table 3-21. Chlorophyll *a* ranged from <0.2 to 5.67 µg L^{-1} with a mean concentration of 1.62 µg L^{-1} over the course of the ambient marine water quality program to date. Electrical

conductivity (EC) ranged from 28.8 to 54.7 mS cm^{-1} with a mean of 47.8 mS cm^{-1}. Total suspended solids (TSS) ranged from 0.78 to 29 mg L^{-1} with a mean of 5.66 mg L^{-1}. pH ranged from 7.43 to 8.40 with a mean pH of 8.16.

Table 3-19. Summary statistics for Nitrogen. Shown are the annual mean, median, 1st quartile (Q1), 3rd quartile (Q3), standard deviation (SD), minimum (Min), maximum (Max), and number of samples (n). Annual values are based on each years reporting period which runs from 1st July to 30th June.

Parameter	Reporting period	Mean	Median	Q1	Q3	SD	Min	Max	n
TN: total nitrogen (µg L^{-1})									
	2017-2018	156.6	152.5	112	184.5	52.64	84	300	20
	2018-2019	178.38	190	140	218	48.93	93	271	37
	2019-2020	203.04	213.5	169	223.25	40.54	123	277	24
	2020-2021	152.5	149	134	168.25	25.03	106	199	18
	2021-2022	144.55	144.5	126	162	25.51	108	186	20
	2022-2023	156.67	160	133.75	170.75	29.55	108	210	18
	Overall	168.33	165	135	204	44.41	84	300	137
TDN: total dissolved nitrogen (µg L^{-1})									
	2017-2018	113.25	110.5	91.75	128.25	26.43	80	173	20
	2018-2019	123.29	120.5	102.5	137.5	30.91	82	243	38
	2019-2020	157.75	168	125.75	181.25	31.72	104	204	24
	2020-2021	119.11	119	102	132	23.09	81	157	19
	2021-2022	113.43	113	105	123	16.79	86	149	21
	2022-2023	121.17	116	101.5	142.25	23.47	92	163	18
	Overall	125.44	120	104.75	145	30.43	80	243	140
PN: particulate nitrogen (µg L^{-1})									
	2017-2018	43.35	27.5	4.5	61.25	50.51	1	190	20
	2018-2019	59.71	54.5	27.5	78	46.57	1	209	38
	2019-2020	45.29	36	26.75	54	31.45	6	149	24
	2020-2021	42.79	30	14.5	49	46.91	4	212	19
	2021-2022	29.6	22	13	48	21.32	1	65	20
	2022-2023	35.5	26.5	19.25	51.75	25.88	3	107	18
	Overall	45.09	35	18	59.5	40.45	1	212	139

Table 3-20. Summary statistics for Phosphorus. Shown are the annual mean, median, 1st quartile (Q1), 3rd quartile (Q3), standard deviation (SD), minimum (Min), maximum (Max), and number of samples (n). Annual values are based on each years reporting period which runs from 1st July to 30th June.

Parameter	Reporting period	Mean	Median	Q1	Q3	SD	Min	Max	n
TP: total phosphorus (µg L^{-1})									
	2017-2018	13.2	12.5	10.75	16.25	3.09	9	18	20
	2018-2019	15.37	15	10	20.75	7.2	3	29	38
	2019-2020	12.79	14	7.75	17	4.62	5	19	24
	2020-2021	13.95	13	11.5	15	3.61	10	24	19
	2021-2022	12.71	14	10	15	3.98	5	19	21
	2022-2023	15.56	16	12.5	18	4.88	7	25	18
	Overall	14.05	14	10	17	5.19	3	29	140
TDP: total dissolved phosphorus (µg L^{-1})									
	2017-2018	8.8	9	7	10	1.82	6	13	20
	2018-2019	9.18	8	5	13	4.8	3	20	38
	2019-2020	8.46	9	5	11	3.41	3	16	24
	2020-2021	7.53	7	6	9	2.59	3	12	19
	2021-2022	6.86	7	5	9	3.18	2	12	21
	2022-2023	9.56	7.5	7	13	3.81	4	16	18
	Overall	8.48	8	6	11	3.67	2	20	140
PP: particulate phosphorus (µg L^{-1})									
	2017-2018	4.43	4	3	7	2.48	0.5	9	20
	2018-2019	6.22	4	2	10	5.69	0.5	22	38
	2019-2020	4.33	3	2	6.25	2.85	1	10	24
	2020-2021	6.42	6	5	7.5	2.48	2	12	19
	2021-2022	5.52	6	2	8	3.58	0.5	13	21
	2022-2023	6.03	5	2.25	8.5	4.5	0.5	18	18
	Overall	5.54	5	3	7	4.07	0.5	22	140

Table 3-21. Summary statistics for chlorophyll-a, electrical conductivity, total suspended solids, and pH. Shown are the annual mean, median, 1st quartile (Q1), 3rd quartile (Q3), standard deviation (SD), minimum (Min), maximum (Max), and number of samples (n). Annual values are based on each years reporting period which runs from 1st July to 30th June. The less-than symbol (<) prefixed before a value indicates values below limit of detection.

Parameter	Reporting period	Mean	Median	Q1	Q3	SD	Min	Max	n
Chlorophyll-a (µg L^{-1})									
	2017-2018	1.41	1.06	0.64	1.84	1.02	0.38	3.65	20
	2018-2019	1.76	1.8	1.04	2.54	0.89	0.29	3.38	38
	2019-2020	1.42	1.4	0.79	1.88	0.77	< 0.2	3.38	24
	2020-2021	1.54	1.39	1.06	1.96	0.72	0.65	2.84	19
	2021-2022	1.79	1.48	1.04	1.84	1.2	0.68	5.67	21
	2022-2023	1.7	1.79	0.98	2.39	0.93	0.21	3.41	18
	Overall	1.62	1.45	0.93	2.26	0.92	< 0.2	5.67	140
Electrical conductivity (µS cm^{-1})									
	2017-2018	46225	48505	44028	49888	5540	32690	51890	20
	2018-2019	48003	49795	46553	51938	5412	33400	54340	38
	2019-2020	50106	52240	50278	52758	5568	33020	54160	24
	2020-2021	47531	52440	43920	53160	7785	28790	54700	19
	2021-2022	46394	49540	45650	50800	6515	32320	51360	21
	2022-2023	47799	50190	42228	52243	4978	39160	52760	18
	Overall	47778	49925	45465	52160	5975	28790	54700	140
Total suspended solids (TSS) (mg L^{-1})									
	2017-2018[#]	-	-	-	-	-	-	-	0
	2018-2019	6.04	5.3	3.15	7.38	4.23	1.7	19	16
	2019-2020	5.68	5.3	3.68	7.78	2.41	1.4	10	24
	2020-2021	6.42	4.4	3.15	7.45	6	2.2	29	19
	2021-2022	5.04	5.1	2.6	6.6	2.87	0.78	12	21
	2022-2023	5.21	3.95	2.75	5.55	4.73	1.3	22	18
	Overall	5.66	4.75	3.2	7	4.09	0.78	29	98
pH									
	2017-2018	8.19	8.19	8.14	8.25	0.08	8.03	8.29	15
	2018-2019	8.17	8.18	8.12	8.24	0.15	7.43	8.39	38
	2019-2020	8.23	8.24	8.2	8.29	0.08	8.01	8.4	24
	2020-2021	8.13	8.14	8.09	8.2	0.08	7.89	8.22	19
	2021-2022	8.09	8.08	7.99	8.18	0.12	7.85	8.3	21
	2022-2023	8.11	8.11	8.04	8.16	0.09	7.97	8.3	18
	Overall	8.16	8.16	8.1	8.24	0.12	7.43	8.4	135

[#]Note: TSS was not measured in 2017-2018

4 Conclusions and Recommendations

4.1 Conclusions

4.1.1 Climatic conditions

1. During the wet season of 2022-2023, a total rainfall of 2446 mm was recorded, contributing to a cumulative water year rainfall of 2469.8 mm. This exceeded precipitation levels observed in all years since the 2010-2011 period. Moreover, the rainfall surpassed the long-term average, reaching approximately the 90th percentile of annual rainfall observed since 1992. This is an important factor to consider when interpreting data during this monitoring period. Comparison of these data with future (and past) years will be important to characterise ambient water quality conditions and to determine metocean drivers of water quality variability. It is important to capture monitoring data over a range of climatic conditions, which continues to be a key conclusion reported as part of this monitoring program.
2. There was an extreme rainfall event in late December/ early January, and a low-pressure system in early March. These climate events led to recognisable signals in the turbidity and PAR logger data, not only from the river flow, but from the associated metocean conditions, such as wind-driven waves, which are a major driver of sediment resuspension.

4.1.2 Ambient water quality

1. There continues to be a seasonal pattern for water temperature, with highest water temperatures experienced during summer months, and cooler conditions in the winter months. This trend is made more variable due to temperature fluctuations caused by climate events, particularly through the wet season.
2. The water column is mostly well mixed, with depth profiles for temperature showing only minor gradients of change. Dissolved oxygen was found to reduce with depth in December and April at Leithen Point, and pH was lower in surface water at all sites, but particularly the estuarine sites, in October. Salinity was markedly reduced at all sites during February following periods of high rainfall.
3. Total nitrogen (TN) shows a slight trend of decreasing concentrations over time, with a seasonal component of concentration peaks in September and troughs in February each year. Particulate nitrogen (PN) shows a trend of decreasing concentration with no seasonality. Total phosphorus (TP) appears stable across years but presents a strong seasonal signal with concentration peaks in August and troughs in March each year. Chlorophyll-a concentrations appear highest in summer, continuing a long-term trend that has been apparent throughout this monitoring program (2017-2023).
4. Trace metal concentrations measured in these waters during the 2022-2023 monitoring period were below the laboratory limit of detection (LOD) for all monitoring sites in both the dry and wet season sampling.

4.1.3 Turbidity

1. Continuous turbidity logging data supports the pattern found more broadly in coastal waters where 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 RMS water depth and NTU/SSC. Large peaks in NTU/SSC and RMS water depth were recorded over periods longer than a week during the January to March period.
2. As the long-term data set here continues to increase, assessment of the turbidity, climate, and rainfall patterns (frequency and duration) can be examined, providing more detailed insight into the rainfall and turbidity relationships in this region.

4.1.4 Benthic photosynthetically active radiation (bPAR)

1. Benthic photosynthetically active radiation (bPAR) was highly variable at all sites throughout the reporting period. bPAR was highest at South Channel and lowest at Leithen Point, with patterns of light similar at both estuarine sites.
2. There were visible signals of extreme weather events in the bPAR data.
3. Highest bPAR occurred in October/November and lowest in January/February at all sites.
4. During periods of high turbidity when water clarity was lowest, the more photosynthetically useful shorter blue wavelengths were much more attenuated than the longer red wavelengths. The spectral peak also shifts from the blue-green part of the spectrum to longer yellow wavelengths.

4.2 Recommendations and future directions

This monitoring program has been underway for five years (2018 to present) and should remain in place to continue to characterise and build a detailed understanding of the water quality dynamics in and around this port facility. This understanding will continue to assist NQBP to manage current activities but will also assist with future strategic planning and management. With an emerging long-term dataset, there is potential for answering important research questions around coastal processes in this remote region of northern Australia.

One question we seek to answer with this emerging long-term dataset is the importance of spectral light wavelengths to benthic habitats. Increasingly, scientists and managers are looking at spectral light as the most important parameter for water quality monitoring. Most monitoring programs to date have focussed on overall photosynthetically active radiation (PAR) and not photosynthetically usable radiation (PUR). This ground-breaking monitoring program is proud to be leading the research and monitoring field in this regard and we continue to build a strong spectral light dataset that has the potential to become a valuable resource for coral reef and seagrass (and other marine species) researchers and managers across Australia and beyond.

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Appendix 1. Quality control procedures

To complement the new loggers that were introduced into the program in the 2021-22 reporting year, a new quality control (QC) process for water quality data has been implemented. The QC process is science-based, sourced from public documentation, and based on the quality assurance of Real Time Oceanographic (QARTOD) program (NOAA, 2020), which is adopted by CSIRO, IMOS, and AIMS. Data goes through both automated and manual quality control steps. The 12 automated control tests are outlined in Table A 1.

Table A 1. Quality Control rules applied to the logger data in the automated process.

QC test 1: Syntax test	QC test 7: Spike tests
QC test 2: Impossible date test	QC test 8: Rate of change test
QC test 3: In/out water test	QC test 9: Stationary test
QC test 4: Global range test	QC test 10: Standard deviation test
QC test 5: Regional range test	QC test 11: Burst count test
QC test 6: Impossible depth test	QC test 12: Orientation test

Dependent on the outcome of these QA tests, data may be flagged ‘good data’ (green), ‘probably good data’ (blue), ‘probably bad data’ (yellow) and ‘bad data’ (red). There are four sensors on each logger: Temperature, Depth, Tilt, and either turbidity (NTU) or photosynthetically active radiation (PAR). For each sensor on the logger the ‘worst’ flag from QC rules 1 to 12 is reported for each 10-minute time interval. Figure A1 1, Figure A1 2, and Figure A1 3 show the logger data from this report with the QC flags applied. End user decides what level of data ‘quality’ they wish to use for their application. For example, for most applications ‘good data’ and ‘probably good data’ is considered acceptable, ‘probably bad data’ could be used with caveats, and ‘bad data’ should be discarded. Unwanted data can easily be masked in excel or other data management programs by filtering by ‘QC flag’. A full technical report with detailed descriptions of the quality control procedures and tests as applied to the data in this project is available on the TropWATER website (Iles et al., 2023).

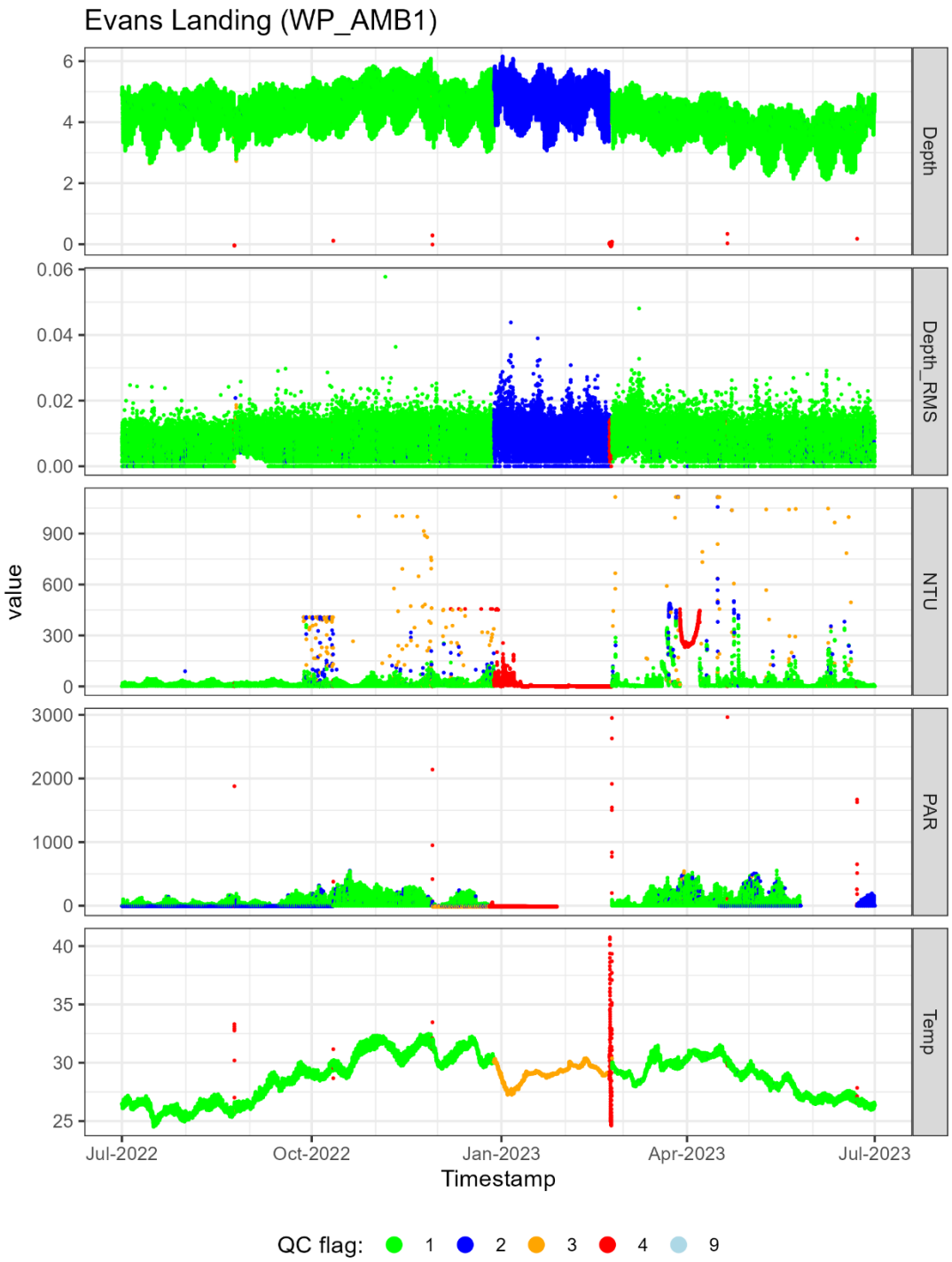

Figure A1 1. Raw data collected at Evans Landing (WP_AMB1) with IMO loggers, passed through automated and manual quality control (QC) steps. Symbol colour indicates QC flag designation where: 1 (green) = Good data, 2 (blue) = Probably good data, 3 (orange) = Suspect data, 4 (red) = Bad data, 9 (light blue) = Missing data.

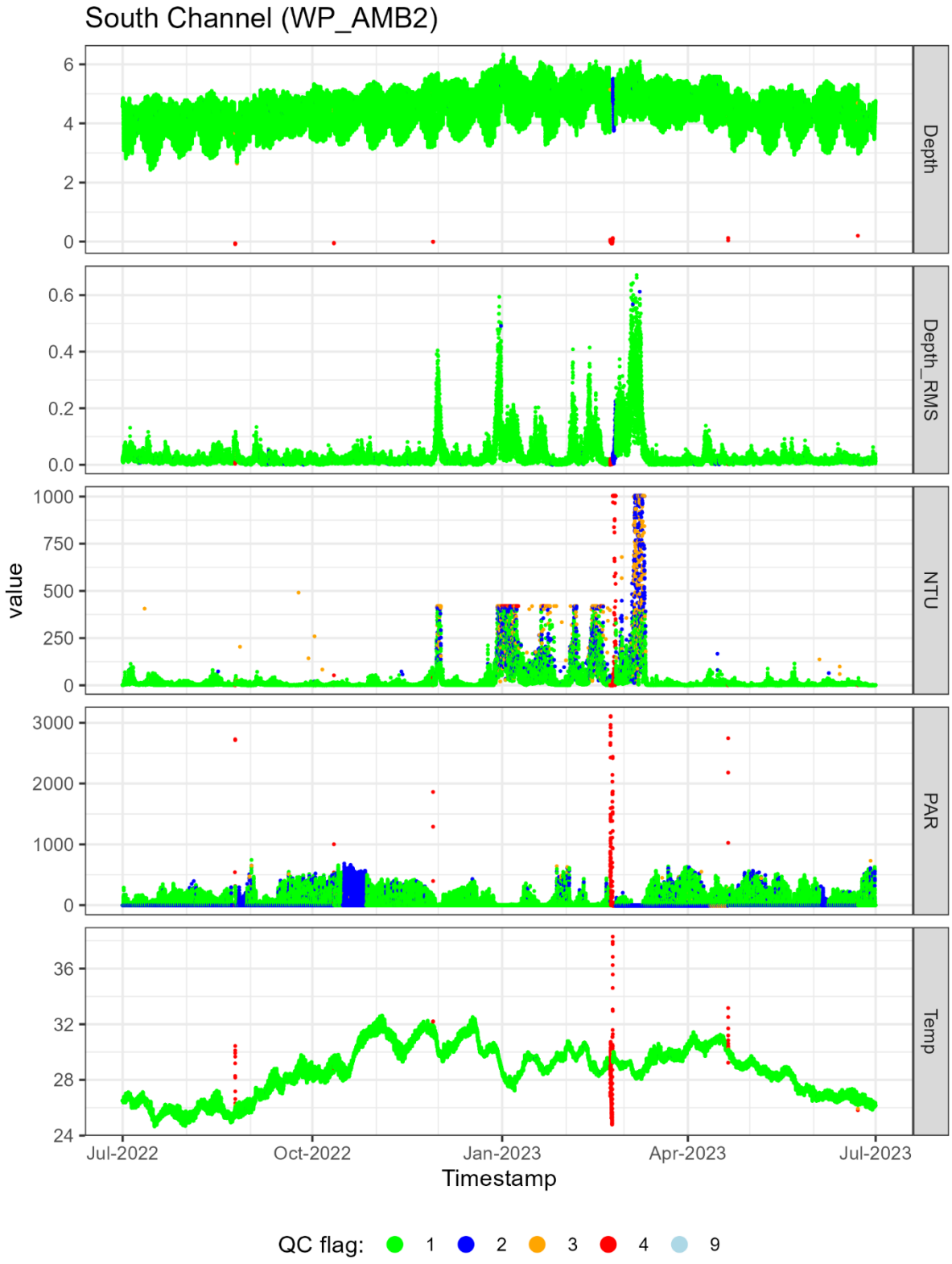

Figure A1 2. Raw data collected at South Channel (WP_AMB2) with IMO loggers. Passed through automated and manual quality control (QC) steps. Symbol colour indicates QC flag designation where: 1 (green) = Good data, 2 (blue) = Probably good data, 3 (orange) = Suspect data, 4 (red) = Bad data, 9 (light blue) = Missing data.

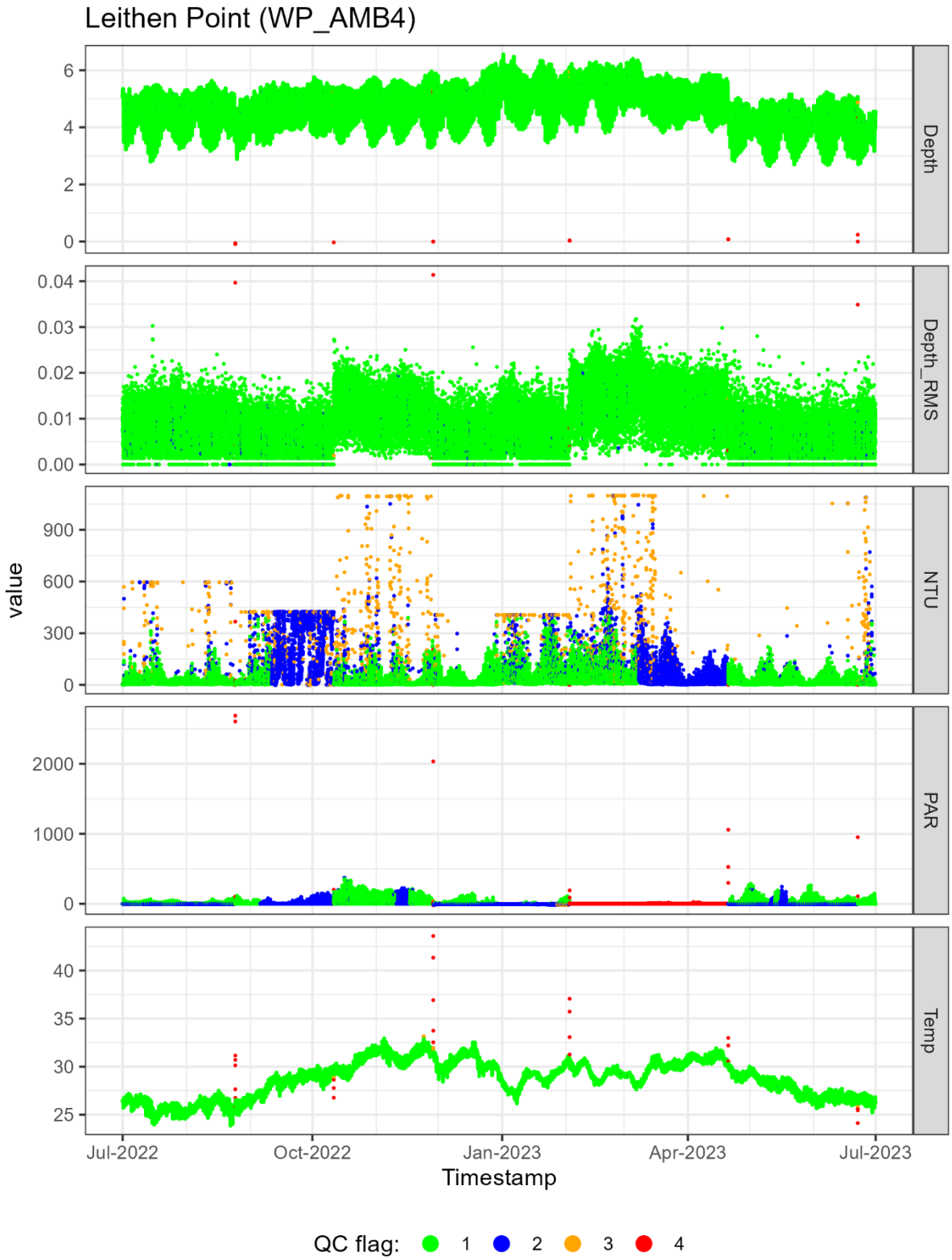

Figure A1 3. Raw data collected at Leithen Point (WP_AMB4) with IMO loggers. Passed through automated and manual quality control (QC) steps. Symbol colour indicates QC flag designation where: 1 (green) = Good data, 2 (blue) = Probably good data, 3 (orange) = Suspect data, 4 (red) = Bad data, 9 (light blue) = Missing data.

Appendix 2. Water quality logger data

Logger data collected at 10-minute intervals which has passed through the quality control process is presented in Figure A2 1, Figure A2 2, and Figure A2 3.

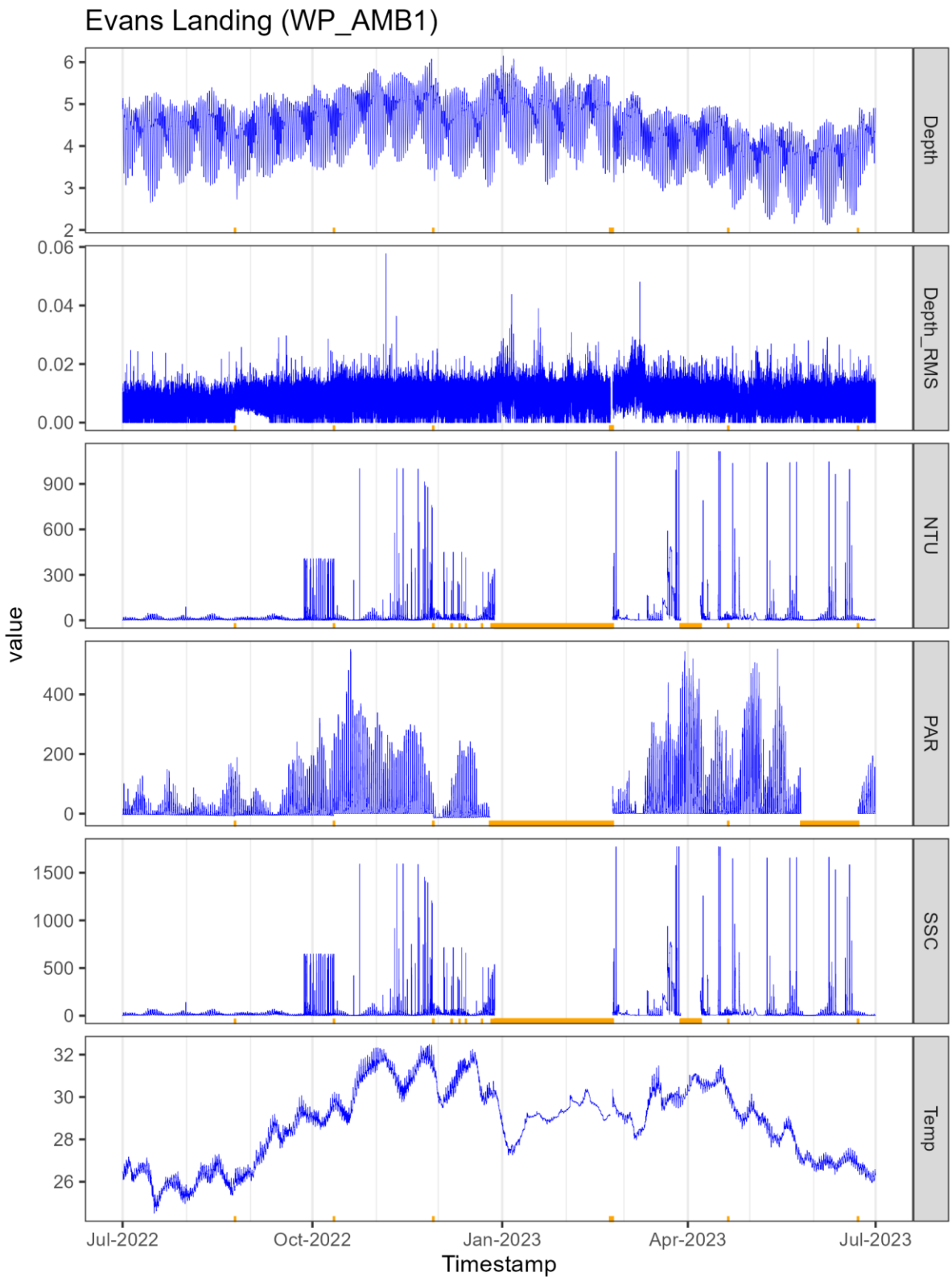

Figure A2 1. Data collected at Evans Landing (WP_AMB1) with In-situ Marine Optics (IMO) dataloggers. Data presented excludes data flagged as flag 4 (Bad data). Periods of missing data are indicated by the orange bar.

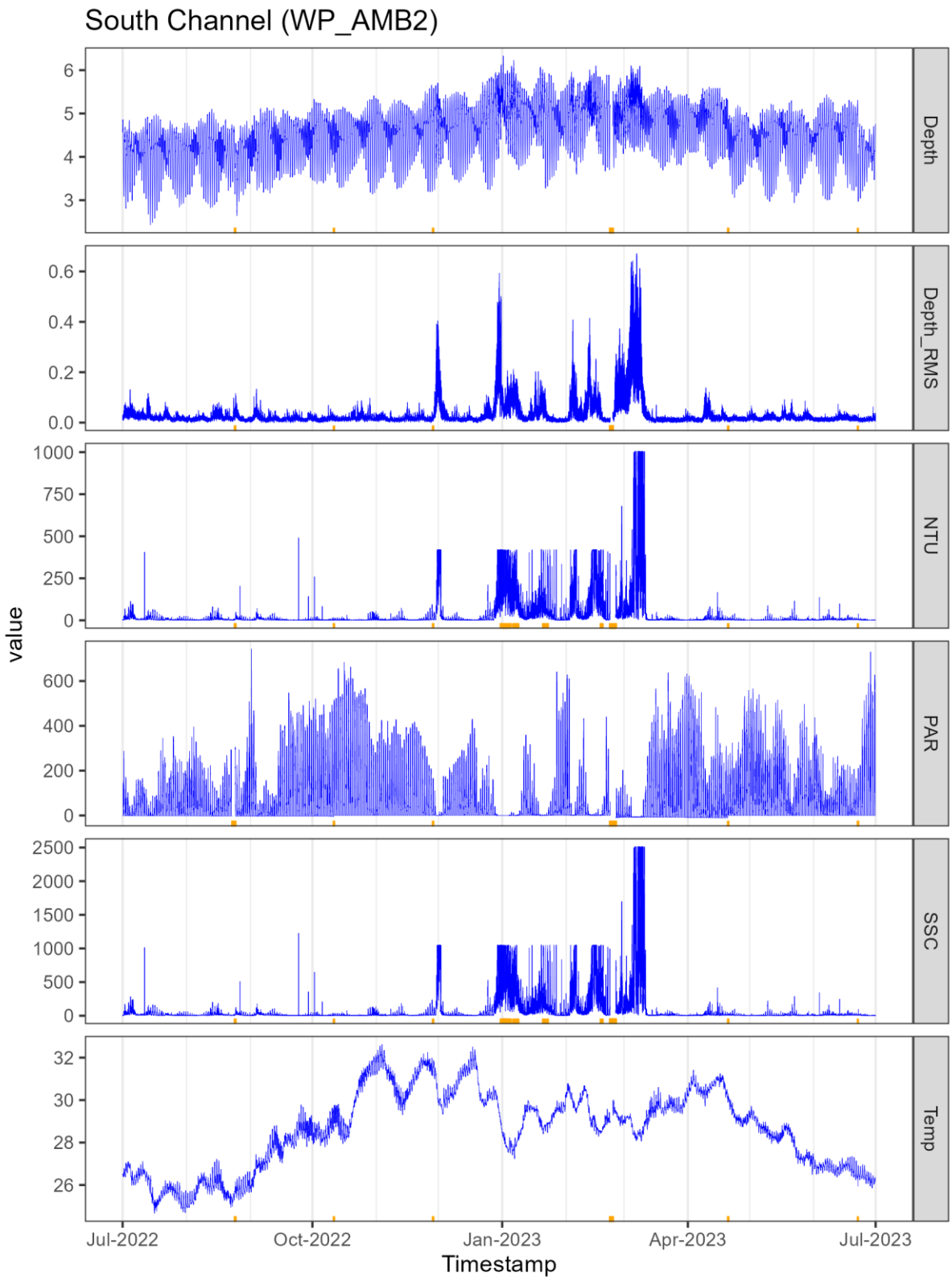

Figure A2 2. Data collected at South Channel (WP_AMB2) with In-situ Marine Optics (IMO) dataloggers. Data presented excludes data flagged as flag 4 (Bad data). Periods of missing data are indicated by the orange bar.

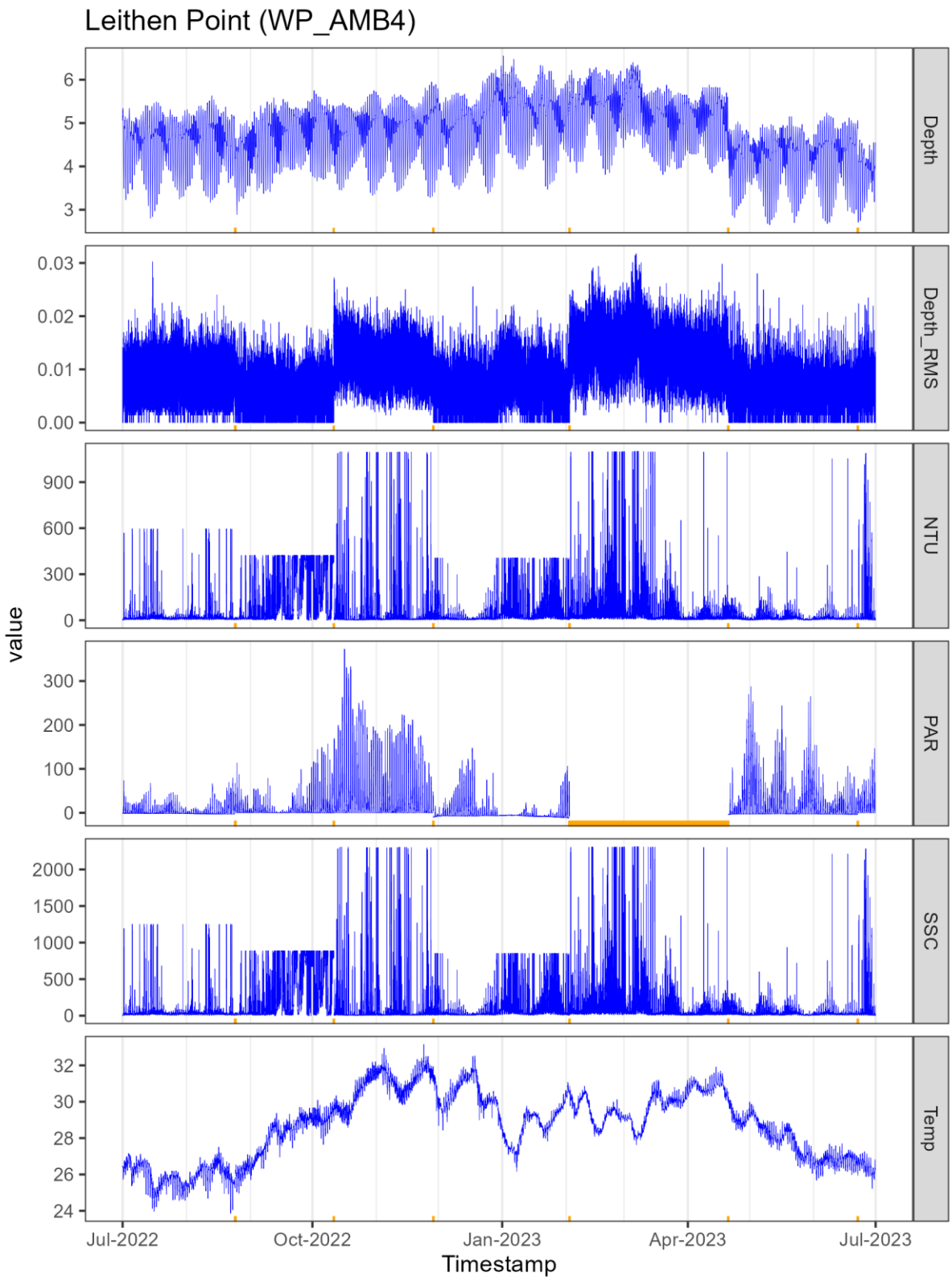

Figure A2 3. Data collected at Leithen Point (WP_AMB4) with In-situ Marine Optics (IMO) dataloggers. Data presented excludes data flagged as flag 4 (Bad data). Periods of missing data are indicated by the orange bar.

Appendix 3. Data recovery

Data recovery and quality control flagging for insitu water quality loggers varied across the sites (Figure A3 1). The temperature (Water temperature) and pressure sensor (water depth, RMS depth) had excellent recoveries, with near 100 % data deemed to be of useable quality. The optical turbidity and light sensors had acceptable recovery, with just a small amount of data discarded due to damage to an instrument and an internal failure. Data flagged as bad data (QC flag 4 – red) was removed prior to preparing figures and tables for this report. A brief description of the quality control process and QC flags is provided in Appendix 1 while more substantive outline of the quality control process undertaken on the logger data is outlined in Iles et al. (2023).

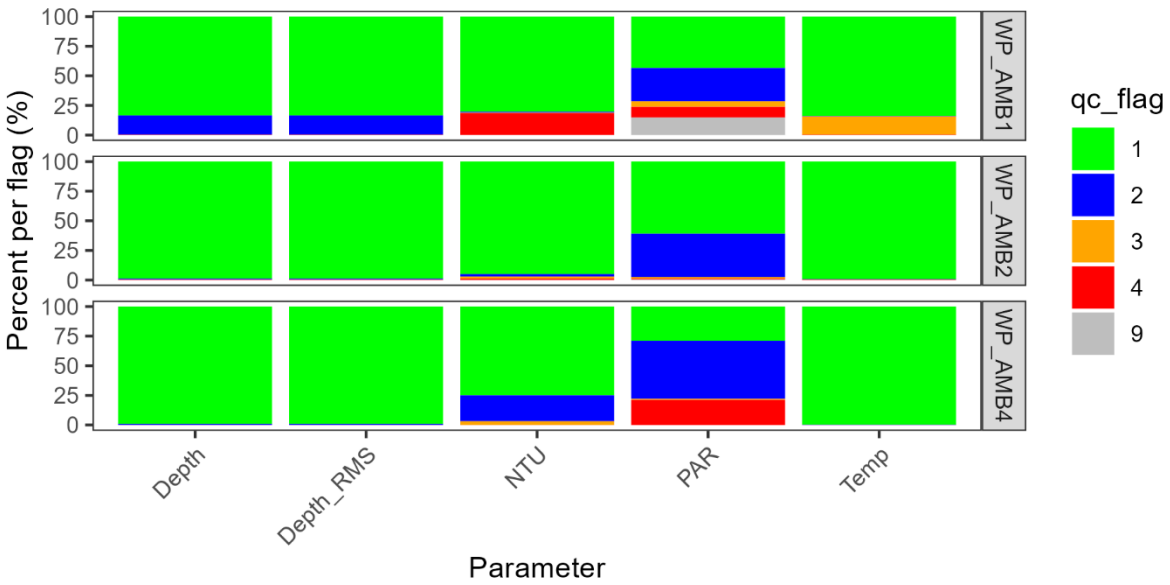

Figure A3 1. Data recovery and qc flags at each of the three logger sites over the reporting period. Flag 1 (green) indicates a 'good value'; flag 2 (blue) indicates a 'probably good value'; flag 3 (yellow) indicates 'probably bad value', flag 4 (red) indicates a 'bad value' and flag 9 (grey) indicates missing data.