

Port of Weipa Marine Water Quality Monitoring Program: Annual Report 2024-2025

November 2025 | Report No. 25/88



Authored by: Paula Cartwright, Jamie Johns, Rory Mulloy, and
Nathan Waltham

Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2024- 2025

Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) James Cook University

Townsville Phone: (07) 4781 4262 Email:

TropWATER@jcu.edu.au

Web: www.jcu.edu.au/tropwater/

© James Cook University, 2025.

The report may be cited as

Cartwright, P, Johns, J, Mulloy, R, and Waltham NJ, 2025, 'Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2024-2025, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 25/88, James Cook University, Townsville, 77 pp.

Contacts

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

This document may only be used for the purpose for which it was commissioned and in accordance with the Terms of Engagement of that commission.

Acknowledgments

We acknowledge the Australian Aboriginal and Torres Strait Islander peoples as the traditional owners of the lands and waters where we live and work.

This program is funded by North Queensland Bulk Ports Corporation (NQBP). We wish to thank the many James Cook University TropWATER staff for their assistance with field work and data analysis and the staff at Juru Enterprises Limited for their assistance in the field.

EXECUTIVE SUMMARY

The Port of Weipa Ambient Marine Water Quality Monitoring Program is a long-term partnership between North Queensland Bulk Ports Corporation (NQBP) and the Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University. The program integrates discrete water sampling, in situ profiling, and continuous seafloor-mounted dataloggers to characterise ambient marine water quality within and adjacent to the Port of Weipa.

This report summarises data collected during the 2024–2025 reporting year (1 July 2024 to 30 June 2025) and places these observations within the context of the longer-term monitoring record (2018–2025). Monitoring is undertaken at three ambient sites spanning estuarine and coastal settings within Albatross Bay, capturing spatial and temporal variability associated with freshwater inputs, tidal mixing, and local hydrodynamic conditions.

Rainfall during the reporting year followed a strongly seasonal monsoonal pattern typical of western Cape York, with a later-than-average wet-season onset followed by concentrated rainfall during January and February 2025. These events produced short-lived freshwater influence and sediment mobilisation but did not result in sustained changes to coastal water quality. Wave conditions throughout the year were generally low-energy and dominated by short-period, wind-driven seas, with limited potential for persistent wave-driven resuspension.

Water quality results were consistent with expectations for a dynamic, tidally energetic tropical coastal system. Nutrient concentrations were dominated by nitrogen, particularly in dissolved form, with variability largely associated with episodic wet-season inputs and particulate mobilisation. Phosphorus concentrations remained comparatively low and stable. Chlorophyll-a concentrations were low to moderate, exhibited clear seasonal structure, and showed no evidence of persistent elevation. Filterable metals and pesticides were either below detection or present at low concentrations, with no indication of localised enrichment.

High-frequency logger data showed that turbidity and benthic light availability were highly variable over short timescales, responding rapidly to episodic hydrodynamic forcing. Turbidity peaks were transient and site-specific, while benthic photosynthetically active radiation (bPAR) varied strongly with water clarity and site exposure. Multispectral irradiance measurements confirmed clear spatial and seasonal differences in benthic light quality, with higher blue–green light availability at the more exposed coastal site relative to estuarine locations.

Long-term trend analysis indicates that water quality in the Weipa region is primarily governed by interannual climatic variability and short-lived hydrodynamic and runoff events rather than progressive change. Nutrients, chlorophyll-a, conductivity, and suspended sediments exhibit seasonal and event-driven variability but show no evidence of sustained or directional long-term degradation.

Overall, the 2024–2025 results indicate that ambient marine water quality in the Port of Weipa region remains stable. Observed variability is dominated by short-lived, event-driven responses to wet-season forcing, consistent with patterns reported in the companion seagrass monitoring program. Together, these datasets indicate episodic environmental drivers. Continued long-term

monitoring remains important for maintaining a robust evidence-base and for supporting effective port management under future climate variability.

TABLE OF CONTENTS

1	Introduction	1
1.1	Background	1
1.2	Program objectives	1
2	Methods	1
2.1	Regional description	1
2.2	Port description	2
2.3	Characterisation of weather, hydrological status, and oceanographic conditions	3
2.3.1	Rainfall and hydrology	3
2.3.2	Wave climate	3
2.4	Monitoring and sampling design	4
2.4.1	Site overview	4
2.4.2	Field sampling schedule	4
2.5	Water quality sampling	5
2.5.1	Water sample collection	5
2.5.2	Chlorophyll and pigment processing	5
2.5.3	Metals and pesticide sampling	5
2.5.4	Laboratory analysis	6
2.5.5	Water quality guidelines	8
2.6	In situ physicochemical measurements	8
2.7	Seafloor mounted continuous dataloggers	8
2.7.1	Logger data processing and quality control	9
2.7.2	Suspended sediment concentration	10
2.7.3	RMS water depth	10
2.7.4	RMS Depth and turbidity analysis	11
2.7.5	Benthic photosynthetically active radiation (bPAR)	11
2.8	Benthic multispectral irradiance	12
2.8.1	Data extraction and normalisation (spectral shape analysis)	12
2.8.2	Turbidity classification for spectral response analysis	13
2.8.3	Spectral Indices	13
2.9	Long term trend analysis	14
3	Results and Discussion	15
3.1	Rainfall and river flows	15

3.2	Wave climate.....	17
3.3	Water quality.....	20
3.3.1	Nutrients.....	20
3.3.2	Chlorophyll.....	22
3.3.3	Filterable metals.....	23
3.3.4	Pesticides	24
3.4	Physicochemical	25
3.4.1	Dissolved oxygen.....	25
3.4.2	Conductivity	27
3.4.3	Salinity	27
3.4.4	Water temperature	29
3.4.5	pH	30
3.4.6	Water clarity	31
3.4.7	Turbidity.....	32
3.5	Seafloor mounted continuous dataloggers	32
3.5.1	Water temperature	32
3.5.2	Water depth and tidal signal	33
3.5.3	Wave activity.....	34
3.5.4	Turbidity.....	35
3.5.5	Benthic photosynthetically active radiation (bPAR)	37
3.5.6	RMS Depth and turbidity analysis.....	38
3.6	Benthic multispectral irradiance and light-quality indices	41
3.7	Long term trend analysis	48
3.7.1	Rainfall and river discharge	48
3.7.2	Generalized additive mixed effects models (GAMM).....	50
3.7.3	Interpretation of Long-Term Trends	54
4	Conclusion.....	55
5	References.....	55
Appendix A	Logger data summaries.....	57
Appendix B	Quality control.....	67
Appendix C	GAMM models outputs	72

TABLE OF FIGURES

Figure 2-1 Map of Weipa showing location of water quality monitoring sites (yellow) and meteorological stations (purple), utilised in the 2024-2025 reporting period. Inset map shows location on Queensland coast.	3
Figure 2-2 Water quality loggers attached to instrument frames ready for seafloor deployment. The horizontally oriented logger is an NTU-LPT turbidity logger; the vertically oriented logger is an MS9-LPT multispectral light logger (In-situ Marine Optics).	9
Figure 3-1. Rainfall recorded at Weipa Aero (station 027045) for the 2024-2025 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/	16
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 1 st July to 30 th June. Solid red line represents median annual rainfall by water year, dashed lines represent 10 th , 25 th , 75 th , and 90 th percentiles. Daily rainfall data was obtained from the Weipa Aero (station 027045) weather station. Data source: http://www.bom.gov.au/climate/data/	16
Figure 3-3. Stream discharge (GL d ⁻¹) from the Watson River at Jackin Creek (station 923001A) during the 2024-2025 reporting period (blue line). Daily rainfall totals from each corresponding stream gauge shown in pink. The nominal wet season period is shaded grey. Data source: https://watermonitoring.information.qld.gov.au/	17
Figure 3-4 Wave rose showing the distribution of wave direction and significant wave height (Hs) at Weipa (Albatross Bay) during the 2024–2025 reporting period (1 July 2024 to 30 June 2025). Colours represent wave-height classes (m).	18
Figure 3-5 Monthly wave roses showing the distribution of wave direction and significant wave height (Hs) at Weipa (Albatross Bay) during the 2024–2025 reporting period. Colours indicate wave-height classes (m).	18
Figure 3-6 Time series of significant wave height (Hs) and maximum wave height (Hmax) recorded at Weipa (Albatross Bay) during the 2024–2025 reporting period (1 July 2024 to 30 June 2025).	19
Figure 3-7 Time series of peak wave period (Tp) and zero-crossing wave period (Tz) recorded at Weipa during the 2024–2025 reporting period (1 July 2024 to 30 June 2025).	20
Figure 3-8 Total nitrogen (TN; µg L ⁻¹), total dissolved nitrogen (TDN; µg L ⁻¹), and particulate nitrogen (PN; µg L ⁻¹) concentrations measured in water samples collected from the three water quality sites in the Weipa region, Evans Landing (WP_AMB1), South Channel (WP_AMB2), and Leithen Point (WP_AMB4), for the 2024-2025 reporting period, with the shaded area representative of the wet season.....	21

Figure 3-9 Total phosphorus (TP), total dissolved phosphorus (TDP), and particulate phosphorus (PP) concentrations measured in water samples collected from the three water quality sites in the Weipa region, Evans Landing (WP_AMB1), South Channel (WP_AMB2), and Leithen Point (WP_AMB4), for the 2024-2025 reporting period, with the shaded area representative of the wet season.....	22
Figure 3-10 Chlorophyll-a concentrations ($\mu\text{g L}^{-1}$) measured in water samples collected from the Weipa sites throughout the reporting period. Grey area indicates wet season.	23
Figure 3-11 Dissolved oxygen concentration (mg L^{-1}) at Weipa ambient sites, shown for surface, mid-water, and bottom depths. Grey area indicates wet season.....	26
Figure 3-12 Dissolved oxygen (% saturation) at Weipa ambient sites. Grey area indicates wet season.....	27
Figure 3-13 Electrical conductivity (mS cm^{-1}) at Weipa ambient sites for surface, mid-water, and bottom depths. Grey area indicates wet season.....	28
Figure 3-14 Salinity (PSU) recorded at Weipa ambient sites for surface, mid-water, and bottom depths. Grey area indicates wet season. Note that salinity was only added to the in-situ measured parameters with the introduction of the YSI probe in November 2024.	29
Figure 3-15 Water temperature recorded at the Weipa ambient sites for surface, mid-water, and bottom depths over the reporting period. Grey area indicates wet season.	30
Figure 3-16 The pH recorded at the Weipa ambient sites for surface, mid-water, and bottom depths over the reporting period. Grey area indicates wet season.	31
Figure 3-17 The Secchi depth values recorded at the Weipa ambient sites over the reporting period. Grey area indicates wet season.....	31
Figure 3-18 Turbidity (FNU) recorded at the Weipa ambient sites over the reporting period. Grey area indicates wet season. Note that turbidity (FNU) was only added to the in-situ measured parameters with the introduction of the YSI probe in November 2024.	32
Figure 3-19 Daily mean water temperature (blue) and daily minimum and maximum (light blue) measured at Weipa ambient sites over the reporting period.	33
Figure 3-20 Daily tidal range measured at Weipa ambient sites over the reporting period.....	34
Figure 3-21 RMS depth (m) measured at Weipa ambient sites over the reporting period. Values presented are daily mean (blue line) +/- standard deviation (light blue ribbon).	35
Figure 3-22 Turbidity measured at the Weipa ambient sites over the reporting period. 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.	36
Figure 3-23 Suspended sediment concentrations measured at the Weipa ambient sites over the reporting period. 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.	37

Figure 3-24 Daily light integral (mol photons m ⁻² d ⁻¹) of benthic photosynthetically active radiation (PAR) measured at Weipa ambient sites over the reporting period. Periods of missing data are indicated by the orange bar.	38
Figure 3-25 Relationship between turbidity (NTU) and RMS depth at Evans Landing (WP_AMB1) for the 2024–2025 reporting period. Points are coloured by tidal stage (rising, falling, stable), with linear regression fits shown for each stage. Correlation coefficients (r) indicate a weak and near-zero relationship between short-period depth variability and turbidity across all tidal conditions. .	39
Figure 3-26 Relationship between turbidity (NTU) and RMS depth at South Channel (WP_AMB2) for the 2024–2025 reporting period. Data are grouped by tidal stage (rising, falling, stable), with fitted linear regressions and corresponding Pearson correlation coefficients (r). Positive correlations across all tidal stages indicate increased turbidity during periods of greater short-period water motion.	40
Figure 3-27 Relationship between turbidity (NTU) and RMS depth at Leithen Point (WP_AMB4) for the 2024–2025 reporting period. Scatter points are coloured by tidal stage, with linear regression lines and correlation coefficients (r) shown for each condition. Correlations are weak and negative, indicating limited coupling between near-bed wave motion and turbidity at this site.....	41
Figure 3-28 Multispectral irradiance profiles at Evans Landing (WP_AMB1) during the dry season (top) and wet season (bottom). Each line represents a daylight-filtered spectral observation (normalised to peak irradiance). Colours denote turbidity class: blue = NTU <1, green = NTU 1–5, red = NTU > 5. Pronounced attenuation of blue and blue-green wavelengths (< 500 nm) occurs under elevated turbidity, with more variable spectral shapes during the wet season.	42
Figure 3-29 Multispectral irradiance profiles at South Channel (WP_AMB2) for dry (top) and wet (bottom) seasons. Spectral signatures show consistently high transmission of blue wavelengths under low-turbidity conditions, with narrow, well-defined peaks. Turbid and wet-season conditions exhibit reduced blue-light penetration and a shift toward green-yellow wavelengths, although attenuation remains lower than at other sites.	43
Figure 3-30 Multispectral irradiance profiles at Leithen Point (WP_AMB4) in the dry (top) and wet (bottom) seasons. Spectral responses are highly variable, reflecting the site’s dynamic hydrodynamic environment. Clear-water periods show strong blue-green irradiance, while increased turbidity—particularly during wind-driven or spring-tide resuspension events—produces stronger blue attenuation and increased dominance of longer wavelengths.....	44
Figure 3-31 Distribution of normalised 490 nm irradiance (N490) recorded at the three Weipa ambient monitoring sites. Higher N490 values indicate stronger transmission of short (blue) wavelengths and generally clearer water conditions. South Channel (WP_AMB2) showed higher N490 values compared to the estuarine sites.....	45
Figure 3-32 Boxplots showing the distribution of PQI across the three sites. PQI represents the proportion of benthic irradiance contributed by blue–green wavelengths (440–570 nm). Higher PQI values correspond to clearer optical conditions and greater availability of photosynthetically usable radiation (PUR). Again, PQI was higher at South Channel compared to the two estuarine sites.....	46

Figure 3-33 PQI values separated into wet-season (Nov–Apr, green boxes) and dry-season (May–Oct, blue boxes) conditions. Dry-season PQI values were generally higher at all sites, reflecting enhanced blue–green light transmission during periods of reduced runoff and calmer hydrodynamic conditions. 46

Figure 3-34 RAR quantifies the relative dominance of red wavelengths (610–700 nm) compared with short and mid-visible wavelengths. Elevated RAR values indicate stronger attenuation of blue–green light under turbid conditions. After trimming extreme outliers, RAR showed higher values for the two estuarine sites, consistent with increased freshwater inflow and sediment resuspension.. 47

Figure 3-35 SlopeBG describes the rate of attenuation between blue (≈ 440 nm) and green (≈ 570 nm) wavelengths. More positive slopes indicate stronger suppression of blue light relative to green, typically associated with turbidity or coloured dissolved organic matter. Estuarine sites, Evans Landing and Leithen Point, showed steeper slopes, indicating higher turbidity compared to South Channel..... 48

Figure 3-36 Daily rainfall time series for the Weipa region from 2018 to 2025. Rainfall is highly seasonal and episodic, with the majority of precipitation occurring during the wet season (November–April) as short-duration, high-intensity events, interspersed with extended dry periods. 49

Figure 3-37 Nutrient concentrations measured at Weipa between 2018 and 2024, including total nitrogen (TN), total phosphorus (TP), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), particulate nitrogen (PN), and particulate phosphorus (PP). Points represent individual water-sample observations, with GAMM fits shown as solid lines and shaded bands indicating standard error (dark blue) and 95% confidence intervals (light blue). Models capture seasonal variability and non-directional interannual fluctuations, with most variability driven by episodic hydrological and resuspension events. Units = $\mu\text{g L}^{-1}$ 51

Figure 3-38 Chlorophyll-a (top) and electrical conductivity (bottom) measured at Weipa between 2018 and 2024. Points represent individual observations, with GAMM fits shown as solid lines and shaded uncertainty bands indicating standard error (dark blue) and 95% confidence intervals (light blue). Chlorophyll-a exhibits strong seasonal variability with limited long-term change, while conductivity shows pronounced seasonal structure linked to wet-season freshwater influence. Units: chlorophyll-a = $\mu\text{g L}^{-1}$; conductivity = $\mu\text{S cm}^{-1}$ 53

Figure 3-39 Total suspended solids (TSS) concentrations measured at Weipa between 2018 and 2024. Points represent individual water-sample observations, with the fitted general additive mixed effects model (GAMM) shown as a solid line. Shaded bands indicate the standard error (dark blue) and 95% confidence intervals (light blue). The model highlights modest interannual variability and weak seasonal structure, with concentrations dominated by short-term event-driven variability. Units = mg L^{-1} 54

1 INTRODUCTION

1.1 Background

The Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) at James Cook University (JCU) partners with North Queensland Bulk Ports (NQBP) to undertake long-term environmental monitoring and research surrounding the Port of Weipa (Figure 2-1). As part of this partnership, an ambient water quality monitoring program has been established incorporating discrete field measurements, continuous dataloggers, and laboratory analysis of nutrients, pesticides, Per- and polyfluoroalkyl substances (PFAS), and trace metals. A suite of key parameters is monitored within the program to describe spatial and temporal variability in water quality and characterise ambient water-quality conditions in the vicinity of the port, adjacent to sensitive seagrass and other coastal habitats in the Weipa region, and to inform ongoing port management decisions. 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 primary objective of the program is to monitor and characterise the ambient marine water quality within the Port of Weipa. This report provides a review and analysis of data collected between 1st July 2024 and 30th June 2025. These data are part of a longer-term commitment to characterise water quality conditions, supporting future planned asset management and protection of this coastal port, and helping to identify and minimise potential impacts to nearby sensitive coastal habitats.

The partnership objective also moves beyond basic compliance monitoring 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.

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. 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 recorded 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 Rivers 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 and unloading facilities. As with other ports in Queensland, Port of Weipa requires routine maintenance dredging to maintain declared navigational depths within the swing basin, berth areas, departure path, and aprons. Necessary dredging activities in the operating ports in the region are undertaken in accordance with Commonwealth and State approvals, with management objectives guided by the Port of Weipa Long Term Dredge Management.

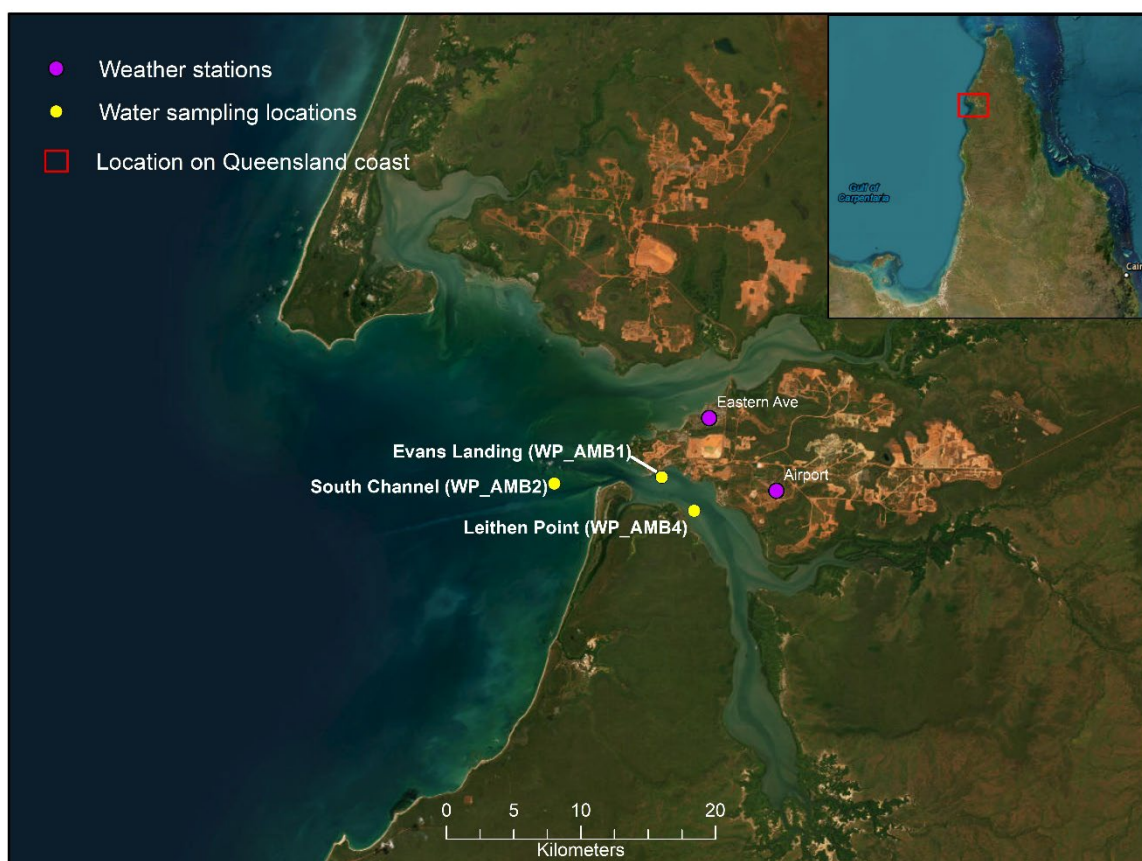


Figure 2-1 Map of Weipa showing location of water quality monitoring sites (yellow) and meteorological stations (purple), utilised in the 2024-2025 reporting period. Inset map shows location on Queensland coast.

2.3 Characterisation of weather, hydrological status, and oceanographic conditions

2.3.1 Rainfall and hydrology

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.

2.3.2 Wave climate

Wave characteristics were derived from the Albatross Bay Wave Buoy located 6 nautical miles offshore from South Channel. Significant wave height (H_s) was used as the primary measure of wave energy and represents the average height of the highest one-third of waves recorded during

each sampling interval. Peak wave direction describes the direction from which the most energetic waves are propagating, based on the dominant component of the wave energy spectrum. These parameters together provide a fundamental description of the height and directional structure of the local wave field and are routinely used to assess coastal hydrodynamics, sediment transport potential, and the influence of regional weather systems.

Wave-period metrics were also examined to further characterise sea-state dynamics. Peak period (T_p) represents the period associated with the strongest spectral energy, while zero-crossing period (T_z) describes the mean interval between successive up-crossings of the average water level. T_p and T_z provide complementary information on the temporal structure of waves, enabling distinction between short-period, locally generated wind-sea and longer-period waves. Collectively, H_s , peak direction, T_p and T_z form a comprehensive description of wave climate conditions relevant to coastal processes and water quality variability within the monitoring region.

2.4 Monitoring and sampling design

2.4.1 Site overview

There are three active ambient marine water quality monitoring sites in the Weipa region (Figure 2-1). Two sites, Evans Landing (WP_AMB1) and Leithen Point (WP_AMB4), are located in the Embley River estuary, with the third, South Channel (WP_AMB2), located in Albatross Bay to the south-west of the river mouth (Table 2-1). 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 physicochemical measurements, and exchange dataloggers (Table 2-2).

More detailed information on the condition of the seagrass meadows adjacent to these water quality sites is available in companion reports (e.g., Reason et al., 2023) accessible via the TropWATER Technical Report page (<https://www.tropwater.com/reports-and-publications>) or the NQBP Research and Reports page (<https://nqbp.com.au/sustainability>).

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

2.4.2 Field sampling schedule

Field sampling is undertaken at all sites approximately every eight weeks. Each visit includes retrieval and re-deployment of dataloggers, collection of discrete water samples for laboratory analysis, and collection of in situ water quality measurements. Table 2-2 lists sampling dates from July 2024 to June 2025.

Table 2-2 Field dates for water sampling, logger maintenance, and dissolved metal sampling in the Weipa region.

Date	Water sampling	Logger maintenance	Metals sampling	Pesticides	Physico-chemical
2024-07-23	Yes	Yes	No	No	Hydrolab
2024-09-26	Yes	Yes	No	No	Hydrolab
2024-11-18	Yes	Yes	Yes	No	ProDSS
2025-01-21	Yes	Yes	No	Yes	ProDSS
2025-03-13	Yes	Yes	No	No	ProDSS
2025-05-21	Yes	Yes	Yes	Yes	ProDSS

2.5 Water quality sampling

2.5.1 Water sample collection

Surface water was collected manually from approximately 0.2 m below the water surface. Samples were obtained for laboratory analysis of nutrients (total nitrogen, total phosphorus, total dissolved nitrogen, total dissolved phosphorus), suspended solids, salinity, electrical conductivity, pH, chlorophyll-a and phaeophytin-a (Table 2-3). Nutrient samples were filtered onsite using 0.45 µm PES syringe filters and stored on ice prior to transport to the laboratory. Total suspended solids (TSS) samples were collected in 1 L bottles, while chlorophyll samples were collected in dark 1 L bottles. Salinity and pH samples were collected in 60 mL vials. All samples were transported on ice and analysed promptly following standard laboratory procedures.

2.5.2 Chlorophyll and pigment processing

Chlorophyll-a samples were filtered within 12 hours of collection using Whatman GF/F 0.45 µm glass fibre filters amended with approximately 0.2 mL of magnesium carbonate. The filters were wrapped in aluminium foil, frozen, and delivered to the TropWATER water quality laboratory for analysis. Chlorophyll-a and phaeophytin-a concentrations were determined spectrophotometrically following APHA Method 10200 H.

2.5.3 Metals and pesticide sampling

Water samples for ultra-trace filterable metals and pesticide analysis were collected on two occasions within the reporting period (Table 2-2). Samples were filtered onsite using 0.45 µm PES syringe filters and stored on ice prior to laboratory analysis. Analytes included arsenic, cadmium, copper, zinc, lead, nickel, silver and mercury, with methods and reporting limits provided in Table 2-4.

Pesticide analytes were grouped according to laboratory analytical method and chemical class, following the National Association of Testing Authorities (NATA)–accredited suite used by the analytical laboratory. These groupings reflect similarities in chemical structure and analytical extraction and detection techniques, rather than environmental behaviour or usage patterns.

Specifically, pesticides were categorised into organophosphate insecticides (EP234A), thiocarbamate and carbamate herbicides (EP234B), dinitroaniline herbicides (EP234C), triazinone herbicides (EP234D), conazole and aminopyrimidine fungicides (EP234E), phenylurea, thiadiazolurea, uracil and sulfonylurea herbicides (EP234F), and triazine herbicides (EP234H).

This categorisation facilitates efficient laboratory analysis and reporting across a broad range of commonly used agricultural chemicals relevant to northern Australian catchments.

2.5.4 Laboratory analysis

Laboratory analysis of routine water quality parameters, nutrients, pigments, and metals followed standard APHA methods. Reporting limits and analytical procedures are detailed in Tables 2-3 and 2-4.

Table 2-3 Water quality parameters that were analysed using water samples collected at sites in the Weipa region, and 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 $\mu\text{S cm}^{-1}$
Total Suspended Solids (TSS)	2540 D @ 103 - 105°C	0.2 mg L ⁻¹
Nutrients		
Total nitrogen (TN)	Simultaneous 4500-NO ₃ -F and 4500-P F analyses after alkaline persulphate digestion	10 $\mu\text{g N L}^{-1}$
Total dissolved nitrogen (TDN)		
Total phosphorus (TP)		1 $\mu\text{g P L}^{-1}$
Total Dissolved phosphorus (TDP)		
Particulate nitrogen (PN)	Calculated as PN = TN - TDN	-
Particulate phosphorus (PP)	Calculated as PP = TP - TDP	-
Chlorophyll		

Chlorophyll- <i>a</i>	10200-H	0.2 µg L ⁻¹
Phaeophytin- <i>a</i>		

Table 2-4 Filterable 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	0.5 µg L ⁻¹
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

2.5.5 Water quality guidelines

Unlike Great Barrier Reef regions, no locally derived numeric water quality objectives have been established for coastal waters of the Weipa region. Water quality results are therefore interpreted in the context of regional baseline conditions and local hydrological variability.

2.6 In situ physicochemical measurements

In situ measurements of temperature, electrical conductivity, pH, dissolved oxygen (% saturation and concentration), and turbidity were collected using either a Hydrolab Quanta multiparameter water quality meter or a YSI ProDSS multiparameter sonde (Table 2.5). Measurements were made at three depths: 0.25 m below the surface, mid-water, and 1 m above the seafloor—to provide an understanding of variability throughout the water column. Photosynthetically active radiation (PAR) was measured concurrently at each depth, and above water, using a LI-192 underwater quantum sensor connected to a LI-250A light meter. Where possible, PAR measurements were collected without interference from clouds or vessel shading, although occasional variability was unavoidable. Water clarity was assessed at each visit using a Secchi disk. The 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.

Table 2-5 Physicochemical 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
Salinity	PSU
pH	
Dissolved Oxygen	%sat
Dissolved Oxygen	mg L ⁻¹
Turbidity	FNU
Light meter	
Photosynthetically active radiation (PAR)	μmol m ⁻² s ⁻¹
Water clarity	
Secchi disk depth	Meters (m)

2.7 Seafloor mounted continuous dataloggers

Continuous water quality measurements were obtained using a pair of seafloor-mounted dataloggers attached to a stainless-steel instrument frame (Figure 2-2). The loggers include an NTU-LPT turbidity logger and an MS9-LPT multispectral light logger, manufactured by In-situ Marine Optics Perth WA (<https://insitumarineoptics.com>). Each logger collected bursts of 50 measurements at 5 Hz every 10 minutes, providing high-frequency data on water temperature (°C),

water depth (m), turbidity (NTU) and underwater light (photosynthetically active radiation; PAR, $\mu\text{mol m}^{-2} \text{s}^{-1}$).



Figure 2-2 Water quality loggers attached to instrument frames ready for seafloor deployment. The horizontally oriented logger is an NTU-LPT turbidity logger; the vertically oriented logger is an MS9-LPT multispectral light logger (In-situ Marine Optics).

The logger pair remained in situ on the seafloor between field visits and were retrieved and redeployed approximately every eight weeks during routine sampling. This deployment approach ensures continuous, comparable data while enabling regular calibration checks, servicing and data download. Specifications for the loggers, including sensor ranges and accuracy, are provided in Table 2- 6.

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	$\mu\text{W cm}^{-2} \text{nm}^{-1}$	0 – 400 $\mu\text{W cm}^{-2} \text{nm}^{-1}$	$2.5 \times 10^{-3} \text{ W cm}^{-2} \text{nm}^{-1}$

2.7.1 Logger data processing and quality control

Following each deployment, dataloggers were returned to the laboratory for pre-processing and quality control. Raw logfiles were initially processed to calculate median values for water temperature, water depth, turbidity and irradiance for each 10-minute burst interval (50 measurements at 5 Hz). These median values form the basis of the high-frequency time-series used in subsequent analysis.

Automated rule-based quality control (QC) was then applied using procedures described in Iles et al. (2023). This automated step detects and flags spurious readings resulting from instrument fouling, low battery voltage, sensor drift, surface interference, shading, or anomalous values outside expected environmental ranges. Following automated QC, each dataset was visually inspected and subjected to manual QC to ensure removal of artefacts not captured by rule-based processes. Final datasets were then ingested into the water quality database for analysis and reporting. A detailed description of QC rules is provided in Appendix B and in Iles et al. (2023).

2.7.2 Suspended sediment concentration

Suspended sediment concentration (SSC) was derived from turbidity measurements by applying site-specific conversion factors established previously for the Weipa region (Cartwright et al., 2022). The relationship between turbidity (NTU) and SSC (mg L^{-1}) is typically site-dependent, reflecting differences in particle size distribution, composition and optical properties of suspended sediments. Although there is no formalised protocol for re-establishing turbidity–SSC relationships, recalibration is recommended periodically, particularly following major hydrodynamic or sediment disturbance events that could alter sediment characteristics at the seabed.

SSC was calculated from logger-derived turbidity values using the following equation:

$$SSC = Turb * Cf \pm e \quad \text{[Equation 1]}$$

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.

2.7.3 RMS water depth

The MS9-LPT logger includes an integrated pressure sensor used to determine water depth and to derive a proxy measure of wave activity at the seafloor. Both the mean water depth and the root mean square (RMS) water depth are useful for examining the influence of tide and wave-driven pressure fluctuations on turbidity, sediment resuspension and benthic light availability.

RMS water depth represents short-term variability in pressure over the 10-second burst interval and is therefore related to wave energy at the seabed. It is important to note that RMS water depth does not measure wave height at the sea surface. Instead, it provides an index of near-bed orbital motion or wave shear stress, which varies with depth. For instance, identical surface wave conditions may produce markedly different RMS values at shallow versus deep sites. Consequently, RMS water depth is a useful relative indicator of potential resuspension between sites of different depths.

For each burst, the pressure sensor records 50 readings over a 10-second period. Average depth (m) and RMS water height are then calculated from these 50 readings.

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

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

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

A Pearson's correlation test was used to assess relationships between RMS water height and turbidity across sites.

2.7.4 RMS Depth and turbidity analysis

Turbidity behaviour was assessed in relation to short-period variation in water depth (RMS depth), which provides an index of high-frequency water-column motion around the sensor. RMS depth was calculated from the 1-minute depth record using a rolling window (7-point centred mean), and the first derivative of the smoothed depth series was used to classify each observation into one of three tidal stages: rising, falling, or stable. Rising tide was defined as periods where the rate of depth increase exceeded 0.005 m per time-step, falling tide where the rate of decrease exceeded 0.005 m per time-step, and all remaining periods were classified as stable.

For each tidal stage, turbidity (NTU) was paired with the corresponding RMS depth value and analysed using Pearson correlation to quantify the strength of association. Scatterplots of RMS depth vs NTU were produced for each site, coloured by tidal stage, with fitted linear regression lines to illustrate differences in slope and data structure among tidal conditions. This approach allowed assessment of whether turbidity variability at each site was linked to short-period water motion and whether this relationship differed between rising, falling and stable tidal states.

2.7.5 Benthic photosynthetically active radiation (bPAR)

Turbidity is often assumed to be the primary driver of light limitation at the seabed (Erftemeijer et al., 2012), but the relationship between turbidity and benthic photosynthetically active radiation (bPAR) is not always consistent (Sofonia & Unsworth, 2010). Because bPAR represents the amount of light reaching benthic photosynthetic habitats (e.g. seagrass, algae, corals), it is considered a more biologically relevant indicator of habitat condition and has been incorporated increasingly into management frameworks and threshold-based guidelines (e.g. Chartrand et al., 2012).

Light attenuation in water follows an exponential decay with depth due to absorption and scattering by dissolved and particulate matter (Kirk, 1994). As a result, absolute bPAR values are not directly comparable among sites with differing depths. To address this, bPAR was calculated from the nine irradiance channels of the MS9 logger, with wavelengths between 400–700 nm interpolated and integrated internally. Median bPAR for each burst was derived from the 50 measurements collected over the 10-second interval.

The daily light integral (DLI), representing the total number of photosynthetically active photons delivered to the seabed over a 24-hour period, was calculated from the bPAR time series using Equation 2.

Daily light integral (DLI) was calculated as follows:

$$DLI = \sum_i PAR_i * \frac{600}{1000000} \quad \text{[Equation 3]}$$

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

1,000,000 is the unit conversion

2.8 Benthic multispectral irradiance

Spectral light is a key determinant of benthic primary production because different phototrophic organisms—such as corals, seagrasses and macroalgae—use specific wavelengths of the visible spectrum with differing efficiency (Jones et al., 2021). Bulk PAR alone does not fully characterise the underwater light environment because spectral composition can vary independently of total irradiance due to turbidity, sediment resuspension, phytoplankton biomass and coloured dissolved organic matter.

Benthic multispectral irradiance was measured at each ambient monitoring site using IMO-LPT MS9 loggers mounted on seafloor frames. Each logger contains nine discrete irradiance channels spanning 410–700 nm (Table 2.4), enabling wavelength-specific assessment of attenuation across the blue, green, yellow and red regions of the spectrum.

2.8.1 Data extraction and normalisation (spectral shape analysis)

Raw spectral irradiance values were extracted from each MS9 logger and filtered to include daylight measurements only. To examine relative spectral shape, irradiance from all nine wavelength channels was normalised to the maximum channel value within each observation. This normalisation removes the influence of absolute light intensity and short-term variability associated with cloud cover, sun angle, and surface conditions, enabling direct comparison of wavelength-specific contributions across time, sites, and seasons. Normalised spectra were used to assess changes in relative spectral composition rather than absolute light availability.

Table 2-7 Wavelength specifications of the In-situ 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

2.8.2 Turbidity classification for spectral response analysis

To support interpretation of spectral-shape variability, each daylight spectral observation was paired with a two-hour mean turbidity value derived from co-located nephelometric sensors. Observations were categorised into three turbidity classes: low (<1 NTU), moderate (1–5 NTU), and high (>5 NTU).

These turbidity classes were applied specifically to interpret normalised multispectral irradiance profiles and to examine how wavelength-specific attenuation patterns varied under contrasting optical conditions associated with sediment resuspension and seasonal hydrodynamics.

2.8.3 Spectral Indices

To quantify changes in benthic light quality, spectral indices were calculated from raw, non-normalised irradiance values. These indices summarise the relative shape of the light field, providing sensitive indicators of turbidity, scattering, absorption, and overall benthic light quality. Because different wavelengths attenuate at different rates—blue light being most sensitive to suspended sediments, and red light strongly absorbed by water—spectral indices allow optical changes to be detected even when total PAR remains relatively unchanged.

These metrics are particularly relevant for assessing habitat condition because seagrass and many coral symbionts rely disproportionately on the blue–green portion of the spectrum for efficient photosynthesis. Changes in spectral quality can therefore influence ecological performance even when light quantity is sufficient.

The following subsections describe each spectral index used in this study and the specific optical processes they represent.

BLUE:GREEN RATIO (BG RATIO)

The BG ratio measures the relative contribution of short-wavelength (blue) light to mid-wavelength (green) light:

$$BG\ ratio = \frac{mean(410-490\ nm)}{mean(520-570\ nm)} \quad [Equation\ 4]$$

Higher values indicate clearer water and lower scattering, as blue wavelengths are preferentially attenuated by suspended sediments.

NORMALISED 490 NM IRRADIANCE (N490)

N490 is the normalised irradiance at 490 nm and serves as an indicator of blue-light penetration. It is particularly sensitive to suspended particulate matter and is widely used in both in situ and remote-sensing optical assessments.

PAR QUALITY INDEX (PQI)

PQI quantifies the proportion of irradiance within the wavelength range most efficiently used by seagrass, macroalgae, and some coral symbionts:

$$PQI = \frac{chan440 + chan490 + chan520 + chan550}{\text{sum of all 9 channels}} \quad [\text{Equation 5}]$$

Higher PQI values correspond to a greater proportion of photosynthetically efficient blue–green light within the total PAR spectrum, and therefore higher-quality benthic light conditions.

RED ATTENUATION RATIO (RAR)

RAR expresses the relative dominance of red wavelengths compared to shorter wavelengths:

$$RAR = \frac{\text{mean}(610-700 \text{ nm})}{\text{mean}(410-570 \text{ nm})} \quad [\text{Equation 6}]$$

Elevated RAR values generally indicate increased turbidity, higher scattering of short wavelengths, or the influence of coloured dissolved organic matter.

BLUE→GREEN SPECTRAL SLOPE (SLOPE_{BG})

The spectral slope between 438.8 nm and 568.3 nm quantifies the rate at which short wavelengths are attenuated relative to green light:

$$\text{Slope}_{BG} = \frac{I_{570} - I_{440}}{570 - 440} \quad [\text{Equation 7}]$$

Positive values indicate strong blue attenuation, while values approaching zero reflect optically clear conditions.

2.9 Long term trend analysis

The Weipa region ambient water quality program has now been running since January 2018. There is now 7 years of data collected which we can begin to use to explore temporal aspects of coastal water quality. To analyse these irregularly spaced time series, Generalized Additive Models (GAMs) were applied using the mgcv package in R (Wood, 2017). Data were pooled across sites to improve power for detecting seasonal and interannual patterns and to provide a regional summary of ambient conditions.

Multi-year data from discrete water sample collections were modelled using the general form:

response ~ s(month, bs = 'cc') + s(time, bs = 'tp');

where the response is the parameter of interest, month represents seasonal cyclicity, and time represents long-term change

Seasonality was modelled using a cyclic cubic regression spline applied to the month term, while long-term trends were modelled using a thin-plate regression spline applied to time. To limit overfitting, spline flexibility was constrained to $k = 5$ for the seasonal component and $k = 20$ for the long-term trend. Outliers were removed only where values failed standard QA/QC procedures or were identified as non-physical (e.g. sensor fouling, calibration artefacts). Environmentally plausible extreme values were retained to preserve the full range of natural variability.

A gamma error distribution with a log link was used, reflecting the non-negative, right-skewed nature of most water quality parameters and its robust performance for environmental time-series data.

Model outputs include two components: a seasonal smooth describing the average wet–dry cycle, and a long-term smooth describing gradual temporal change. The fitted values shown in the plots represent the combined effect of these components, with seasonal oscillations superimposed on the broader multi-year trend. Examining both smooths together allows assessment of whether observed variability is dominated by seasonal processes, longer-term change, or short-term event-driven fluctuations.

3 RESULTS AND DISCUSSION

3.1 Rainfall and river flows

Rainfall across the Weipa region during the 2024–2025 reporting period followed a strongly seasonal monsoonal pattern typical of western Cape York, characterised by very dry conditions through the mid-year dry season, a delayed but abrupt wet-season onset, and a pronounced mid-wet-season rainfall peak associated with monsoonal and trough-driven systems (Figure 3-1). Daily rainfall was negligible from July through October 2024, with only isolated light falls recorded during this period, consistent with dry-season conditions.

Using cumulative rainfall since 1 September to define the functional onset of the wet season, the 2024–2025 rainfall onset occurred on 2 December 2024, when cumulative rainfall exceeded 50 mm. This represents a later-than-average onset relative to many years in the long-term record, reflecting the delayed establishment of monsoonal conditions across the southern Gulf of Carpentaria. Although isolated rainfall occurred in late November, sustained wet-season rainfall did not develop until early December.

Rainfall intensity increased markedly during January and peaked during February 2025, when several high-intensity rainfall events were recorded. Multiple days exceeded 50 mm, with a maximum daily total of approximately 99 mm recorded on 1 February. This period corresponded to active monsoonal conditions and embedded troughs, producing short-duration but intense rainfall typical of the Weipa wet season. Rainfall declined through March and April, with fewer high-intensity events, and returned to very low and sporadic totals by May 2025, marking a clear transition back to dry-season conditions.

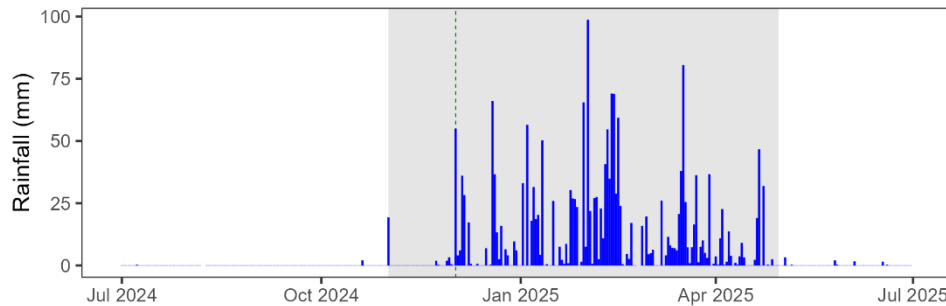


Figure 3-1. Rainfall recorded at Weipa Aero (station 027045) for the 2024-2025 water year. The nominal wet season period is shaded grey. Green vertical dash indicates northern rainfall onset. Data source: <http://www.bom.gov.au/climate/data/>

In a longer-term context, the 2024–2025 rainfall year falls within the range of natural interannual variability observed at Weipa (Figure 3-2). Total rainfall was slightly above the long-term median, but well below the extreme totals associated with major monsoonal or cyclone-influenced years, while still exhibiting a clearly defined wet-season peak. The delayed onset followed by concentrated mid-season rainfall is characteristic of years in which monsoonal activity is established later but remains episodically intense. Overall, the 2024–2025 rainfall pattern reflects a climatically typical year for the Weipa region, dominated by strong seasonal contrast and short-lived, high-intensity wet-season rainfall events.

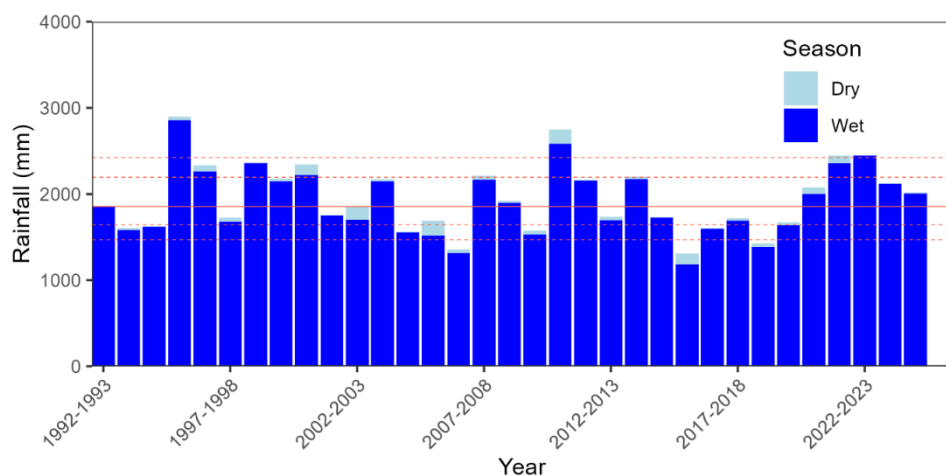


Figure 3-2. Annual rainfall by water year for the Weipa region during wet season (blue) and dry season (light blue). Totals were calculated for the wet season period 1st November to 30th April for each water year. Water year runs from 1st July to 30th June. Solid red line represents median annual rainfall 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 in early January with consecutive large pulses every 1-2 weeks following throughout the wet season (Figure 3-3). Total discharge for the 2024-2025 water year was 923 GL. There was evidence of a significant discharge event occurring in the Embley River in late January 2025.

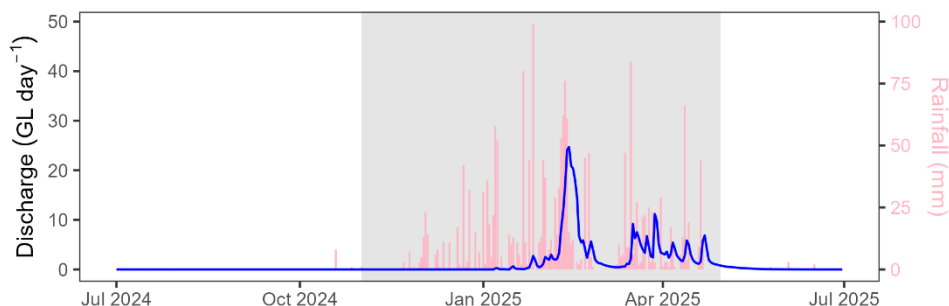


Figure 3-3. Stream discharge (GL d^{-1}) from the Watson River at Jackin Creek (station 923001A) during the 2024-2025 reporting period (blue line). Daily rainfall totals from each corresponding stream gauge shown in pink. The nominal wet season period is shaded grey. Data source: <https://watermonitoring.information.qld.gov.au/>

3.2 Wave climate

Wave conditions in the Weipa region during the 2024–2025 reporting period were generally low-energy and strongly directional, reflecting the sheltered nature of Albatross Bay and the dominance of local wind-generated seas (Figure 3-4). The overall wave rose shows a clear predominance of waves approaching from the east to southeast, with a secondary contribution from the northeast, consistent with regional trade-wind and sea-breeze forcing. Wave heights were typically small, with the majority of observations falling below 0.7 m, and only infrequent occurrences of larger waves exceeding 1–2 m.

Monthly wave roses highlight modest seasonal shifts in wave direction and energy (Figure 3-5). During the dry season months, wave conditions were dominated by low-height easterly and southeasterly waves with little directional spread. In contrast, the wet season exhibited slightly greater directional variability and a higher frequency of moderate wave heights, reflecting increased wind variability associated with monsoonal troughs and transient weather systems. Despite this seasonal contrast, wave heights remained relatively small throughout the year.

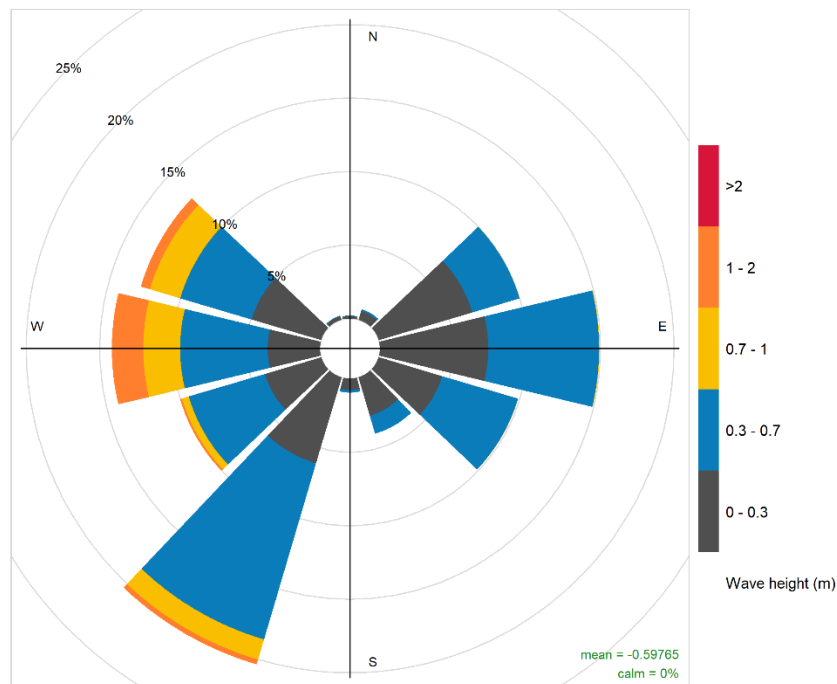


Figure 3-4 Wave rose showing the distribution of wave direction and significant wave height (Hs) at Weipa (Albatross Bay) during the 2024-2025 reporting period (1 July 2024 to 30 June 2025). Colours represent wave-height classes (m).

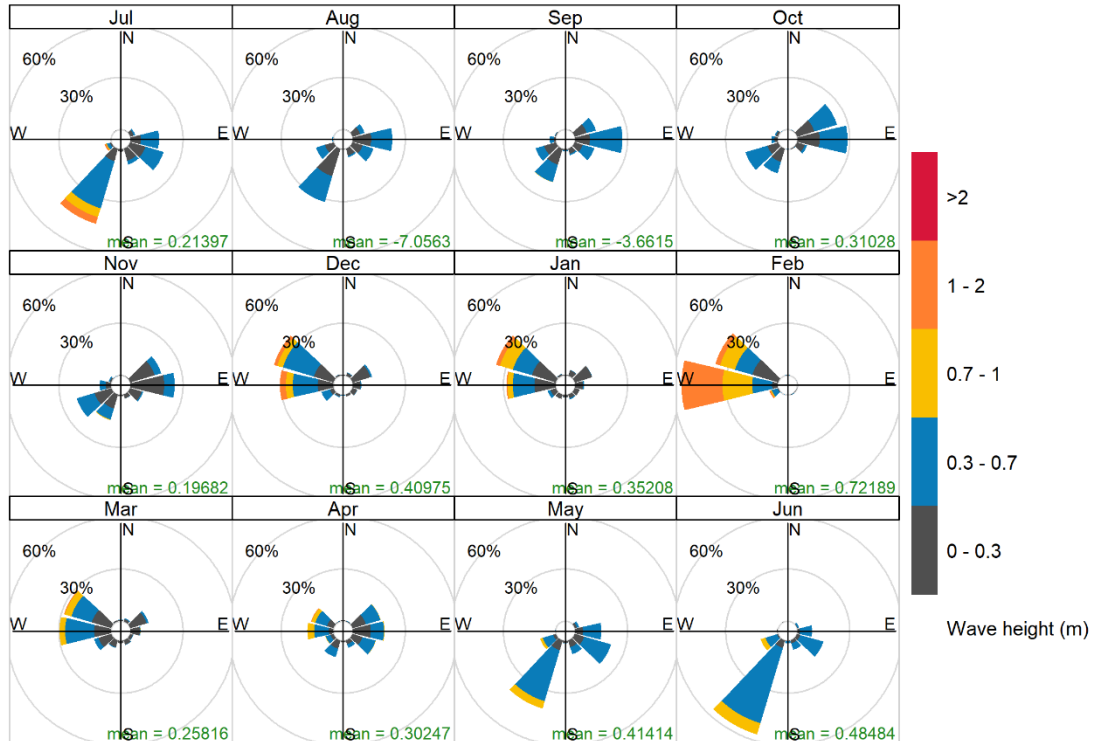


Figure 3-5 Monthly wave roses showing the distribution of wave direction and significant wave height (Hs) at Weipa (Albatross Bay) during the 2024-2025 reporting period. Colours indicate wave-height classes (m).

Time-series analysis of significant wave height (H_s) and maximum wave height (H_{max}) shows persistently calm conditions for much of the year, interrupted by short-lived increases associated with episodic wind events (Figure 3-6). Periods of elevated wave heights occurred sporadically during the wet season, particularly between December 2024 and March 2025, but these events were brief and did not result in sustained increases in wave energy. Outside these periods, wave heights remained consistently low, particularly through the dry season.

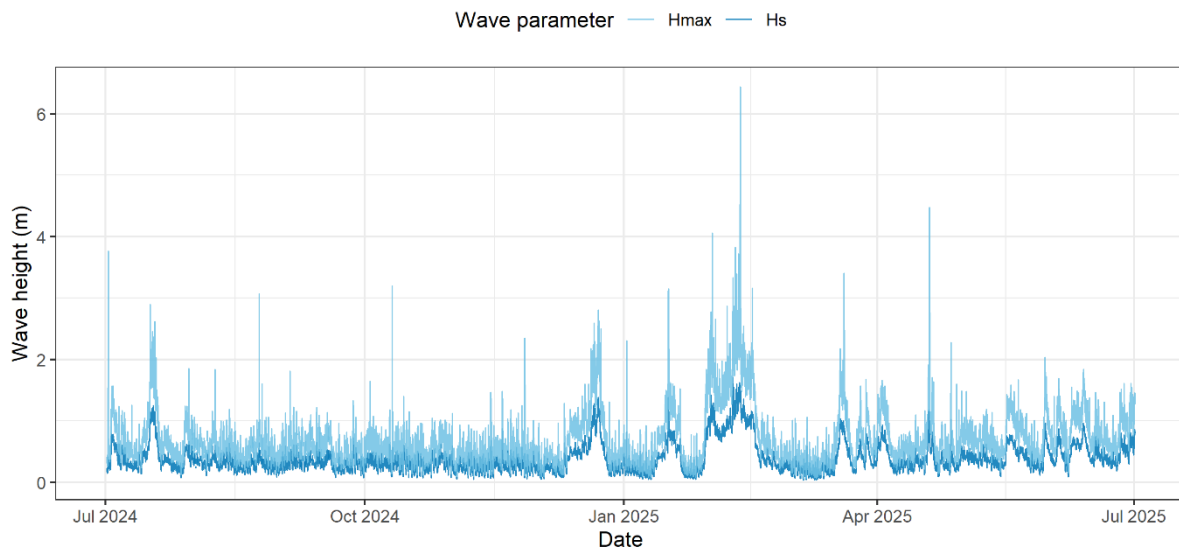


Figure 3-6 Time series of significant wave height (H_s) and maximum wave height (H_{max}) recorded at Weipa (Albatross Bay) during the 2024–2025 reporting period (1 July 2024 to 30 June 2025).

Wave period time series indicate that zero-crossing periods (T_z) were generally short and stable, consistent with locally generated seas (Figure 3-7). Peak wave periods (T_p) showed greater variability than T_z but did not indicate persistent long-period swell influence. Together, the wave height, direction and period data indicate that the Weipa wave climate is dominated by short-period, wind-driven waves rather than sustained swell.

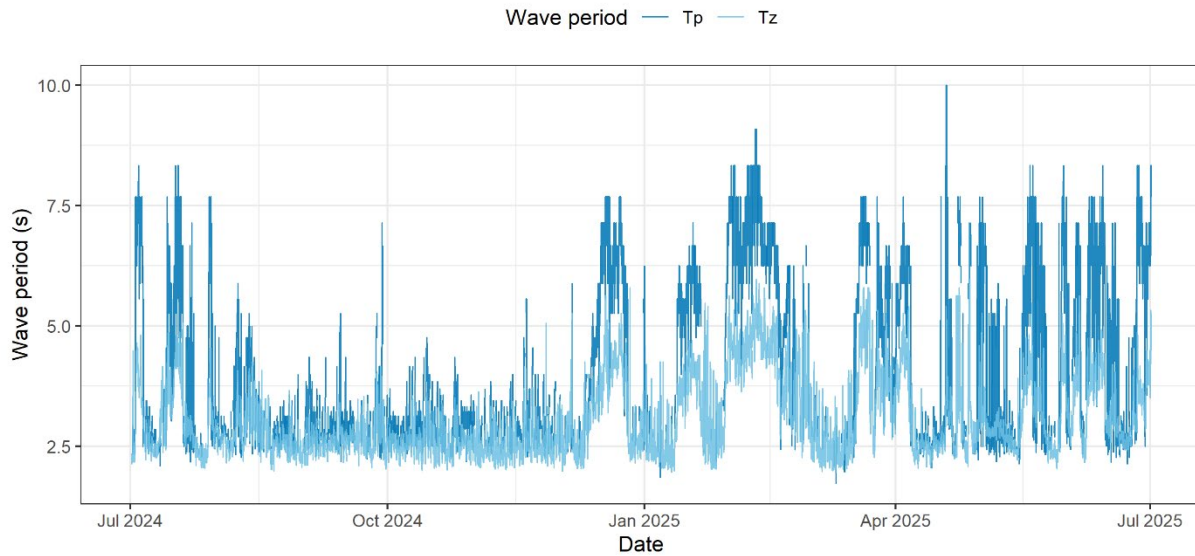


Figure 3-7 Time series of peak wave period (T_p) and zero-crossing wave period (T_z) recorded at Weipa during the 2024–2025 reporting period (1 July 2024 to 30 June 2025).

3.3 Water quality

3.3.1 Nutrients

Nutrient concentrations across the Weipa ambient monitoring sites were broadly characteristic of inshore tropical coastal waters influenced by episodic wet-season runoff and strong tidal mixing, with low to moderate nitrogen concentrations and generally low phosphorus levels over the 2024–2025 monitoring period (Figure 3-8; Figure 3-9).

Total nitrogen (TN) concentrations ranged from 120 to 270 $\mu\text{g L}^{-1}$ across the three Weipa sites, with values most commonly between approximately 140 and 200 $\mu\text{g L}^{-1}$. Temporal variability was evident, with higher TN concentrations generally recorded during wet-season sampling (January–March 2025), consistent with episodic wet-season runoff and particulate mobilisation. The highest TN concentration (270 $\mu\text{g L}^{-1}$) was recorded at Leithen Point in January 2025 and coincided with elevated suspended material, indicating an increased particulate contribution during this period. Outside wet-season sampling, TN concentrations were comparatively stable and showed limited seasonal contrast.

Total dissolved nitrogen (TDN) ranged from 114 to 162 $\mu\text{g L}^{-1}$ and represented the dominant fraction of TN at all sites and sampling occasions. Dissolved nitrogen concentrations showed relatively limited temporal variability compared with particulate fractions, remaining consistently elevated across seasons. This pattern is consistent with strong coastal mixing and the persistence of background dissolved nitrogen in the Weipa nearshore environment.

Particulate nitrogen (PN) exhibited the greatest variability among nitrogen fractions, ranging from 2 to 120 $\mu\text{g L}^{-1}$. Elevated PN concentrations were largely restricted to wet-season sampling, particularly at Leithen Point in January 2025, when increased suspended solids were also observed.

At other times, PN concentrations were generally low to moderate and typically comprised a smaller proportion of total nitrogen relative to the dissolved fraction.

Total phosphorus (TP) concentrations ranged from 6 to 40 $\mu\text{g L}^{-1}$, with most values between approximately 8 and 16 $\mu\text{g L}^{-1}$. Total dissolved phosphorus (TDP) ranged from 4 to 10 $\mu\text{g L}^{-1}$ and showed relatively limited temporal variability across sites and seasons. Particulate phosphorus (PP) concentrations were generally low, typically $\leq 5 \mu\text{g L}^{-1}$, with higher values occurring sporadically during wet-season sampling and coinciding with elevated suspended material.

Overall, nutrient patterns in the Weipa region were dominated by nitrogen, particularly in dissolved form, with phosphorus concentrations remaining comparatively low and stable. Variability in particulate nutrient fractions was largely associated with short-lived wet-season events rather than persistent changes in background conditions. These results are consistent with a system influenced by episodic freshwater inputs and sediment mobilisation superimposed on a well-mixed tropical coastal environment.

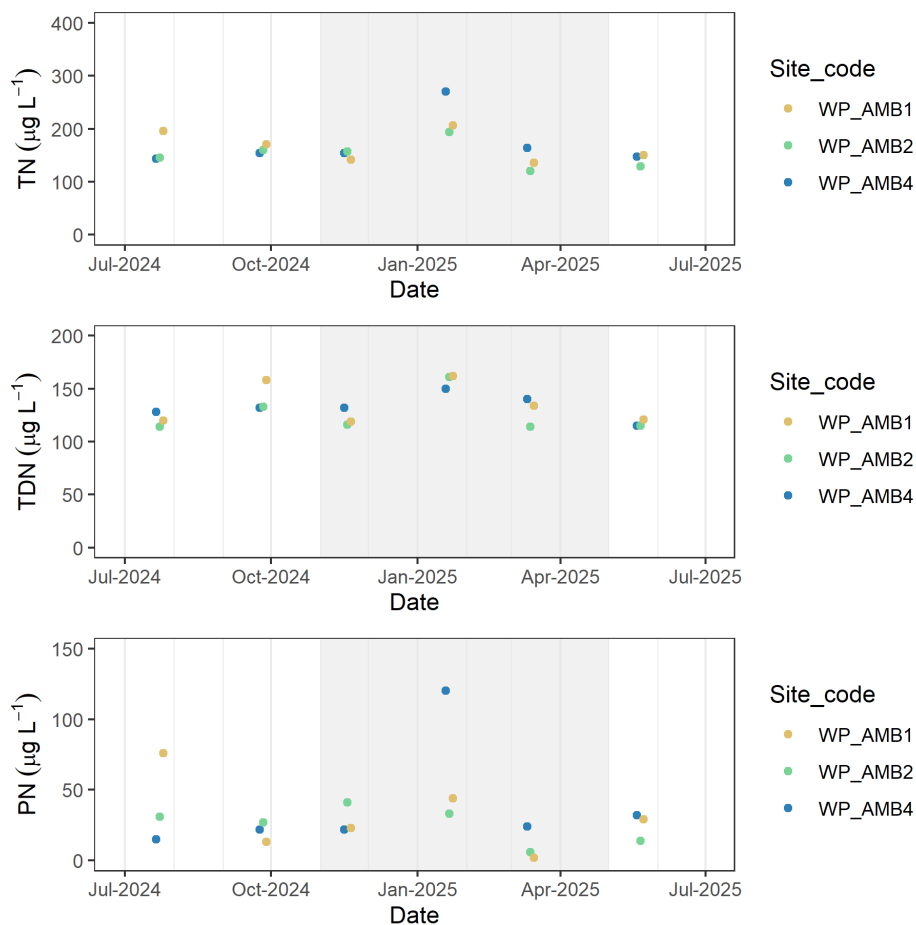


Figure 3-8 Total nitrogen (TN; $\mu\text{g L}^{-1}$), total dissolved nitrogen (TDN; $\mu\text{g L}^{-1}$), and particulate nitrogen (PN; $\mu\text{g L}^{-1}$) concentrations measured in water samples collected from the three water quality sites in the Weipa region, Evans Landing (WP_AMB1), South Channel (WP_AMB2), and Leithen Point

(WP_AMB4), for the 2024-2025 reporting period, with the shaded area representative of the wet season.

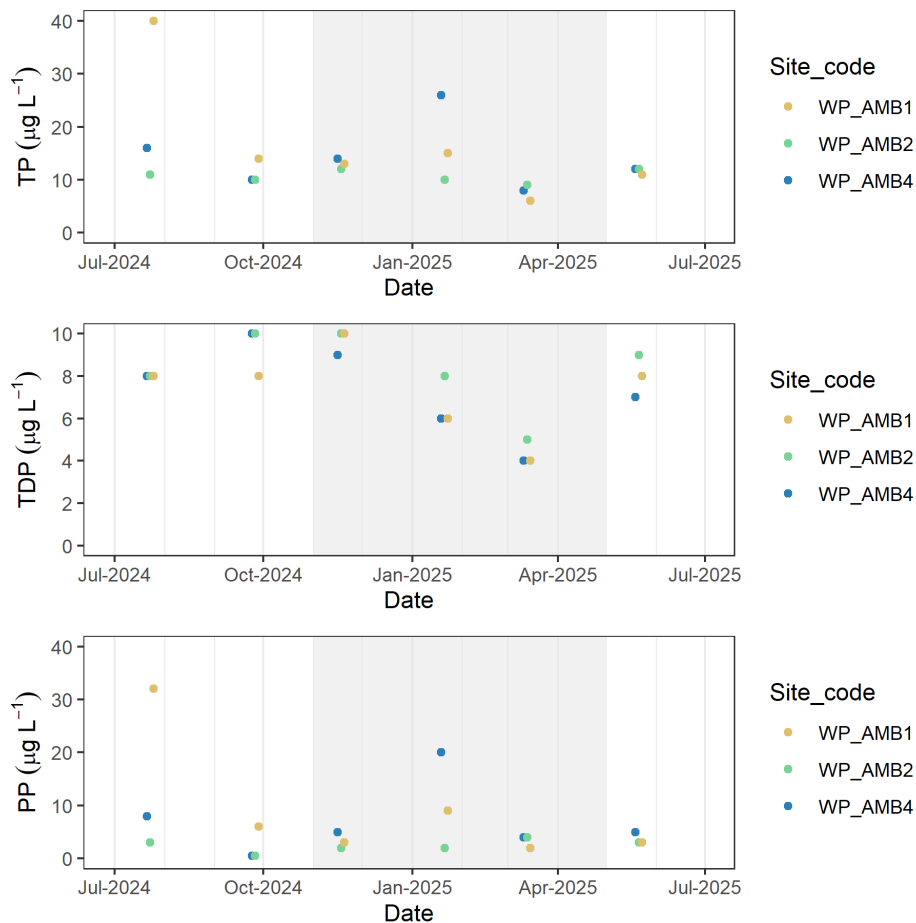


Figure 3-9 Total phosphorus (TP), total dissolved phosphorus (TDP), and particulate phosphorus (PP) concentrations measured in water samples collected from the three water quality sites in the Weipa region, Evans Landing (WP_AMB1), South Channel (WP_AMB2), and Leithen Point (WP_AMB4), for the 2024-2025 reporting period, with the shaded area representative of the wet season.

3.3.2 Chlorophyll

Chlorophyll-a concentrations across the Weipa ambient monitoring sites were generally low to moderate over the 2024–2025 monitoring period, with values ranging from 0.56 to 3.72 $\mu\text{g L}^{-1}$ (Figure 3-10). Most measurements fell between approximately 0.9 and 2.2 $\mu\text{g L}^{-1}$, with higher concentrations observed during wet-season sampling, particularly in January and March 2025. The highest chlorophyll-a concentration (3.72 $\mu\text{g L}^{-1}$) was recorded at Leithen Point in January 2025 and coincided with elevated total nitrogen, particulate nitrogen and suspended solids, indicating increased phytoplankton biomass during periods of enhanced wet-season influence.

Spatially, chlorophyll-a concentrations were broadly comparable across Evans Landing, South Channel and Leithen Point, with no site exhibiting persistently elevated levels relative to the others. Temporal variability was more pronounced than spatial variability, with short-lived increases occurring during wet-season conditions and lower concentrations during the dry season. Phaeophytin-a concentrations were generally low ($<0.35 \mu\text{g L}^{-1}$ in most samples), suggesting limited pigment degradation and an absence of sustained phytoplankton turnover. Overall, chlorophyll-a patterns in the Weipa region appear to reflect episodic wet-season responses rather than persistent or progressive changes in phytoplankton biomass.

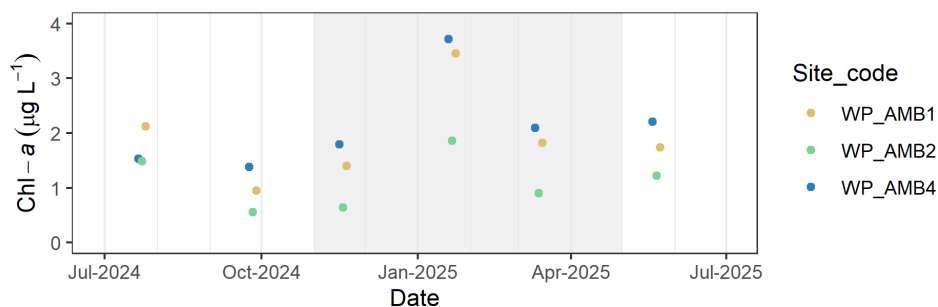


Figure 3-10 Chlorophyll-a concentrations ($\mu\text{g L}^{-1}$) measured in water samples collected from the Weipa sites throughout the reporting period. Grey area indicates wet season.

3.3.3 Filterable metals

Filterable metal concentrations measured at the Weipa ambient monitoring sites in November 2024 and May 2025 were generally low and consistent across Evans Landing, South Channel and Leithen Point (Table 3-1). Silver, cadmium and mercury were below laboratory reporting limits in all samples. Copper was at or below the reporting limit ($\leq 1 \mu\text{g L}^{-1}$) at all sites and sampling times, with no consistent spatial or temporal pattern evident. Lead concentrations were low, with values at or below $0.6 \mu\text{g L}^{-1}$, and nickel concentrations were similarly low, ranging from below detection to $0.6 \mu\text{g L}^{-1}$.

Arsenic concentrations were detectable at all sites, ranging from 1.3 to $2.1 \mu\text{g L}^{-1}$, with slightly higher values observed during the November 2024 sampling relative to May 2025. These concentrations were spatially consistent across sites and showed no indication of localised enrichment. Overall, trace metal concentrations in the Weipa region during the 2024–2025 monitoring period were low, exhibited limited temporal variability, and were broadly consistent with concentrations typically observed in tropical coastal waters.

When assessed against ANZG (2018) default guideline values, applying 95% or 99% species protection criteria according to site-specific environmental value and management intent as defined in the EPP (2019), no guideline exceedances were recorded during either dry- or wet-season sampling.

Table 3-1 Filterable metal concentrations from the three ambient marine monitoring sites in Weipa over the reporting period. Bold values indicate values above limit of detection, orange values exceed the 99% level of species protection, red values exceed the 95% level of species protection.

Location	Month	Silver	Cadmium	Copper	Lead	Nickel	Arsenic	Mercury
	Units	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	mg/L
	Reporting limits (LOD)	0.1	0.2	1	0.2	0.5	0.5	0.0001
	ANZECC 95% level	1.4	5.5	1.3	4.4	70	-	0.4
	ANZECC 99% level	0.8	0.7	0.3	2.2	7	-	0.1
Evans Landing	Nov-2024	<0.1	<0.2	1	0.3	<0.5	1.8	<0.0001
South Channel	Nov-2024	<0.1	<0.2	<1	<0.2	<0.5	1.8	<0.0001
Leithen Point	Nov-2024	<0.1	<0.2	<1	0.6	<0.5	2.1	<0.0001
Evans Landing	May-2025	<0.1	<0.2	<1	<0.2	0.6	1.3	<0.0001
South Channel	May-2025	<0.1	<0.2	<1	<0.2	0.5	1.3	<0.0001
Leithen Point	May-2025	<0.1	<0.2	<1	<0.2	0.6	1.3	<0.0001

3.3.4 Pesticides

All pesticide analytes measured during the reporting period were below laboratory limits of reporting at all sampling sites (Table 3-2). No detections were recorded for any compounds analysed, and concentrations were consistently below applicable reporting limits across all samples. These results indicate no detectable pesticide residues in ambient marine waters at the time of sampling.

Table 3-2 Pesticide concentrations measured in ambient marine water samples collected from three monitoring sites in the Weipa region in January 2025 (wet season) and May 2025 (early dry season). All analytes were below laboratory limits of reporting.

Analyte (µg/L)	WP_AMB1 Evans Landing	WP_AMB2 South Channel	WP_AMB4 Leithen Point	WP_AMB1 Evans Landing	WP_AMB2 South Channel	WP_AMB4 Leithen Point	Chemical class/ analytic method
	Wet Season			Dry Season			
Chlorpyrifos	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	EP234A
Malathion	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Diazinon	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Pirimiphos-methyl	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Thiobencarb	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	EP234B

Pendimethalin	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	EP234C
Hexazinone	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	EP234D
Propiconazole	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	EP234E
Hexaconazole	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Difenoconazole	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Tebuconazole	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Flusilazole	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Penconazole	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Diuron	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	EP234F
Ametryn	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	EP234H
Atrazine	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Cyanazine	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Prometryn	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Propazine	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Simazine	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Terbutylazine	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	
Terbutryn	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	

3.4 Physicochemical

3.4.1 Dissolved oxygen

Dissolved oxygen (DO) concentrations were consistently high across all Weipa ambient monitoring sites, generally ranging from 5.59–6.75 mg L⁻¹ (Figure 3-11). Corresponding oxygen saturation levels ranged from 84–102.8% (Figure 3-12), reflecting well-oxygenated conditions throughout the water column. A slight increase in saturation values at the start of the dry season sampling events likely reflects enhanced photosynthetic activity under clear conditions.

Vertical differences were minor, although DO saturation was typically highest at the surface and marginally lower at deeper depths, consistent with reduced light availability and slightly higher biological oxygen demand near the seabed. No hypoxic conditions were observed at any site or time. DO is reported both as mg L⁻¹ (absolute concentration) and % saturation (relative to solubility at the measured temperature and salinity), allowing clearer interpretation under varying seasonal and physical conditions.

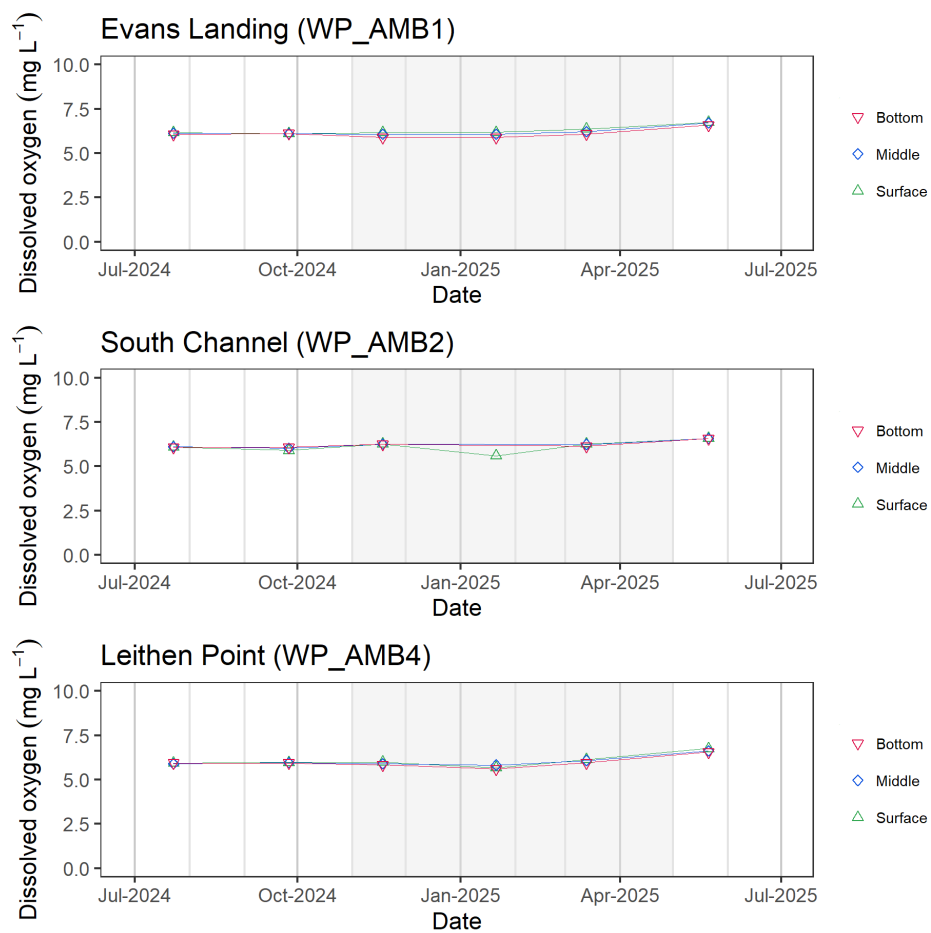


Figure 3-11 Dissolved oxygen concentration (mg L⁻¹) at Weipa ambient sites, shown for surface, mid-water, and bottom depths. Grey area indicates wet season.

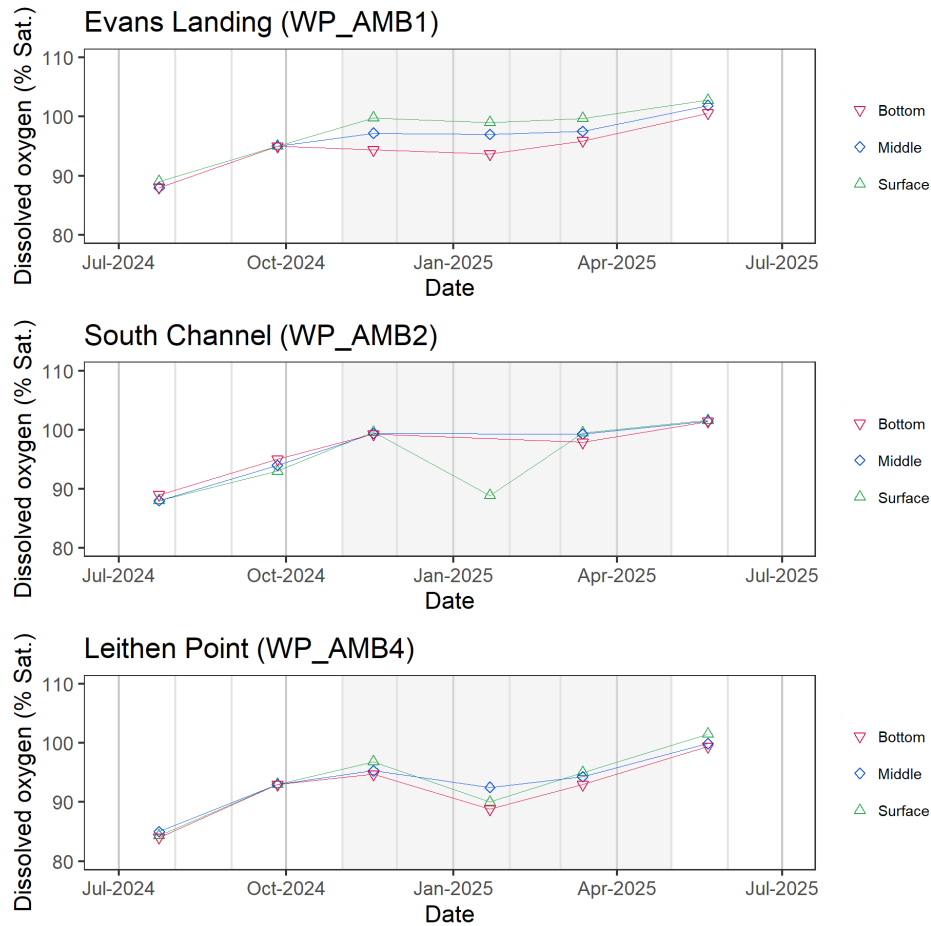


Figure 3-12 Dissolved oxygen (% saturation) at Weipa ambient sites. Grey area indicates wet season.

3.4.2 Conductivity

Electrical conductivity (EC) showed the expected seasonal pattern for tropical inshore waters (Figure 3-13). EC ranged from 38.8–54.6 mS cm⁻¹, with the lowest values recorded during the late wet season (March 2025), coinciding with slight freshwater influence and lower salinity. The highest EC values occurred at the end of the dry and start of the wet season (September–November 2024), reflecting reduced rainfall and stronger evaporative concentration.

Conductivity values showed strong seasonal variation with a decrease in EC measurements during the late wet season due to dilution from freshwater runoff and rainfall, particularly in the estuarine sites at Evans Landing and Leithen Point, but also noticeable in the coastal site at South Channel.

3.4.3 Salinity

Salinity varied in line with expected seasonal patterns (Figure 3-14) with the effects of rainfall and freshwater inflow evident in measurements during the late wet season. Values ranged from 24.9 PSU during the wet season to 36.4 PSU in the dry season.

Vertical salinity gradients were minimal, indicating a generally well-mixed water column during sampling. However, minor stratification was evident in the wet season where surface salinity values were slightly lower.

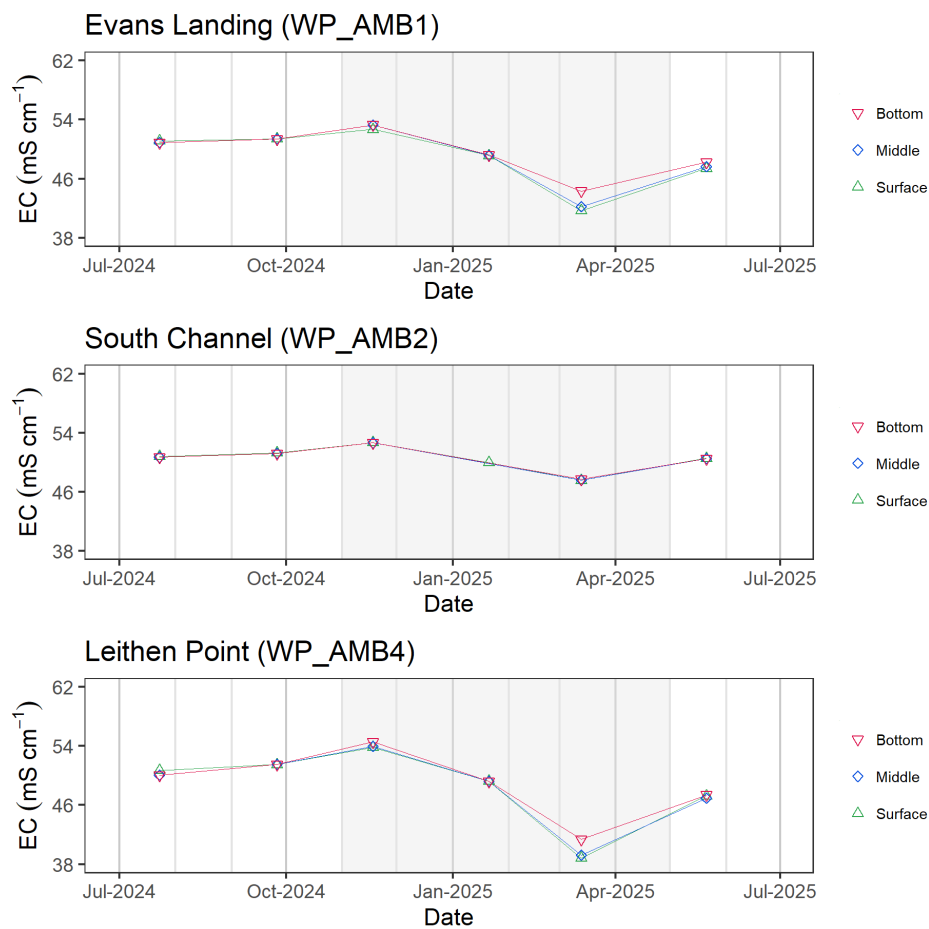


Figure 3-13 Electrical conductivity (mS cm^{-1}) at Weipa ambient sites for surface, mid-water, and bottom depths. Grey area indicates wet season.

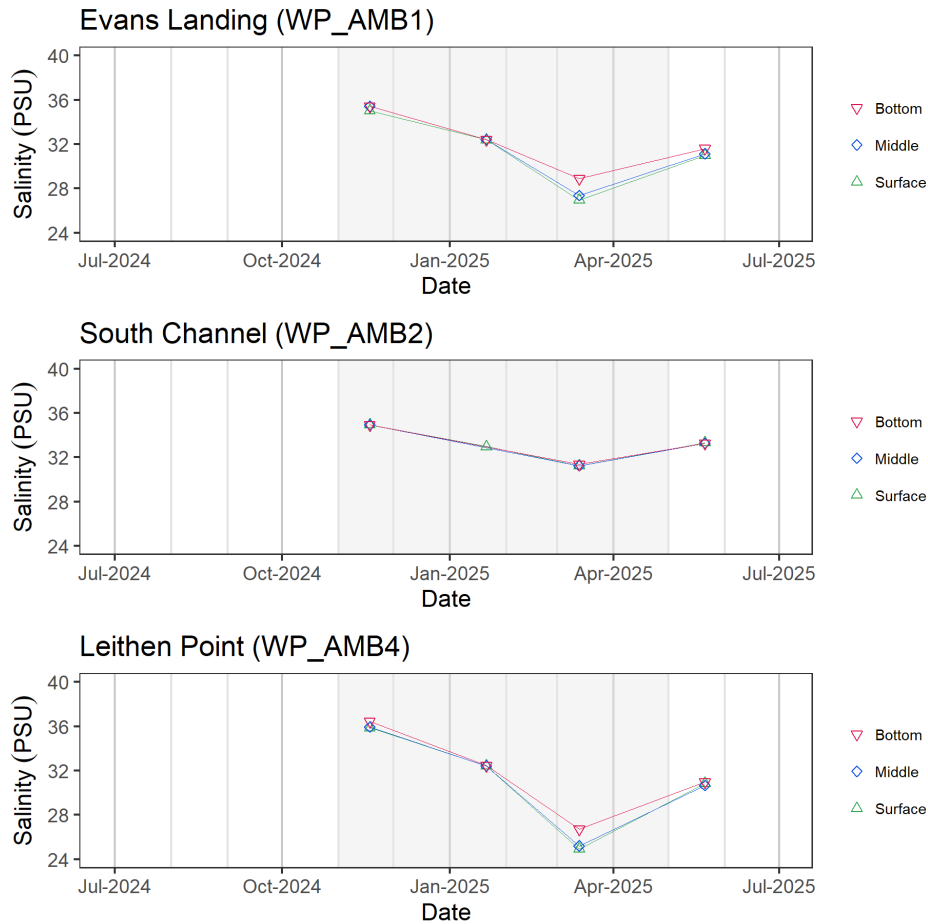


Figure 3-14 Salinity (PSU) recorded at Weipa ambient sites for surface, mid-water, and bottom depths. Grey area indicates wet season. Note that salinity was only added to the in-situ measured parameters with the introduction of the YSI probe in November 2024.

3.4.4 Water temperature

Water temperature displayed clear seasonal variation characteristic of tropical coastal waters (Figure 3-15). The coolest temperatures were observed in July 2024 (23 °C), with temperatures steadily increasing into summer and peaking between 30-31.2 °C in March 2025. Temperature differences among depths were negligible, indicating a vertically mixed water column during all sampling events. No thermal stratification was observed.

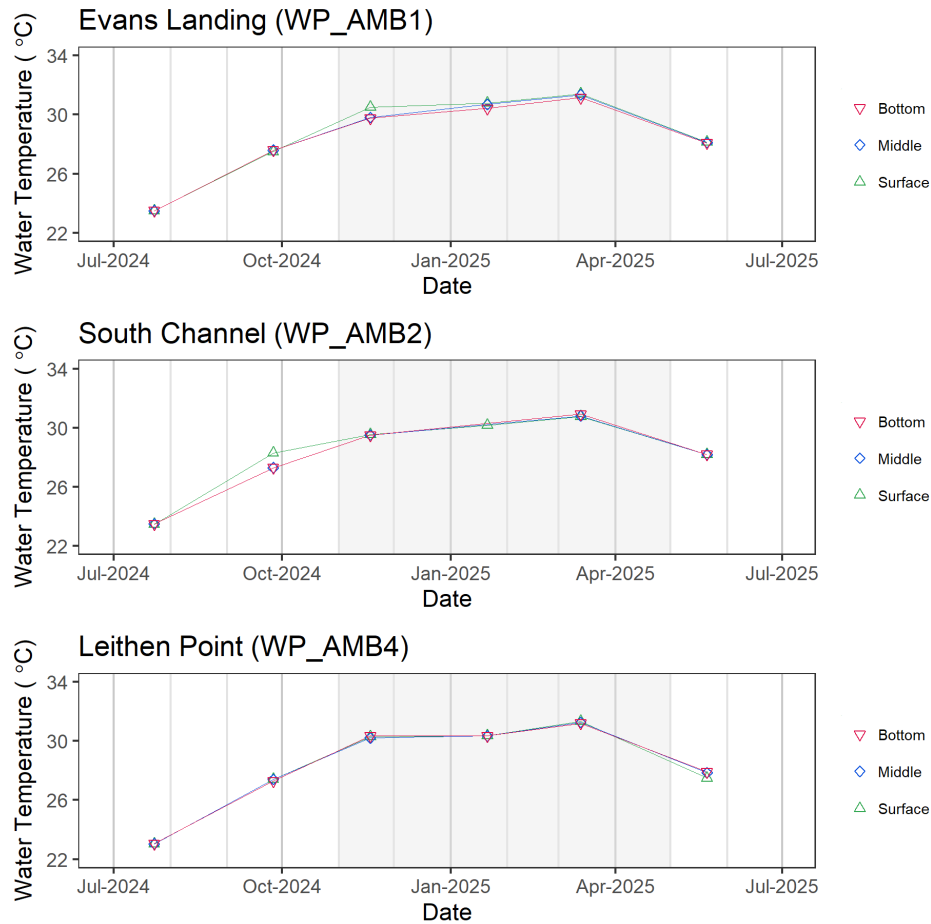


Figure 3-15 Water temperature recorded at the Weipa ambient sites for surface, mid-water, and bottom depths over the reporting period. Grey area indicates wet season.

3.4.5 pH

pH values remained stable across all sites and depths, ranging from 7.9–8.4 (Figure 3-16). This narrow range is characteristic of well-buffered inshore marine waters. Slightly elevated pH values (8.2-8.4) in September may indicate increased photosynthetic activity under high-light, low-turbidity conditions. No acidification events or departures from typical marine pH ranges were observed.

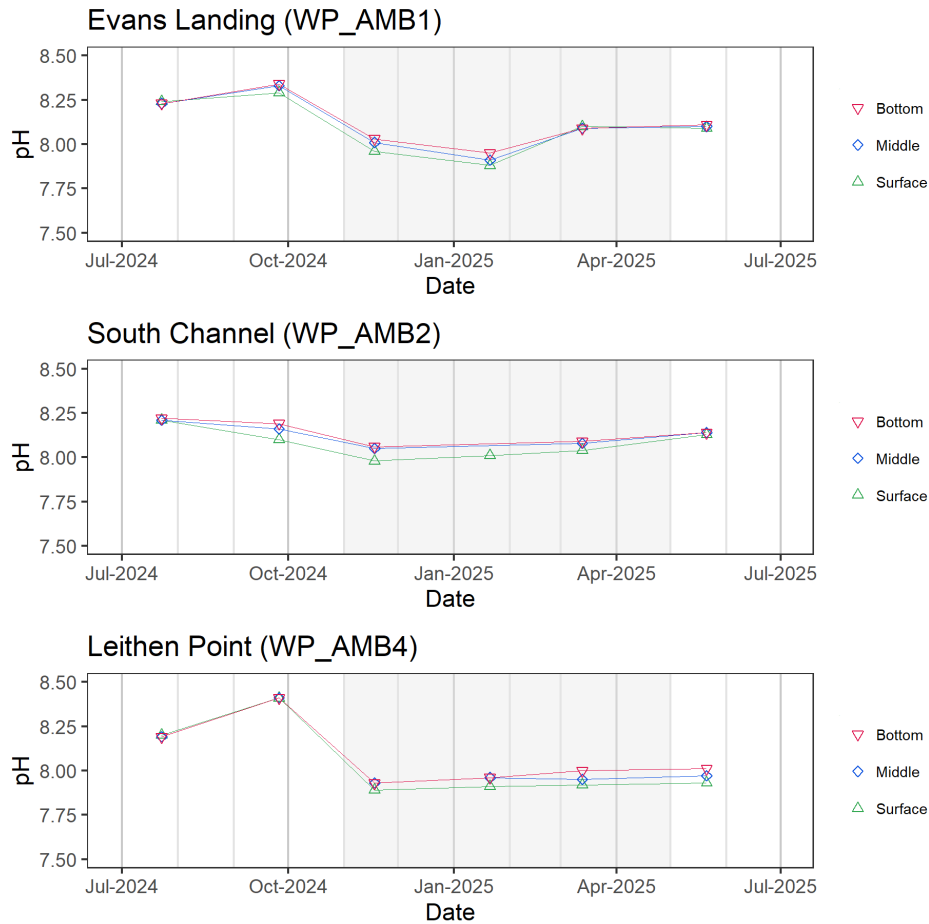


Figure 3-16 The pH recorded at the Weipa ambient sites for surface, mid-water, and bottom depths over the reporting period. Grey area indicates wet season.

3.4.6 Water clarity

Secchi depth measurements ranged from 0.8–4.1 m across the monitoring period. These values are consistent with expected water clarity in the Embley River estuary, with reduced Secchi depths, indicating higher turbidity, observed during the wet season months (November–December 2024) due to rainfall and runoff.

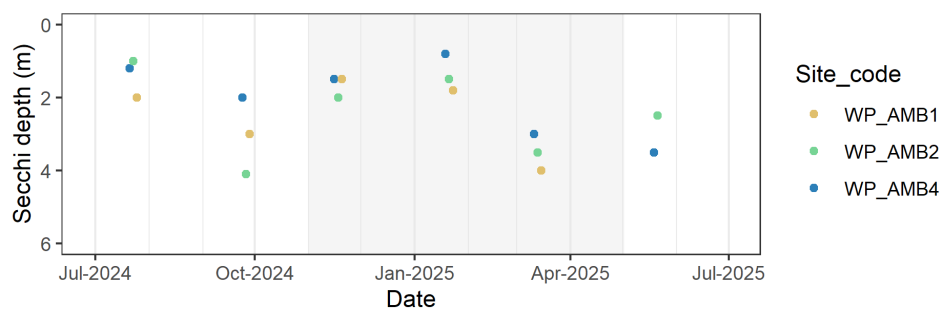


Figure 3-17 The Secchi depth values recorded at the Weipa ambient sites over the reporting period. Grey area indicates wet season

3.4.7 Turbidity

In-situ turbidity measurements (FNU) ranged from 0.82–19.57 FNU, with the highest values recorded during wet-season sampling in the estuarine sites (Figure 3-18). Turbidity values at the coastal site (South Channel) not vary as much during the wet season. Observed turbidity reduced towards the end of the wet season and into the dry, consistent with reduced freshwater inflow, rainfall, and sediment resuspension.

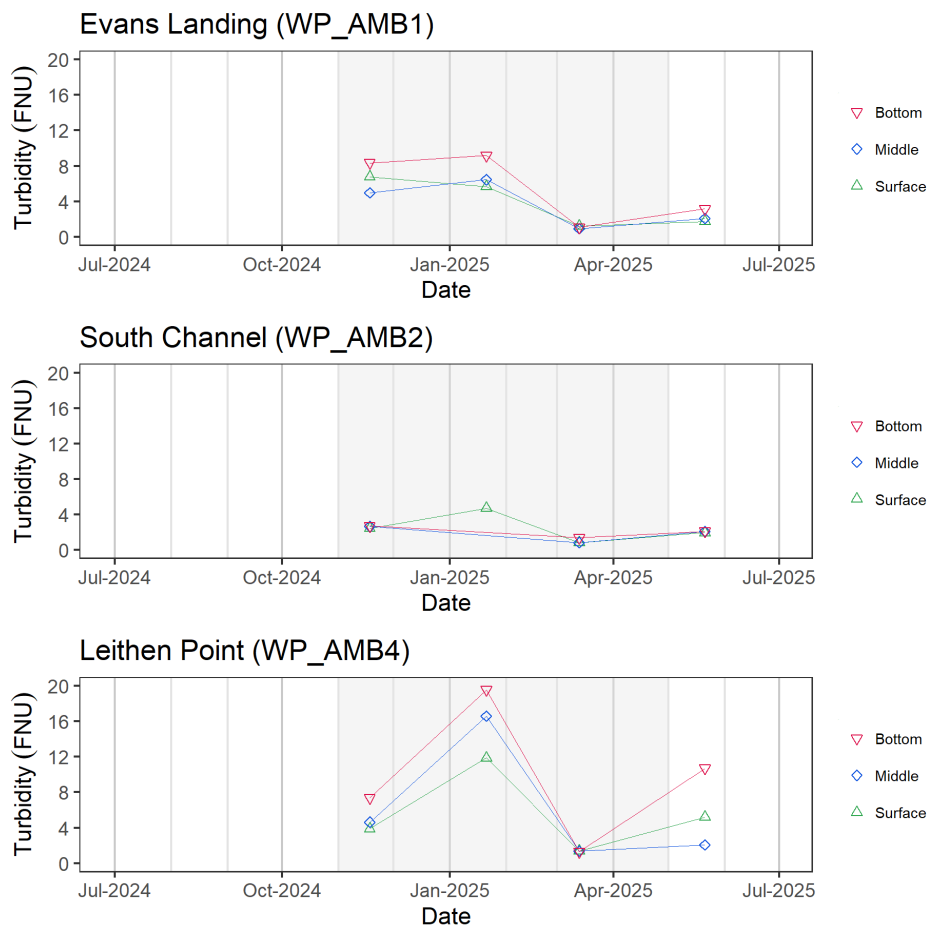


Figure 3-18 Turbidity (FNU) recorded at the Weipa ambient sites over the reporting period. Grey area indicates wet season. Note that turbidity (FNU) was only added to the in-situ measured parameters with the introduction of the YSI probe in November 2024.

3.5 Seafloor mounted continuous dataloggers

3.5.1 Water temperature

Seafloor temperatures across the Weipa ambient monitoring sites showed a clear, consistent seasonal cycle, warming from the dry season (July–September) into the wet season (November–March) and cooling again through May–June (Figure 3-15). Across all three sites, daily mean temperatures were typically ~25–27 °C in winter and early spring, increased rapidly from October, and remained elevated through summer with sustained periods near ~30–31 °C. A short-lived

cooling event is also evident in mid–late February 2025 across sites, followed by renewed warming into March.

Temperature ranges were similar among sites over the 2024–2025 reporting period. Evans Landing (WP_AMB1) ranged from 23.2 to 32.5 °C (median 28.9 °C), South Channel (WP_AMB2) ranged from 22.9 to 32.8 °C (median 28.8 °C), and Leithen Point (WP_AMB4) ranged from 21.4 to 33.0 °C (median 28.9 °C). Seasonal summaries (see Appendix A for full summary table) indicate dry-season mean temperatures of ~27.0 °C at all sites, increasing to ~30.3 °C during the wet season, reflecting the strong seasonal thermal signal typical of tropical coastal waters.

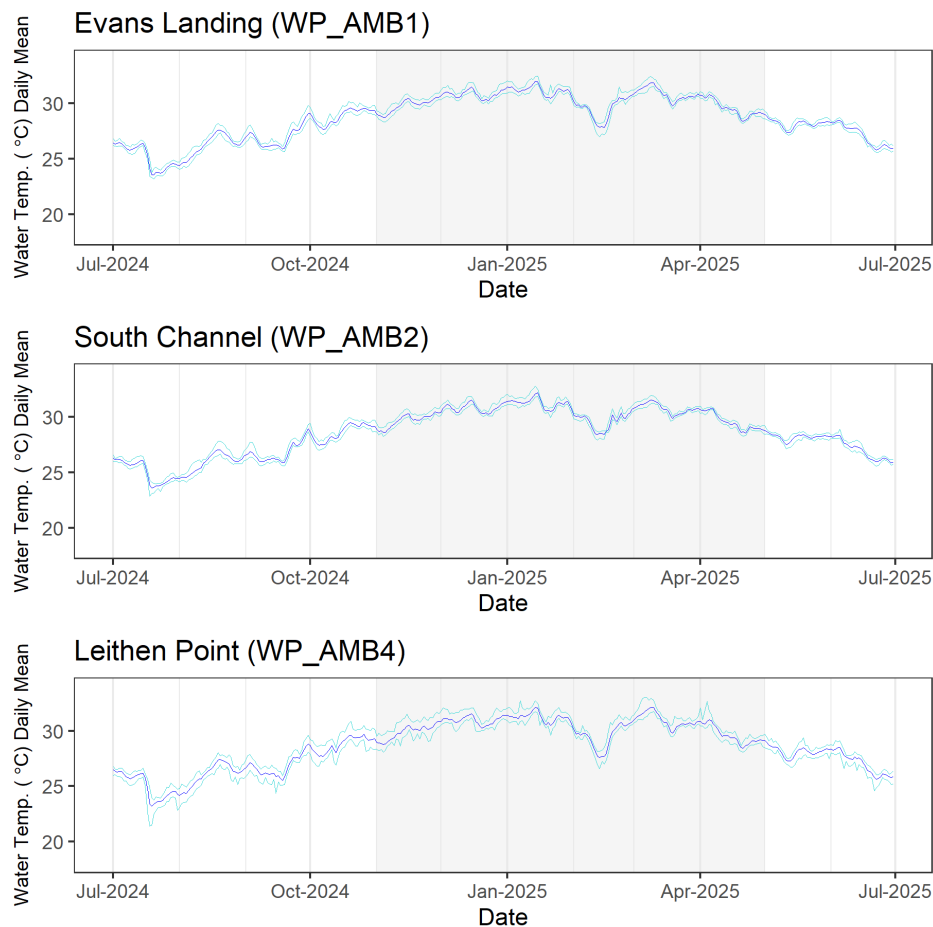


Figure 3-19 Daily mean water temperature (blue) and daily minimum and maximum (light blue) measured at Weipa ambient sites over the reporting period.

3.5.2 Water depth and tidal signal

The daily tidal range for each site is presented in Figure 3-20. Tides in the Weipa region are mixed semi-diurnal with a marked diurnal inequality. When the inequality is pronounced it can result in only one tidal cycle occurring in a 24-hour period. Daily tidal range was measured to be from 0.66–2.72 m during the reporting period. The water depth where the loggers were positioned was recorded at an average of 4.2–5.1 m between sites, but actual depth as a result of tides varied between 2.3–6.6 m. Leithen Point is the shallower of the sites with a mean depth recorded 4.2 m and a maximum of 5.8 m, whereas South Channel recorded a mean depth of 4.7 m and a maximum

of 6.3, and Evans Landing is the slightly deeper of the sites with a mean depth of 5.1 m and a maximum of 6.6 m.

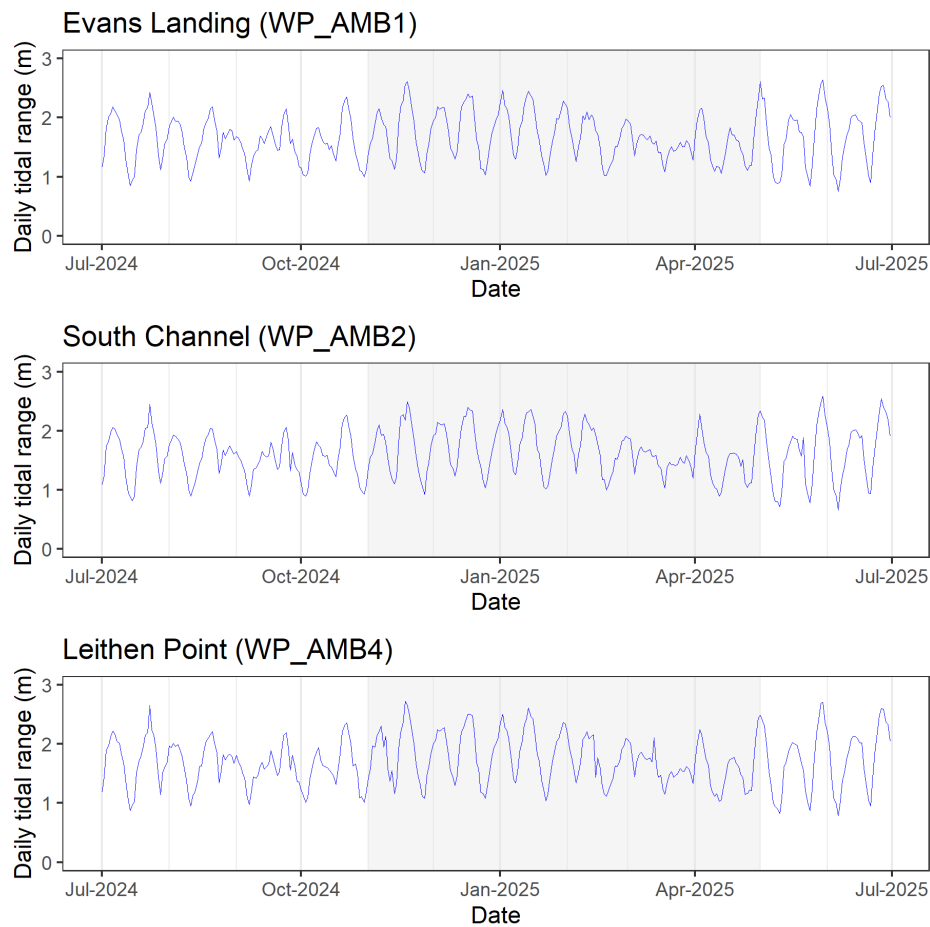


Figure 3-20 Daily tidal range measured at Weipa ambient sites over the reporting period.

3.5.3 Wave activity

Near-bed wave activity in the Weipa region, assessed using the RMS depth metric, was generally low over the 2024–2025 monitoring period, indicating that seabed conditions were dominated by tidal processes rather than persistent wave-driven orbital motion (Figure 3-21). RMS depths at Evans Landing (WP_AMB1) and Leithen Point (WP_AMB4) remained consistently low throughout the year, typically around 0.01 m, with little distinction between dry and wet seasons. These values indicate limited wave influence at the seabed and reflect the relatively sheltered, tidally influenced nature of these sites.

South Channel (WP_AMB2) exhibited higher RMS depth values and greater variability than the other two sites, consistent with its more exposed setting and greater susceptibility to wind-driven wave activity. While RMS depths at South Channel were still generally low in absolute terms, short-lived increases were observed during the wet season, including elevated values in February 2025. Despite this variability, RMS depths across all sites remained at the low-energy end of the spectrum overall, indicating that wave-forced seabed mobilisation was limited and episodic, with tidal processes remaining the dominant driver of near-bed hydrodynamics.

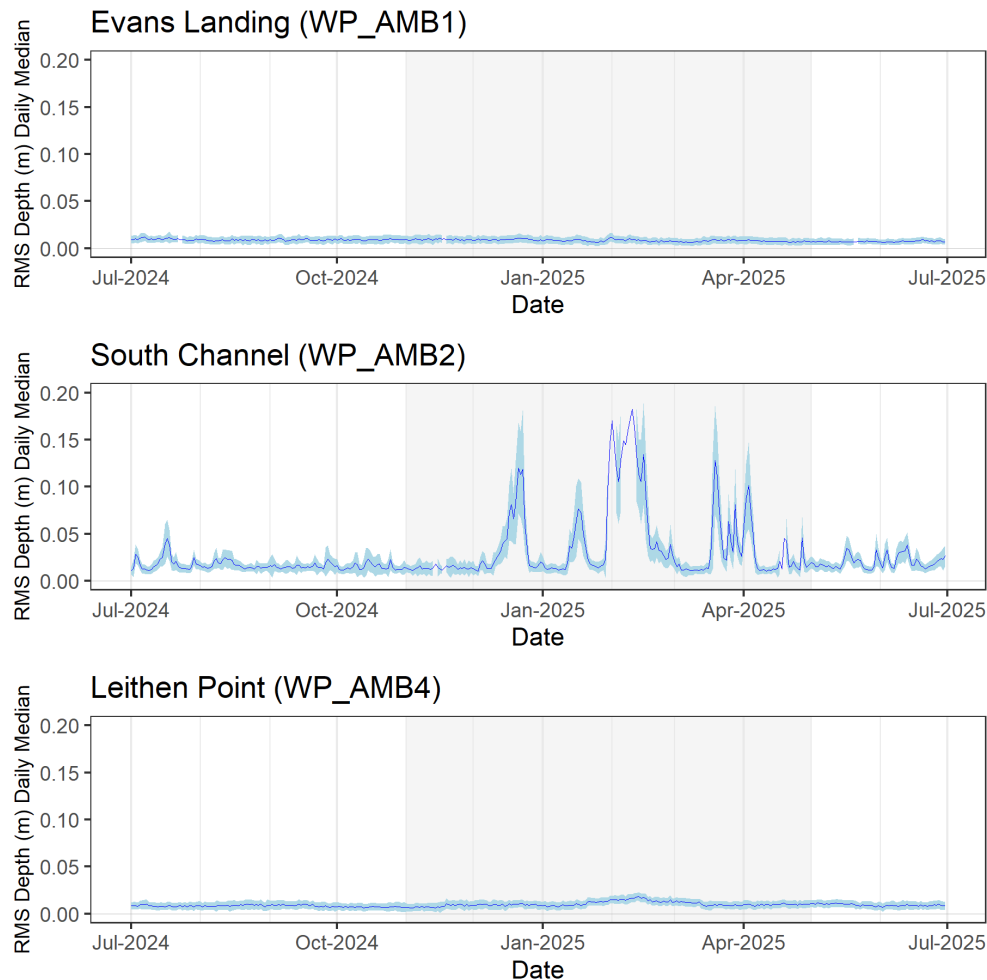


Figure 3-21 RMS depth (m) measured at Weipa ambient sites over the reporting period. Values presented are daily mean (blue line) +/- standard deviation (light blue ribbon).

3.5.4 Turbidity

Turbidity across the Weipa ambient monitoring sites exhibited strong temporal variability over the 2024–2025 reporting period, characterised by short-lived peaks superimposed on generally low to moderate background conditions (Figure 3-22). Patterns across all sites were consistent with a shallow, tidally energetic coastal environment, where turbidity responds rapidly to wind-driven resuspension and episodic wet-season forcing.

Evans Landing (WP_AMB1) recorded relatively low median turbidity values for most of the year, with daily medians remaining below ~10 NTU. Short-duration increases were evident during late spring and early wet-season months, particularly between October 2024 and January 2025, when episodic peaks exceeded 100 NTU. A short data gap occurred during February–March 2025 due to a temporary disturbance to logger orientation (cause unknown), with affected data excluded during routine quality control. Following this period, turbidity returned to lower and more stable levels through autumn and early winter.

South Channel (WP_AMB2) exhibited the greatest temporal variability, with frequent short-duration turbidity peaks throughout the wet season. Median turbidity increased during December

2024 to February 2025, with multiple events exceeding 100 NTU and occasional higher-magnitude spikes. Outside these episodic events, turbidity values generally remained low, indicating that elevated conditions were transient rather than persistent.

Leithen Point (WP_AMB4) consistently recorded higher turbidity than the other sites, with elevated baseline conditions and frequent high-magnitude events throughout the year. Daily median turbidity commonly ranged between ~10 and 50 NTU, with repeated peaks exceeding 100 NTU during both dry- and wet-season periods. This pattern is consistent with the site's more exposed setting and greater susceptibility to sediment resuspension under wind and tidal forcing.

Overall, turbidity dynamics across the Weipa region were dominated by short-term variability rather than sustained elevated conditions. Observed peaks were episodic and site-specific, reflecting physical resuspension processes rather than persistent degradation of water clarity across the monitoring period.

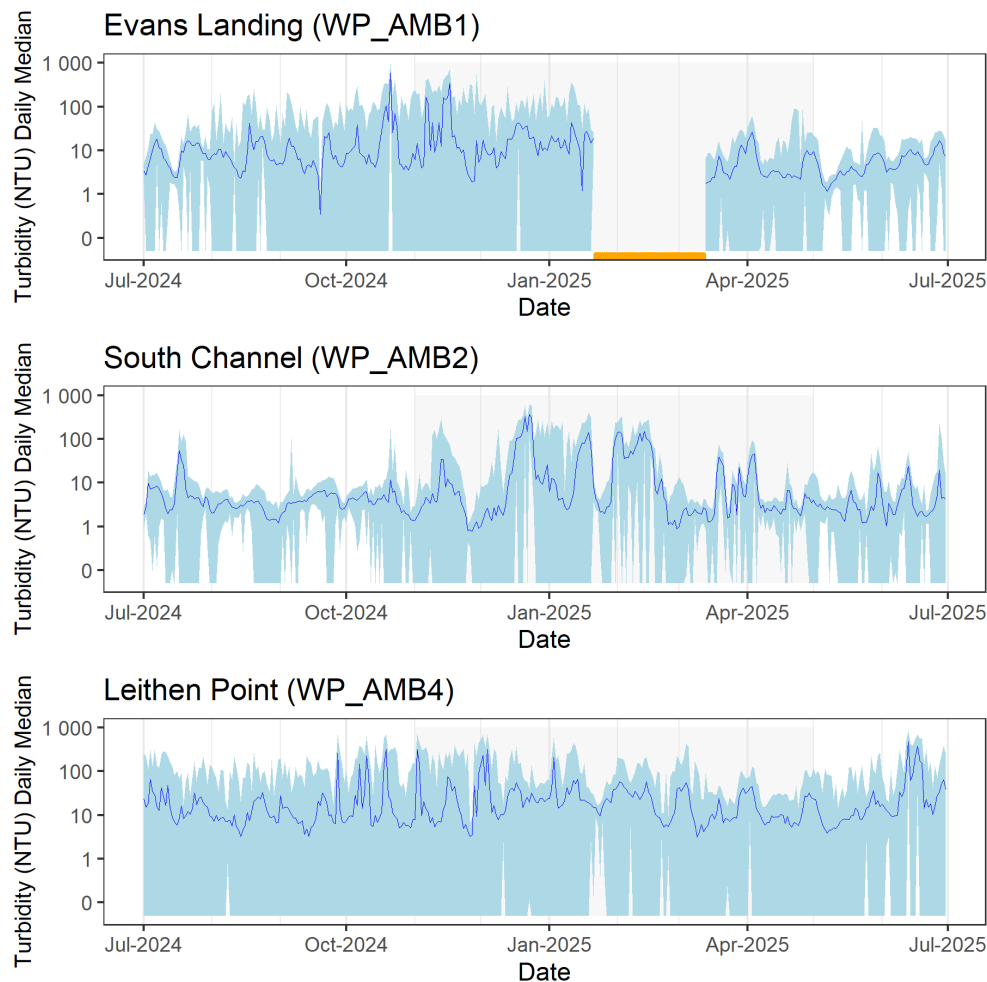


Figure 3-22 Turbidity measured at the Weipa ambient sites over the reporting period. Results presented are daily mean (blue line) and standard deviation (light blue). Y-axis is in log scale. Periods of missing data are indicated by the orange bar.

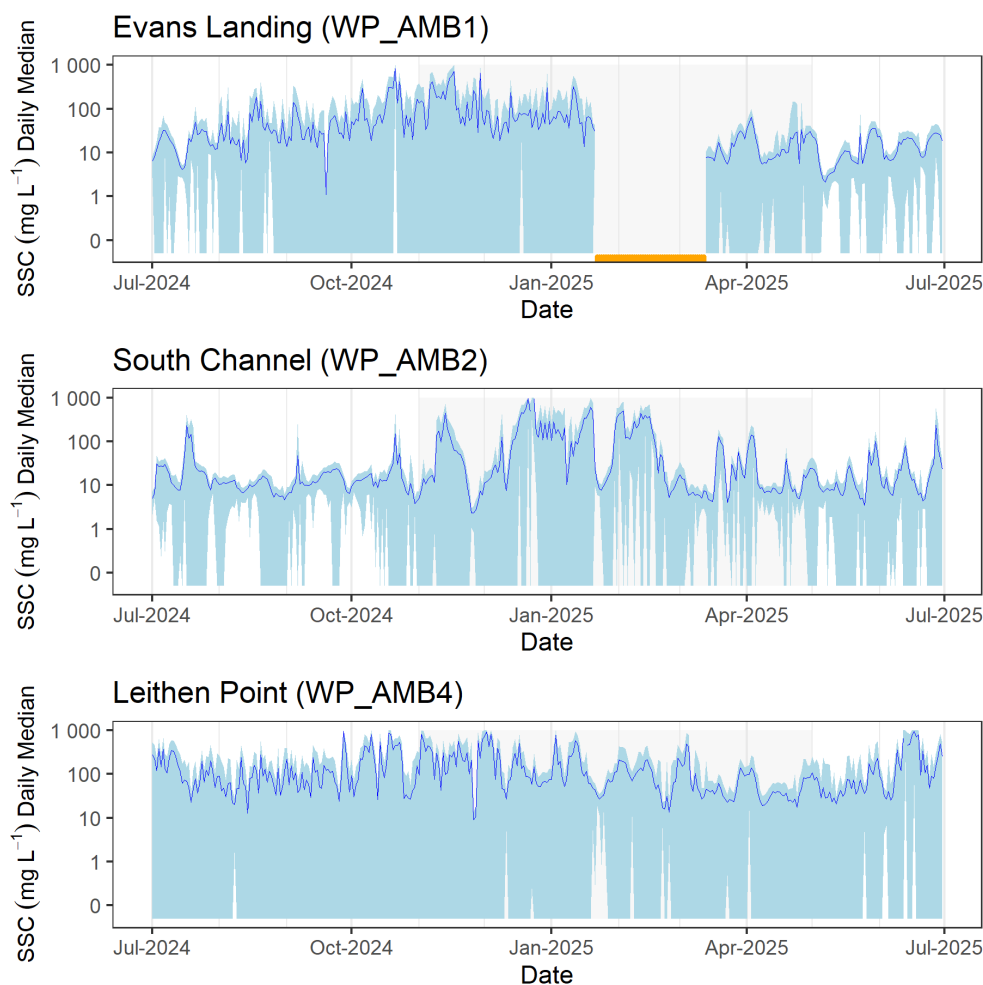


Figure 3-23 Suspended sediment concentrations measured at the Weipa ambient sites over the reporting period. Results presented are daily mean (blue line) and standard deviation (light blue). Y-axis is in log scale.

3.5.5 Benthic photosynthetically active radiation (bPAR)

Benthic photosynthetically active radiation (PAR) exhibited strong temporal variability across all Weipa ambient monitoring sites during the 2024–2025 reporting period (Figure 3-24). South Channel consistently recorded the highest benthic PAR levels, reflecting greater light availability at the seabed, while Leithen Point exhibited the lowest overall PAR values. Evans Landing showed intermediate conditions, with benthic PAR generally lower than South Channel but higher than Leithen Point over most of the year.

Short-term variability in benthic PAR was pronounced and primarily associated with changes in water clarity driven by tidal and hydrodynamic processes. Periods of elevated PAR commonly coincided with calmer conditions and reduced sediment resuspension, whereas sustained reductions were observed during wetter months when turbidity increased. Episodic declines in PAR were also evident following rainfall and runoff events, consistent with enhanced light attenuation in nearshore waters. A data gap occurred during February–March 2025 after a temporary change in logger orientation, with affected data excluded during routine quality control.

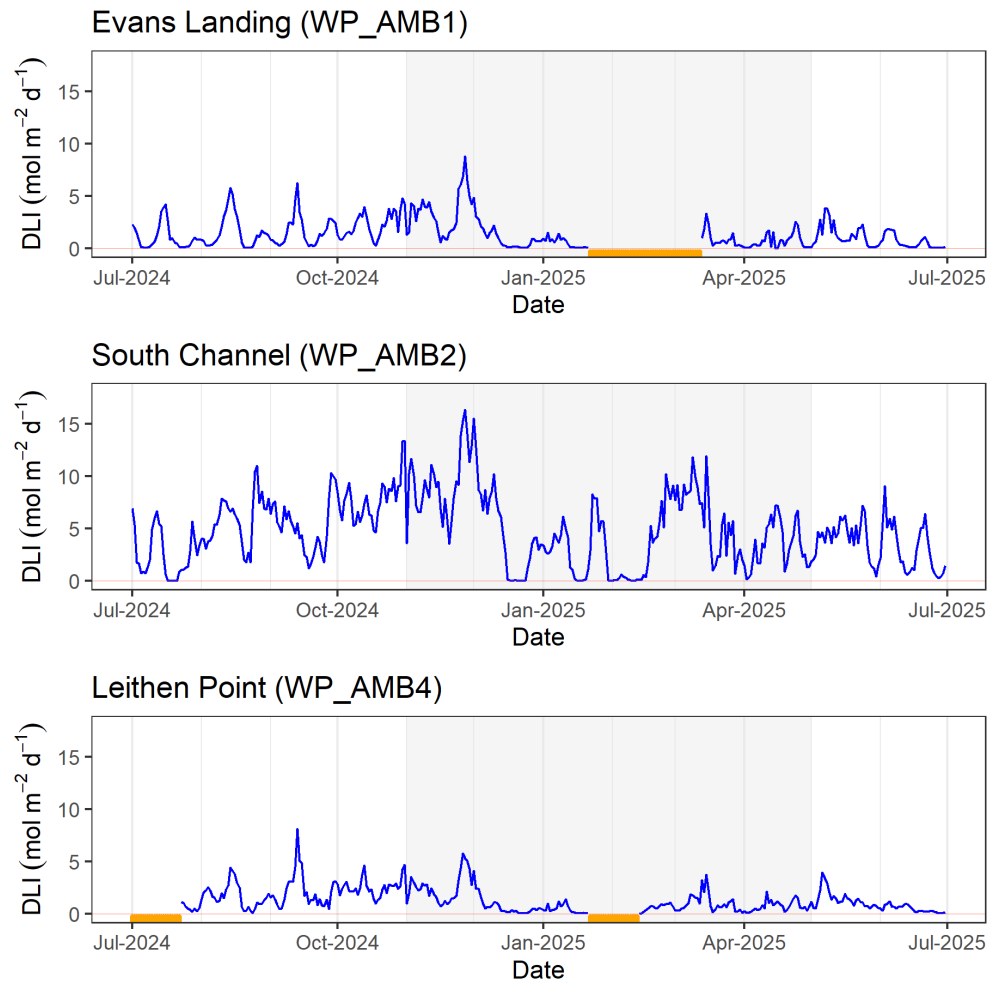


Figure 3-24 Daily light integral ($\text{mol photons m}^{-2} \text{d}^{-1}$) of benthic photosynthetically active radiation (PAR) measured at Weipa ambient sites over the reporting period. Periods of missing data are indicated by the orange bar.

3.5.6 RMS Depth and turbidity analysis

Relationships between turbidity (NTU) and RMS depth differed markedly among the three Weipa ambient monitoring sites and between tidal stages. At Evans Landing (WP_AMB1), correlations between RMS depth and turbidity were consistently weak and slightly negative across all tidal states (stable: $r = -0.003$; falling: $r = -0.038$; rising: $r = -0.017$; Figure 3-25). These values indicate no meaningful linear association between short-period water motion and turbidity at this site, despite the large number of observations. Turbidity variability at Evans Landing therefore appears largely decoupled from near-bed wave motion at the temporal scales captured by the RMS metric.

In contrast, South Channel (WP_AMB2) exhibited clear positive relationships between RMS depth and turbidity under all tidal stages, with correlation strength increasing from stable ($r = 0.24$) to falling ($r = 0.34$) and rising tides ($r = 0.38$; Figure 3-26). This indicates that periods of increased short-period water motion were consistently associated with higher turbidity at this site, particularly during active tidal transitions. The stronger correlations at South Channel suggest that

local sediment resuspension is more sensitive to near-bed hydrodynamic forcing compared with the other Weipa sites.

At Leithen Point (WP_AMB4), correlations were again weak and negative across all tidal stages (stable: $r = -0.043$; falling: $r = -0.030$; rising: $r = -0.012$; Figure 3-27), indicating minimal coupling between RMS depth and turbidity. Although this site experienced occasional elevated turbidity events, these did not scale with short-period depth variability, implying that other processes—such as background suspended material, advection, or longer-period forcing—are more important drivers of turbidity variability.

Overall, the RMS depth analysis highlights strong site-specific differences in turbidity response to near-bed water motion within the Weipa region. While South Channel shows a clear and consistent positive association indicative of wave- or current-driven sediment resuspension, Evans Landing and Leithen Point display weak to negligible relationships, suggesting that short-period hydrodynamic forcing plays a limited role in controlling turbidity at those locations.

Evans Landing (WP_AMB1)

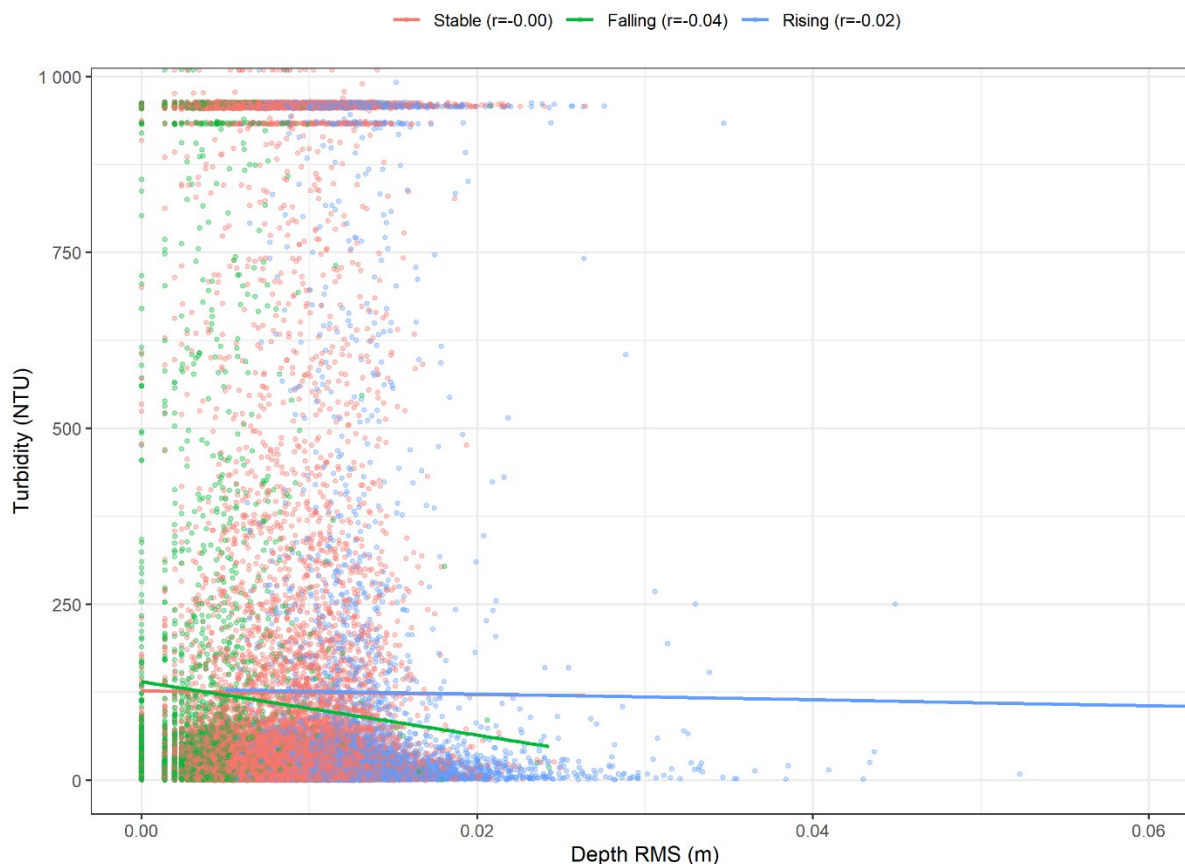


Figure 3-25 Relationship between turbidity (NTU) and RMS depth at Evans Landing (WP_AMB1) for the 2024–2025 reporting period. Points are coloured by tidal stage (rising, falling, stable), with linear regression fits shown for each stage. Correlation coefficients (r) indicate a weak and near-zero relationship between short-period depth variability and turbidity across all tidal conditions.

South Channel (WP_AMB2)

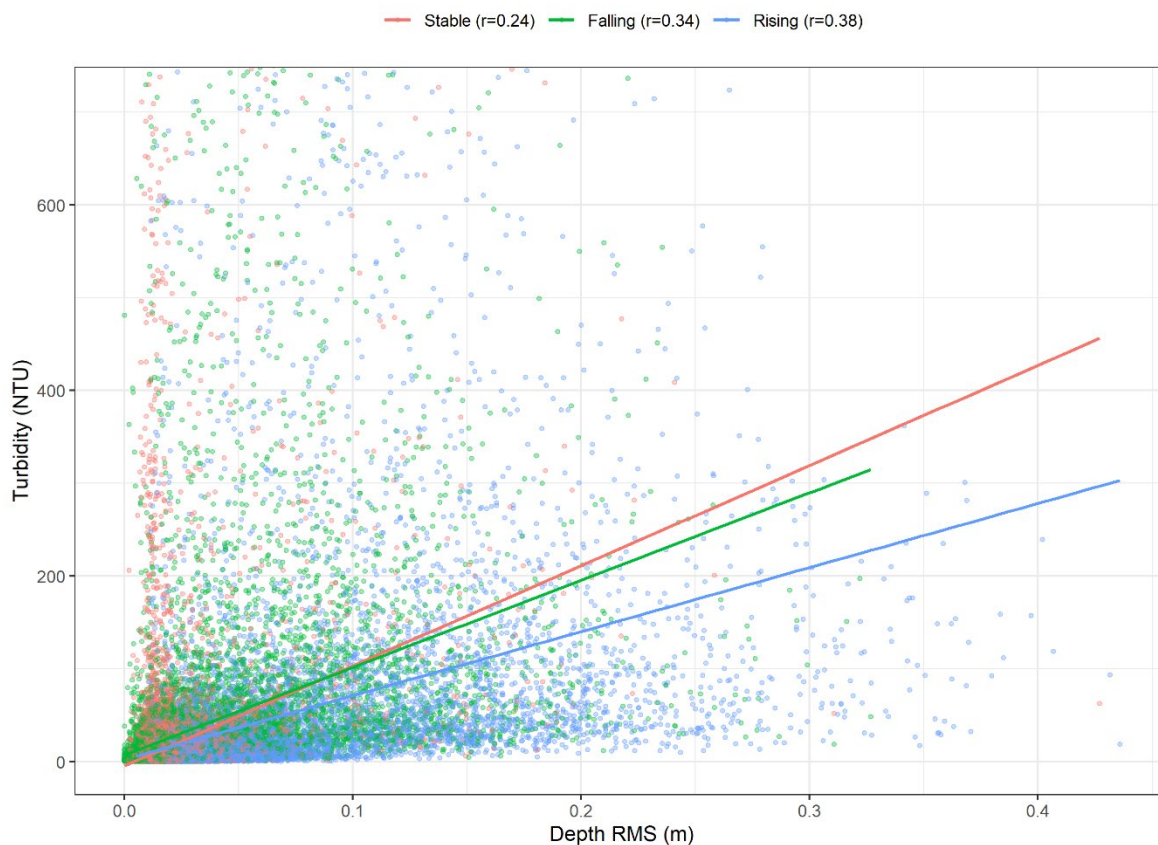


Figure 3-26 Relationship between turbidity (NTU) and RMS depth at South Channel (WP_AMB2) for the 2024–2025 reporting period. Data are grouped by tidal stage (rising, falling, stable), with fitted linear regressions and corresponding Pearson correlation coefficients (r). Positive correlations across all tidal stages indicate increased turbidity during periods of greater short-period water motion.

Leithen Point (WP_AMB4)



Figure 3-27 Relationship between turbidity (NTU) and RMS depth at Leithen Point (WP_AMB4) for the 2024–2025 reporting period. Scatter points are coloured by tidal stage, with linear regression lines and correlation coefficients (r) shown for each condition. Correlations are weak and negative, indicating limited coupling between near-bed wave motion and turbidity at this site.

3.6 Benthic multispectral irradiance and light-quality indices

Benthic multispectral irradiance at the Weipa monitoring sites showed strong and consistent variation in spectral composition associated with turbidity level, season, and site exposure. Across all sites, spectral shape was strongly governed by water clarity, with consistent contrasts between clearer dry-season conditions and more optically degraded wet-season periods. These patterns are illustrated in the normalised multispectral wavelength profiles for each site, separated by season and turbidity class (Figure 3-28; Figure 3-29; Figure 3-30).

During low-turbidity conditions (<1 NTU), spectra at all sites exhibited pronounced blue–green dominance, with broad maxima centred between approximately 490 and 550 nm. These conditions occurred most frequently during the dry season and were associated with relatively stable spectral shapes and reduced variability. In contrast, periods of elevated turbidity (>5 NTU), more common during the wet season, were associated with strong attenuation of blue wavelengths (410–490 nm), compression of the blue–green peak, and increased relative contribution from green–yellow and red wavelengths. Wet-season spectra were more dispersed, indicating highly variable benthic light environments during episodic sediment resuspension and runoff events.

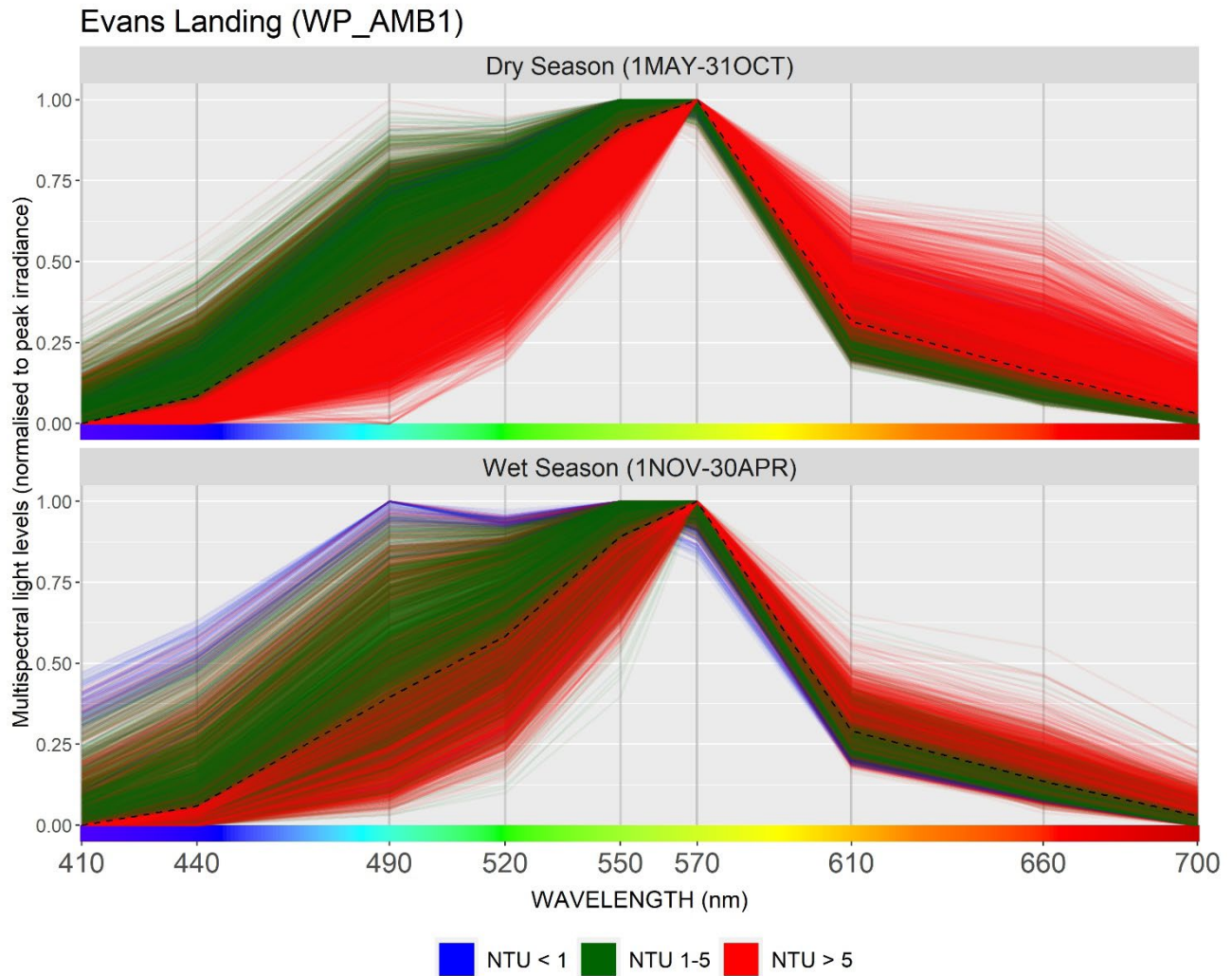


Figure 3-28 Multispectral irradiance profiles at Evans Landing (WP_AMB1) during the dry season (top) and wet season (bottom). Each line represents a daylight-filtered spectral observation (normalised to peak irradiance). Colours denote turbidity class: blue = NTU <1, green = NTU 1–5, red = NTU > 5. Pronounced attenuation of blue and blue-green wavelengths (< 500 nm) occurs under elevated turbidity, with more variable spectral shapes during the wet season.

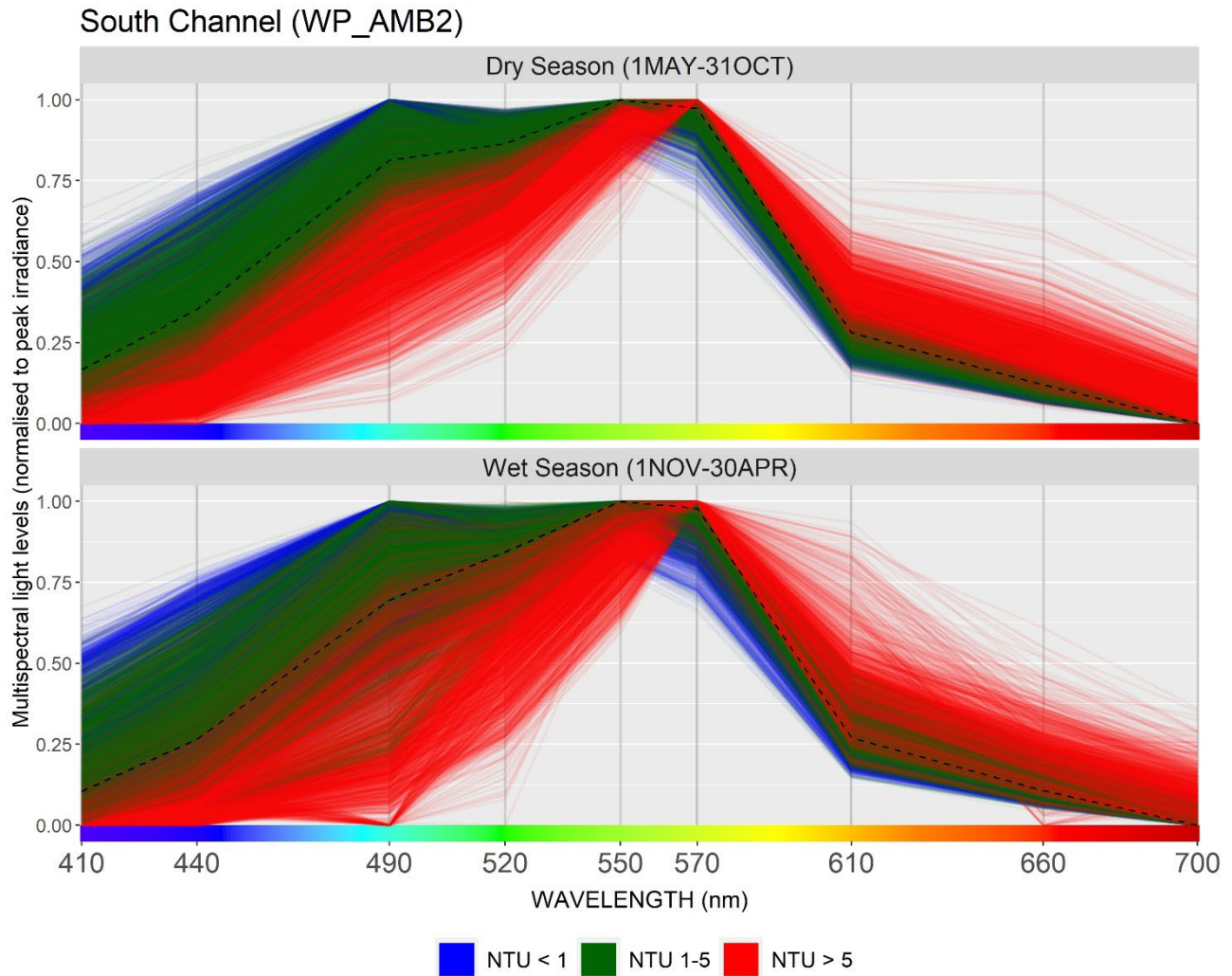


Figure 3-29 Multispectral irradiance profiles at South Channel (WP_AMB2) for dry (top) and wet (bottom) seasons. Spectral signatures show consistently high transmission of blue wavelengths under low-turbidity conditions, with narrow, well-defined peaks. Turbid and wet-season conditions exhibit reduced blue-light penetration and a shift toward green-yellow wavelengths, although attenuation remains lower than at other sites.

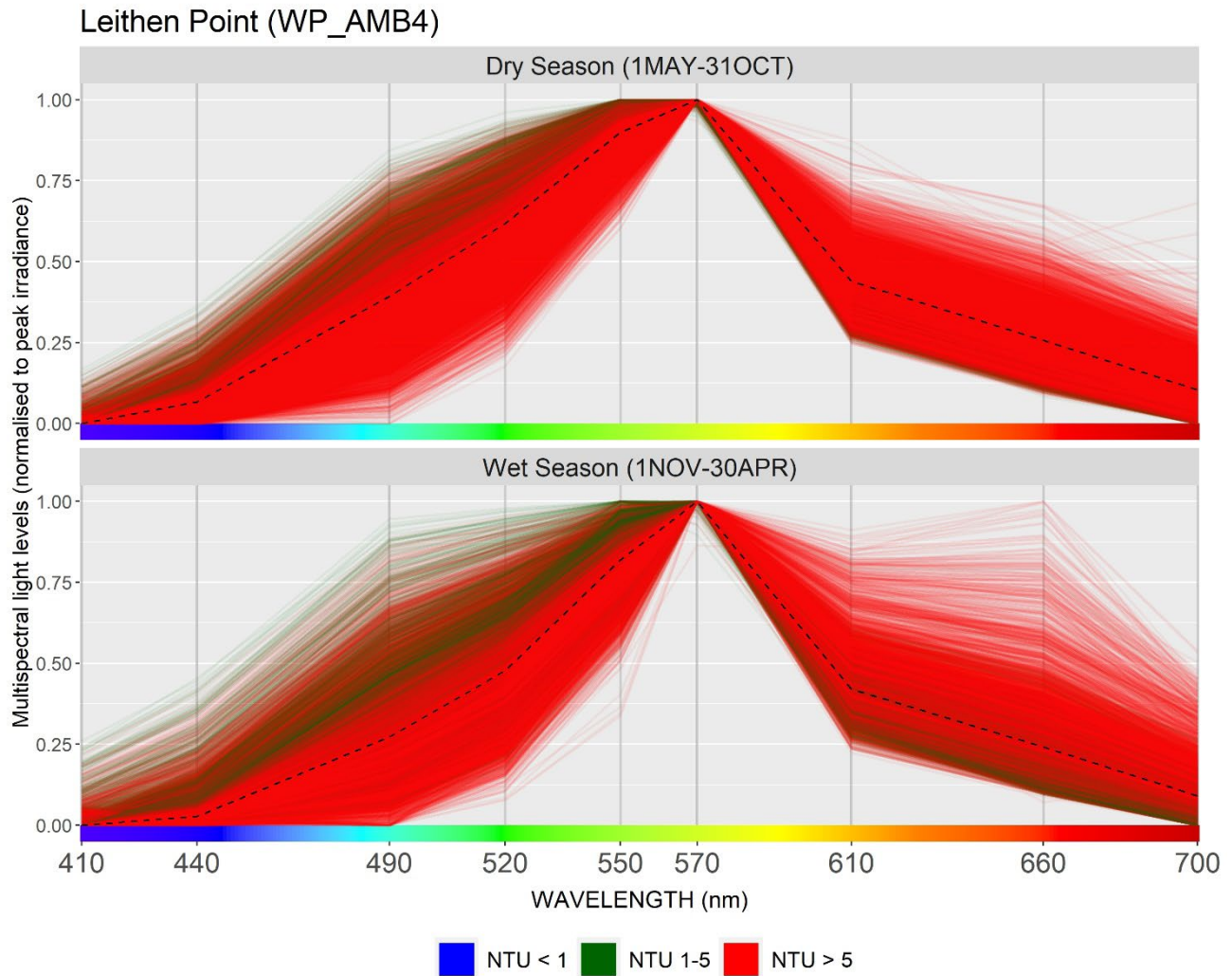


Figure 3-30 Multispectral irradiance profiles at Leithen Point (WP_AMB4) in the dry (top) and wet (bottom) seasons. Spectral responses are highly variable, reflecting the site's dynamic hydrodynamic environment. Clear-water periods show strong blue-green irradiance, while increased turbidity—particularly during wind-driven or spring-tide resuspension events—produces stronger blue attenuation and increased dominance of longer wavelengths.

To summarise wavelength-specific patterns in benthic light availability at Weipa, five spectral indices were calculated from multispectral irradiance measurements: blue–green ratio (BG), normalised blue irradiance (N490), PAR Quality Index (PQI), Red Attenuation Ratio (RAR), and the blue–green spectral slope (Slope_BG); Figure 3-31; Figure 3-32; Figure 3-33; Figure 3-34; Figure 3-35).

Across all sites, N490 and PQI were highest under clearer water conditions, indicating enhanced transmission of blue and blue–green wavelengths and higher-quality photosynthetically usable radiation. In contrast, elevated RAR and more positive Slope_BG values were associated with periods of increased turbidity, reflecting preferential attenuation of blue wavelengths and a relative shift toward red-dominated spectra under sediment-influenced conditions.

While these turbidity–spectral relationships were consistent across the study area, clear site-level differences were evident:

- South Channel (WP_AMB2) exhibited the highest overall light quality, with consistently elevated N490 and PQI values across seasons. This site also showed lower median RAR and relatively stable Slope_BG, consistent with its deeper, well-flushed channel setting and reduced susceptibility to near-bed resuspension.
- Evans Landing (WP_AMB1) showed intermediate light quality, with moderate N490 and PQI values and greater variability through time. Periodic increases in RAR and changes in Slope_BG suggest episodic turbidity events, consistent with its proximity to nearshore and estuarine sediment sources.
- Leithen Point (WP_AMB4) displayed the lowest overall light quality across indices, with reduced N490 and PQI and comparatively higher RAR values. Seasonal separation was more pronounced at this site, indicating stronger sensitivity to wet-season sediment inputs and reduced blue-light penetration during higher-turbidity conditions.

Seasonal stratification of PQI further demonstrated that wet-season conditions were associated with broader variability and lower median light quality at Evans Landing and Leithen Point, whereas South Channel retained comparatively high PQI values across both seasons.

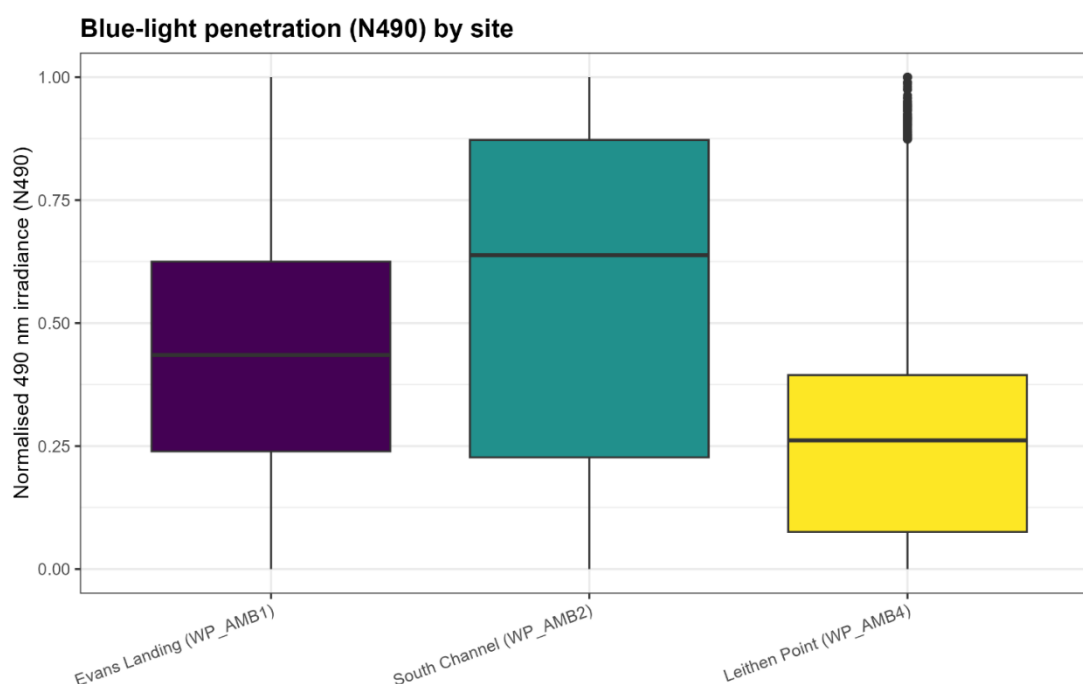


Figure 3-31 Distribution of normalised 490 nm irradiance (N490) recorded at the three Weipa ambient monitoring sites. Higher N490 values indicate stronger transmission of short (blue) wavelengths and generally clearer water conditions. South Channel (WP_AMB2) showed higher N490 values compared to the estuarine sites.

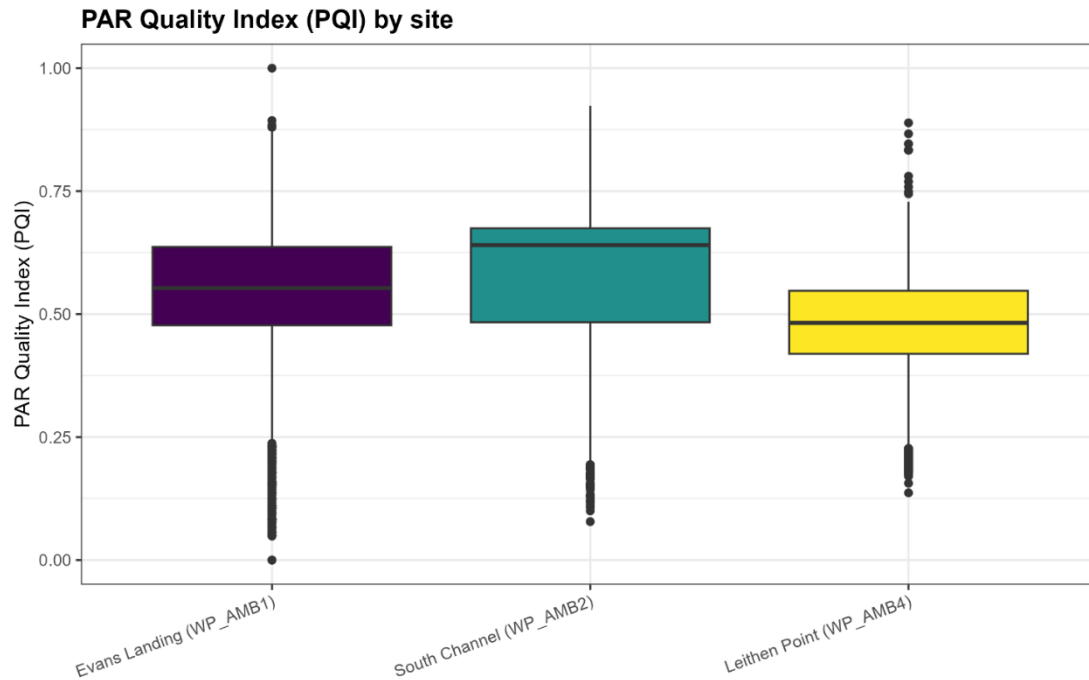


Figure 3-32 Boxplots showing the distribution of PQI across the three sites. PQI represents the proportion of benthic irradiance contributed by blue–green wavelengths (440–570 nm). Higher PQI values correspond to clearer optical conditions and greater availability of photosynthetically usable radiation (PUR). Again, PQI was higher at South Channel compared to the two estuarine sites.

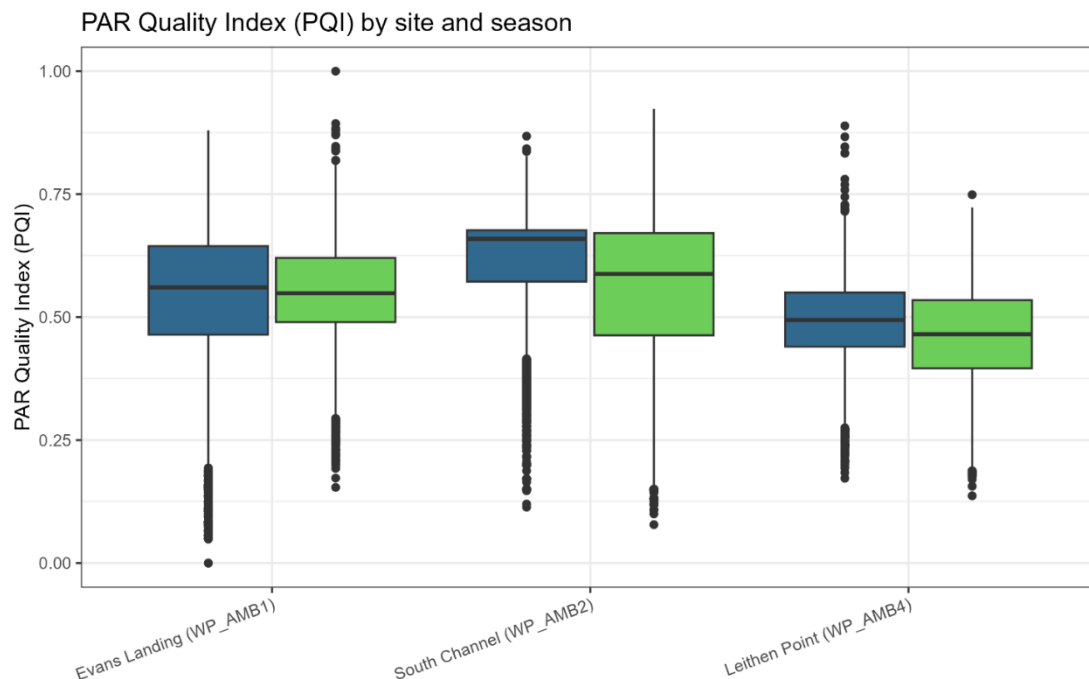


Figure 3-33 PQI values separated into wet-season (Nov–Apr, green boxes) and dry-season (May–Oct, blue boxes) conditions. Dry-season PQI values were generally higher at all sites, reflecting enhanced blue–green light transmission during periods of reduced runoff and calmer hydrodynamic conditions.

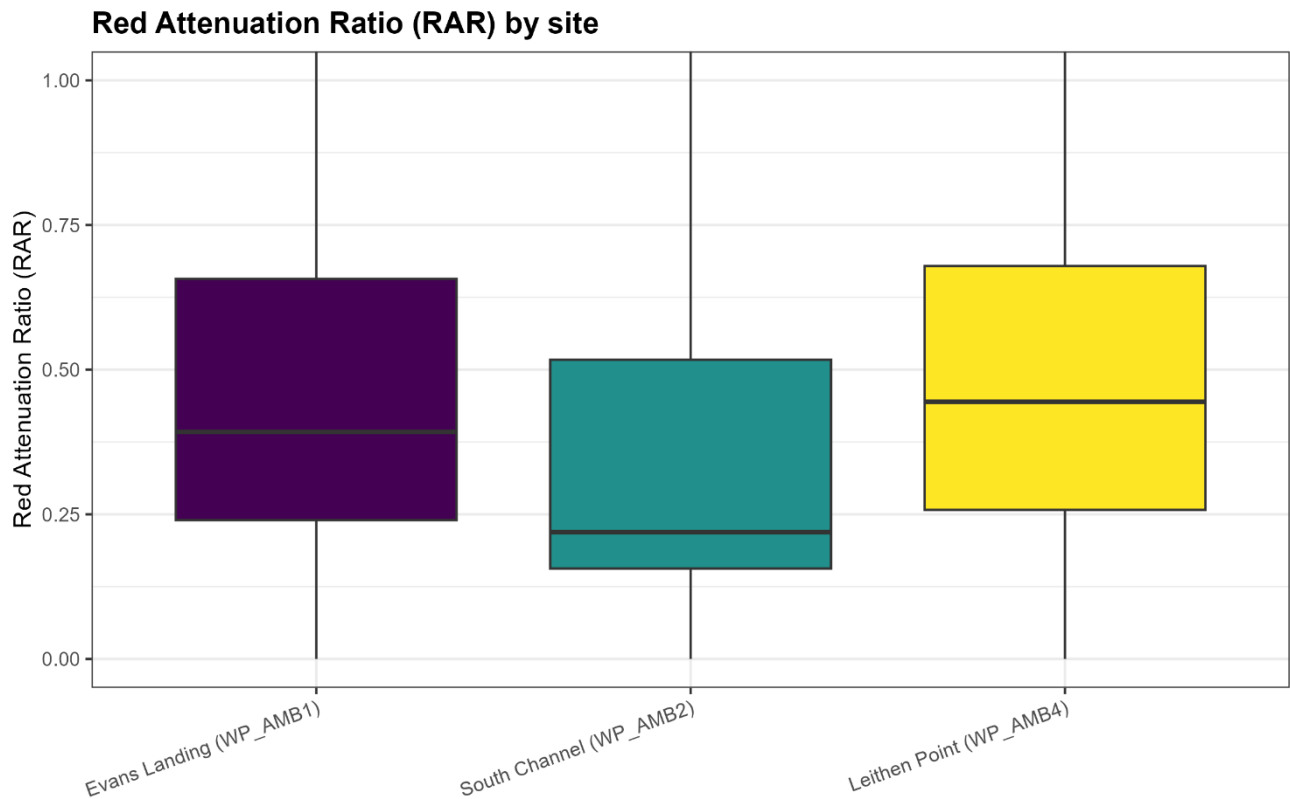


Figure 3-34 RAR quantifies the relative dominance of red wavelengths (610–700 nm) compared with short and mid-visible wavelengths. Elevated RAR values indicate stronger attenuation of blue–green light under turbid conditions. After trimming extreme outliers, RAR showed higher values for the two estuarine sites, consistent with increased freshwater inflow and sediment resuspension.

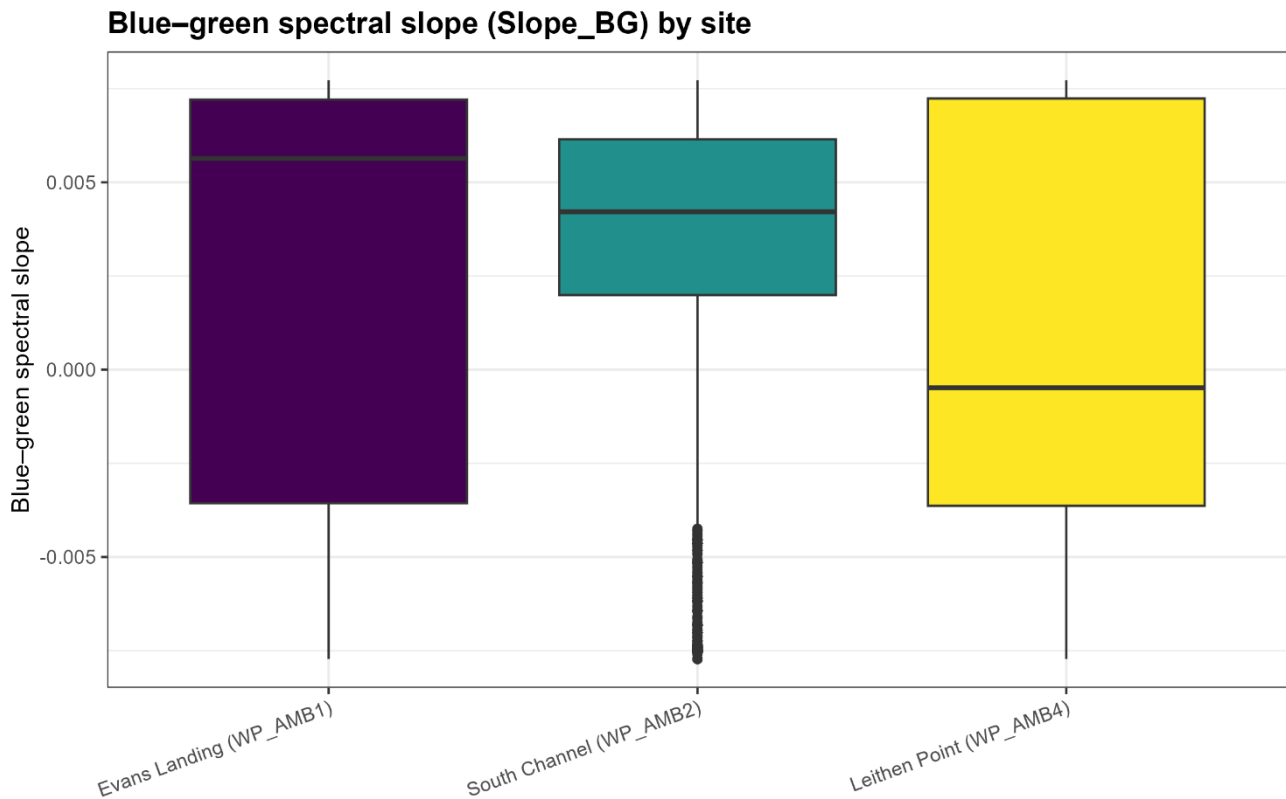


Figure 3-35 SlopeBG describes the rate of attenuation between blue (≈ 440 nm) and green (≈ 570 nm) wavelengths. More positive slopes indicate stronger suppression of blue light relative to green, typically associated with turbidity or coloured dissolved organic matter. Estuarine sites, Evans Landing and Leithen Point, showed steeper slopes, indicating higher turbidity compared to South Channel.

Collectively, these results indicate that benthic spectral irradiance at Weipa is governed by short-duration turbidity events superimposed on predictable seasonal hydrological cycles, with local depth, exposure, and hydrodynamic regime exerting a strong influence on light quality. The applied spectral indices provide a sensitive, process-based framework for distinguishing between clear-water and sediment-affected conditions and for resolving site-specific responses that are not apparent from bulk metrics such as turbidity or chlorophyll-a alone.

Within the context of ongoing port and coastal monitoring, these findings highlight the value of integrating multispectral light metrics with routine water-quality observations. Indices such as N490, PQI, RAR and Slope_BG offer a robust means of detecting episodic reductions in benthic light availability, improving attribution of observed changes to natural versus operational drivers, and supporting the development of site- and depth-specific light thresholds relevant to benthic phototrophic communities.

3.7 Long term trend analysis

3.7.1 Rainfall and river discharge

Long-term rainfall records for the Weipa region (2018–2025) show a highly seasonal and episodic pattern characteristic of the monsoonal climate of western Cape York Peninsula (Figure 3-36). Most

rainfall occurs during the wet season (November–April) and is delivered through short-duration, high-intensity events, with extended dry periods dominating the remainder of the year.

Across the monitoring period, wet seasons were characterised by clusters of intense daily rainfall events rather than sustained moderate rainfall. Several years recorded daily totals exceeding 150–200 mm, with particularly pronounced activity in 2018, 2021–2022 and 2023. These periods were separated by years of comparatively subdued rainfall, highlighting strong interannual variability in both the timing and intensity of wet-season precipitation. Rapid transitions between dry and wet conditions reflect the influence of monsoon bursts, tropical lows and convective storm systems.

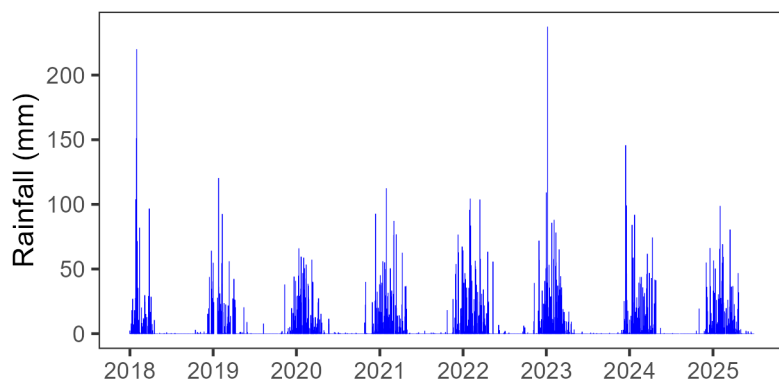


Figure 3-36 Daily rainfall time series for the Weipa region from 2018 to 2025. Rainfall is highly seasonal and episodic, with the majority of precipitation occurring during the wet season (November–April) as short-duration, high-intensity events, interspersed with extended dry periods.

Wet-season onset, defined as the first accumulation of 50 mm rainfall after 1 September, showed substantial interannual variability over the 2017–2018 to 2024–2025 period (Table 3-3). Onset dates ranged from late October to mid-December, with most seasons commencing in November or early December. The 2024–2025 wet season began on 2 December 2024, placing it toward the later end of the observed range but consistent with several recent years.

Table 3-3 Wet-season rainfall onset dates for the Weipa region from 2017–2018 to 2024–2025, defined as the first accumulation of 50 mm rainfall after 1 September. Onset timing shows substantial interannual variability, ranging from late October to mid-December.

Reporting year	Rainfall onset
2017-2018	30/11/2017
2018-2019	13/12/2018
2019-2020	03/12/2019
2020-2021	31/10/2020
2021-2022	19/11/2021
2022-2023	09/11/2022
2023-2024	11/12/2023
2024-2025	02/12/2024

The episodic nature of rainfall at Weipa has important implications for coastal and nearshore water quality, with short-lived, high-intensity events driving rapid runoff responses and brief pulses of freshwater and sediment delivery to the coastal zone. Years with multiple large rainfall events therefore have the potential to exert a disproportionate influence on turbidity and light conditions, while years with delayed or weaker wet seasons result in minimal freshwater influence. This rainfall context provides essential background for interpreting interannual variability observed in the ambient marine water-quality record.

3.7.2 Generalized additive mixed effects models (GAMM)

GAMM outputs for nutrients and particulate fractions from the Weipa ambient monitoring program are presented in Figure 3-37, with model summaries provided in Appendix C. Across most parameters, the models identified statistically significant seasonal structure, consistent with wet-season freshwater influence and dry-season marine dominance. Where long-term smooths were significant, they reflected interannual variability rather than sustained directional change. As expected for a highly dynamic, tidally energetic coastal system, the proportion of variance explained by long-term structure was modest.

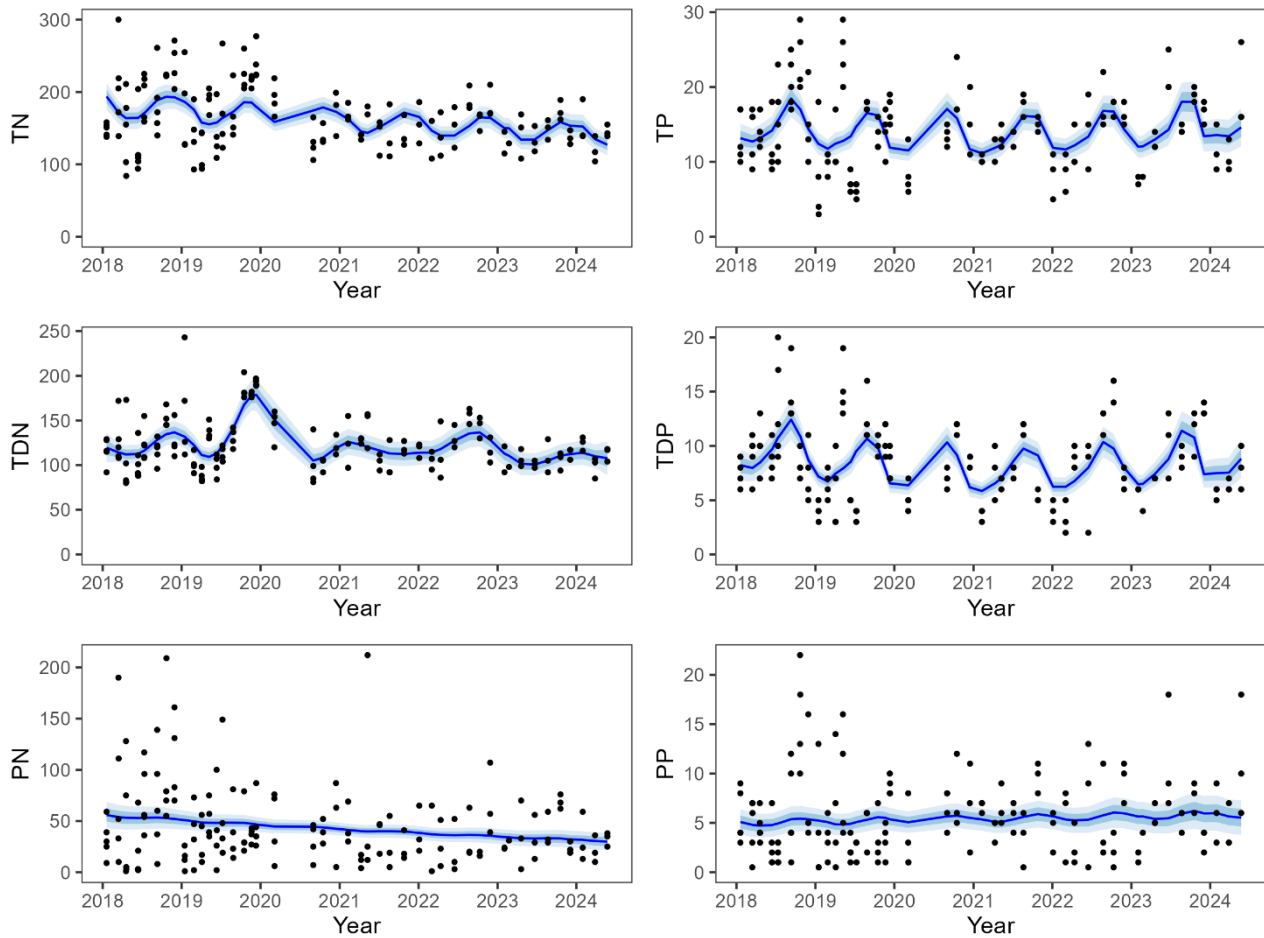


Figure 3-37 Nutrient concentrations measured at Weipa between 2018 and 2024, including total nitrogen (TN), total phosphorus (TP), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), particulate nitrogen (PN), and particulate phosphorus (PP). Points represent individual water-sample observations, with GAMM fits shown as solid lines and shaded bands indicating standard error (dark blue) and 95% confidence intervals (light blue). Models capture seasonal variability and non-directional interannual fluctuations, with most variability driven by episodic hydrological and resuspension events. Units = $\mu\text{g L}^{-1}$.

NUTRIENTS

Total nitrogen (TN) exhibited a significant long-term smooth characterised by broad, non-directional interannual variability over the monitoring period. Concentrations were higher during the earlier part of the record and gradually declined toward more recent years, without evidence of a sustained monotonic trend. Seasonal structure was present but comparatively weak, indicating that TN variability at Weipa is influenced by episodic wet-season inputs superimposed on longer-term climatic variability.

Total dissolved nitrogen (TDN) showed both a statistically significant seasonal component and a significant long-term smooth. The temporal smooth indicated elevated concentrations during the middle of the record followed by relatively stable values in recent years. This pattern is consistent with sensitivity to variability in wet-season forcing rather than persistent enrichment or depletion.

Particulate nitrogen (PN) exhibited a statistically significant long-term temporal signal ($p = 0.0059$), indicating systematic variation through time. The fitted smooth suggests a gradual reduction in PN concentrations over the monitoring period, with higher values earlier in the record and lower values in more recent years. However, the magnitude of change was modest relative to short-term variability, and concentrations remained strongly influenced by episodic events rather than showing a sustained progressive decline.

Total phosphorus (TP) exhibited weak seasonal structure and a significant long-term smooth characterised by low-amplitude interannual variability. Concentrations fluctuated modestly through time but did not show a consistent upward or downward trajectory, suggesting stability in background TP levels with variability driven primarily by episodic events.

Total dissolved phosphorus (TDP) showed a clear seasonal signal associated with wet-season inputs, while long-term variability was comparatively weak. The fitted smooth indicated gradual fluctuations across the record, without evidence of persistent long-term change.

Particulate phosphorus (PP) showed no coherent seasonal or long-term pattern. Concentrations fluctuated around a low background with occasional event-driven spikes, consistent with mobilisation during short-lived runoff or resuspension events.

Overall, the nutrient GAMMs indicate relatively stable background concentrations at Weipa, with variability governed primarily by episodic hydrological inputs, sediment resuspension and interannual climatic variability rather than progressive long-term change.

CHLOROPHYLL-A

GAMM outputs for chlorophyll-a indicate a strong and highly significant seasonal signal ($p < 2 \times 10^{-16}$), reflecting recurring intra-annual variability consistent with wet-season and dry-season differences in hydrological and optical conditions (Figure 3-38). In contrast, the long-term smooth was not statistically significant ($p = 0.233$), and the estimated temporal component was linear (edf = 1), indicating no evidence of sustained monotonic change in chlorophyll-a concentrations over the 2018–2025 period.

The fitted GAMM shows modest interannual variability, with short-lived increases in chlorophyll-a occurring intermittently rather than as part of a consistent upward or downward trajectory. The adjusted R^2 (0.15) indicates that while seasonal structure explains a meaningful proportion of variability, much of the remaining scatter is driven by short-duration events and localised conditions not captured by smooth temporal trends. Overall, chlorophyll-a concentrations at Weipa appear seasonally structured but temporally stable, with no indication of progressive biomass accumulation or long-term enrichment.

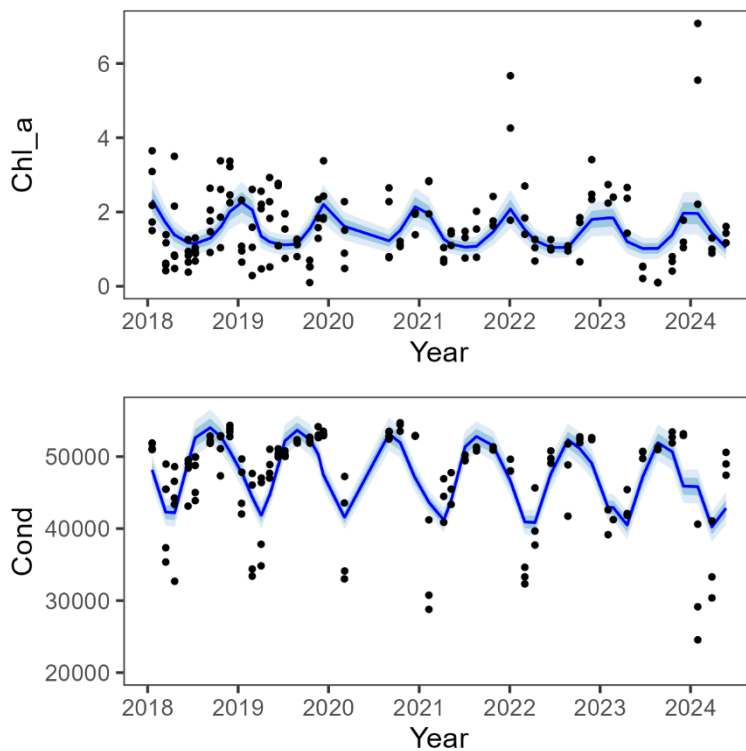


Figure 3-38 Chlorophyll-a (top) and electrical conductivity (bottom) measured at Weipa between 2018 and 2024. Points represent individual observations, with GAMM fits shown as solid lines and shaded uncertainty bands indicating standard error (dark blue) and 95% confidence intervals (light blue). Chlorophyll-a exhibits strong seasonal variability with limited long-term change, while conductivity shows pronounced seasonal structure linked to wet-season freshwater influence. Units: chlorophyll-a = $\mu\text{g L}^{-1}$; conductivity = $\mu\text{S cm}^{-1}$.

ELECTRICAL CONDUCTIVITY

Electrical conductivity exhibited a very strong seasonal cycle ($p < 2 \times 10^{-16}$), with pronounced and repeatable intra-annual fluctuations reflecting wet-season freshwater influence and dry-season marine dominance (Figure 3-38). These seasonal patterns are consistent with episodic rainfall and runoff inputs characteristic of the Weipa region.

The long-term smooth for conductivity was weak and not statistically significant at the 5% level ($p = 0.079$), indicating no clear evidence of a sustained directional change in salinity conditions over the monitoring period. The temporal smooth was linear ($\text{edf} \approx 1$), suggesting that any gradual variation is minor relative to the dominant seasonal signal. The relatively high adjusted R^2 (0.43) reflects the strong explanatory power of the seasonal component rather than long-term change.

Overall, conductivity dynamics at Weipa are dominated by recurring seasonal freshwater inputs and tidal mixing, with no indication of progressive freshening or salinisation across the 2018–2025 record.

TOTAL SUSPENDED SOLIDS (TSS)

GAMM analysis of total suspended solids (TSS) indicates that concentrations at Weipa are primarily controlled by short-term variability rather than persistent seasonal or long-term change (Figure 3-39). The model identified no significant long-term temporal smooth ($p = 0.25$), providing no evidence for a monotonic increase or decrease in background TSS over the monitoring period. Seasonal structure was weak, with only marginal support for a monthly effect ($p = 0.069$), consistent with episodic wet-season and resuspension events rather than a stable seasonal cycle. The low adjusted R^2 (0.011) reflects the dominance of short-lived hydrodynamic and runoff-driven processes in controlling TSS variability.

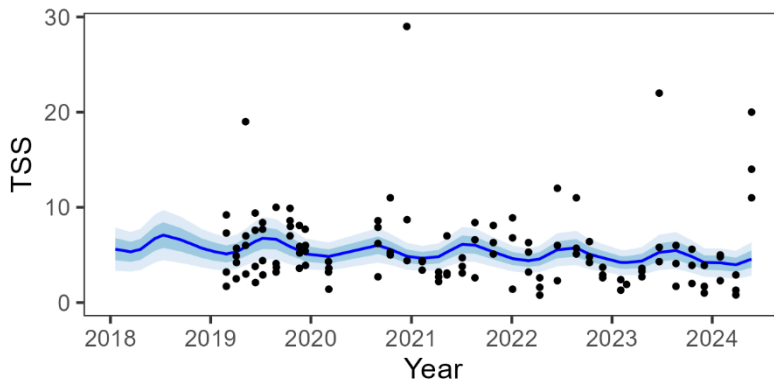


Figure 3-39 Total suspended solids (TSS) concentrations measured at Weipa between 2018 and 2024. Points represent individual water-sample observations, with the fitted general additive mixed effects model (GAMM) shown as a solid line. Shaded bands indicate the standard error (dark blue) and 95% confidence intervals (light blue). The model highlights modest interannual variability and weak seasonal structure, with concentrations dominated by short-term event-driven variability. Units = mg L^{-1} .

3.7.3 Interpretation of Long-Term Trends

Taken together, the GAMM results indicate that long-term water quality in the Weipa region is primarily governed by interannual climatic variability and short-duration hydrodynamic and runoff events, rather than by progressive or directional change. Nutrient concentrations show pronounced variability associated with episodic wet-season inputs and resuspension processes, but there is no evidence of sustained enrichment across the monitoring period. Chlorophyll-a remains low and seasonally structured, with no indication of persistent increases or bloom development, while total suspended solids exhibit modest interannual variability without a consistent long-term trend.

Seasonal structure across most parameters is evident but irregular, reflecting the highly episodic nature of monsoonal rainfall, rapid catchment responses, and strong tidal mixing within Albatross Bay. Where statistically significant long-term smooths are present, these represent gradual, non-linear fluctuations rather than monotonic increases or declines, and explain only a modest proportion of total variance relative to event-driven processes.

Overall, the available evidence indicates that ambient marine water quality in the Weipa region has remained broadly stable over the monitoring period, with conditions dominated by climatic and hydrodynamic drivers. Continued long-term monitoring remains important, particularly in the context of future climate variability and extreme rainfall, but current results do not suggest

increasing nutrient, sediment, or productivity-related stress within the ambient monitoring network.

4 CONCLUSION

The Port of Weipa Ambient Marine Water Quality Monitoring Program continues to provide a robust and increasingly valuable evidence base for understanding coastal water quality dynamics in Albatross Bay. Data collected during the 2024–2025 reporting period, together with the growing multi-year record, indicate that ambient marine water quality in the Weipa region is primarily shaped by natural climatic variability, episodic wet-season forcing, and site-specific hydrodynamic conditions rather than progressive or directional change.

Across the monitoring network, nutrient concentrations, chlorophyll-a, suspended sediments and physicochemical parameters exhibited clear seasonal and event-driven variability consistent with monsoonal rainfall, freshwater inflow and sediment resuspension processes. Dissolved nutrients dominated nitrogen pools, phosphorus concentrations remained low and stable, chlorophyll-a levels were modest and seasonally structured, and turbidity and suspended sediments were characterised by short-lived peaks rather than sustained elevation. Long-term GAMM analyses support these observations, indicating interannual variability without evidence of persistent enrichment, increasing turbidity, or declining water quality across the monitoring period.

High-frequency seafloor logger data and multispectral light measurements provided critical insight into near-bed processes not captured by discrete sampling alone. Benthic light availability and spectral quality were highly dynamic and strongly modulated by turbidity and site exposure, with South Channel consistently supporting the highest-quality benthic light environment and estuarine sites experiencing more frequent optical limitation during resuspension events. These findings underscore the importance of coupling continuous optical measurements with traditional water-quality metrics when assessing potential risks to benthic phototrophic habitats.

Overall, the results indicate that ambient marine water quality in the Port of Weipa remains broadly stable and resilient, with observed variability well explained by natural hydrological and oceanographic drivers. Continued long-term monitoring remains essential, particularly in the context of future climate variability, extreme rainfall events, and ongoing port operations. The program provides NQBP with a scientifically robust foundation to support informed port management, environmental stewardship, and adaptive decision-making in this dynamic tropical coastal environment.

5 REFERENCES

ANZECC/ARMCANZ. (2000). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

- Australian and New Zealand Governments (ANZG). (2018). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Canberra: Australian and New Zealand Governments and Australian State and Territory Governments.
- Baker, R., & Sheppard, R. (2006). Fisheries Resources of Albatross Bay, Gulf of Carpentaria. Retrieved from Queensland Department of Primary Industries and Fisheries Information Series, QI06062
- Cartwright, P., Johns, J., & Waltham, N.J. (2022). *Establishing turbidity–suspended sediment concentration relationships for North Queensland port waters*. TropWATER Technical Report, James Cook University, Townsville.
- Chartrand, K.M., Rasheed, M.A., & Unsworth, R.K.F. (2012). Predicting the impact of reduced light availability on seagrass meadows in coastal waters. *Marine Pollution Bulletin*, 65(5), 293–305.
- Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., & Todd, P.A. (2012). Environmental impacts of dredging and other sediment disturbances on corals: A review. *Marine Pollution Bulletin*, 64(9), 1737–1765.
- Iles, A., Cartwright, P., & Waltham, N.J. (2023). *Automated Quality Control of High-Frequency Marine Water Quality Data*. TropWATER Technical Report, James Cook University, Townsville.
- Jones, A.R., Skidmore, J.A., & McKinna, L.I.W. (2021). Advances in optical remote sensing for monitoring water quality and benthic habitats. *Frontiers in Marine Science*, 8, 625938.
- Kirk, J.T.O. (1994). *Light and Photosynthesis in Aquatic Ecosystems* (2nd ed.). Cambridge University Press, Cambridge.
- Larcombe, P., & Taylor, J. (1997). Port of Weipa water and sediment quality monitoring baseline surveys, January 1995 - February 1996. Retrieved from Ports Corporation of Queensland, Brisbane.
- Queensland Government. (2019). *Environmental Protection (Water and Wetland Biodiversity) Policy 2019*. Department of Environment and Science, Brisbane.
- Reason, C. L., McKenna, S.A., Smith T., & Rasheed, M.A., (2024) Port of Weipa Long-Term Seagrass Monitoring Program - 2023', Centre for Tropical Water & Aquatic Ecosystem Research, Cairns.
- Sofonia, J.J., & Unsworth, R.K.F. (2010). Development and assessment of a spatially explicit light attenuation model for seagrass. *Marine Ecology Progress Series*, 406, 135–144.
- Somers, I. F., & Long, B. G. (1994). Note on the sediments and hydrology of the Gulf of Carpentaria, Australia. *Marine and Freshwater Research*, 45(3). doi:10.1071/mf9940283
- Wood, S. N. (2017). *Generalized Additive Models: An introduction with R* (2nd ed.): Chapman and Hall/CRC.

APPENDIX A LOGGER DATA SUMMARIES

Summary	Site_code	param	MY	mean	median	sd	min	max	Q1	Q3	n	Month	Year	Season
Monthly	WP_AMB1	Depth	1/7/2024	4.54	4.65	0.53	2.91	5.38	4.26	4.95	4462	Jul	2024	NA
Monthly	WP_AMB1	Depth	1/8/2024	4.57	4.66	0.53	3.14	5.51	4.23	4.98	4464	Aug	2024	NA
Monthly	WP_AMB1	Depth	1/9/2024	4.71	4.79	0.49	3.47	5.73	4.37	5.09	4319	Sep	2024	NA
Monthly	WP_AMB1	Depth	1/10/2024	4.86	4.92	0.48	3.47	5.87	4.52	5.24	4464	Oct	2024	NA
Monthly	WP_AMB1	Depth	1/11/2024	5.02	5.09	0.54	3.35	5.96	4.69	5.41	4317	Nov	2024	NA
Monthly	WP_AMB1	Depth	1/12/2024	5.30	5.41	0.57	3.83	6.28	4.95	5.76	4464	Dec	2024	NA
Monthly	WP_AMB1	Depth	1/1/2025	5.43	5.53	0.59	3.94	6.54	5.00	5.87	4462	Jan	2025	NA
Monthly	WP_AMB1	Depth	1/2/2025	5.52	5.60	0.52	4.28	6.63	5.15	5.90	4032	Feb	2025	NA
Monthly	WP_AMB1	Depth	1/3/2025	5.43	5.50	0.47	4.25	6.20	5.09	5.79	4461	Mar	2025	NA
Monthly	WP_AMB1	Depth	1/4/2025	5.27	5.38	0.50	3.61	6.47	4.91	5.62	4320	Apr	2025	NA
Monthly	WP_AMB1	Depth	1/5/2025	5.05	5.17	0.55	3.40	6.18	4.73	5.44	4462	May	2025	NA
Monthly	WP_AMB1	Depth	1/6/2025	5.06	5.19	0.56	3.29	6.04	4.73	5.46	4320	Jun	2025	NA
Seasonal	WP_AMB1	Depth	NA	4.80	4.86	0.57	2.91	6.18	4.44	5.22	26491	NA	NA	Dry
Seasonal	WP_AMB1	Depth	NA	5.33	5.41	0.56	3.35	6.63	4.95	5.73	26056	NA	NA	Wet
Fiscal	WP_AMB1	Depth	NA	5.06	5.11	0.62	2.91	6.63	4.66	5.52	52547	NA	NA	NA
Monthly	WP_AMB2	Depth	1/7/2024	4.29	4.41	0.52	2.63	5.13	4.00	4.68	4462	Jul	2024	NA
Monthly	WP_AMB2	Depth	1/8/2024	4.37	4.45	0.51	2.94	5.30	4.06	4.75	4464	Aug	2024	NA
Monthly	WP_AMB2	Depth	1/9/2024	4.51	4.57	0.48	3.17	5.58	4.21	4.85	4317	Sep	2024	NA
Monthly	WP_AMB2	Depth	1/10/2024	4.47	4.51	0.48	3.20	5.53	4.14	4.86	4464	Oct	2024	NA
Monthly	WP_AMB2	Depth	1/11/2024	4.66	4.74	0.52	2.91	5.67	4.36	5.04	4319	Nov	2024	NA
Monthly	WP_AMB2	Depth	1/12/2024	5.02	5.10	0.56	3.53	6.09	4.67	5.48	4464	Dec	2024	NA
Monthly	WP_AMB2	Depth	1/1/2025	4.96	5.05	0.60	3.57	6.12	4.48	5.39	4462	Jan	2025	NA
Monthly	WP_AMB2	Depth	1/2/2025	4.98	5.06	0.51	3.72	6.27	4.65	5.36	4032	Feb	2025	NA
Monthly	WP_AMB2	Depth	1/3/2025	4.84	4.90	0.45	3.65	5.68	4.50	5.19	4461	Mar	2025	NA
Monthly	WP_AMB2	Depth	1/4/2025	4.80	4.90	0.47	3.34	5.94	4.49	5.13	4320	Apr	2025	NA

Monthly	WP_AMB2	Depth	1/5/2025	4.48	4.57	0.53	2.80	5.43	4.15	4.85	4462	May	2025	NA
Monthly	WP_AMB2	Depth	1/6/2025	4.46	4.58	0.53	2.83	5.50	4.14	4.84	4320	Jun	2025	NA
Seasonal	WP_AMB2	Depth	NA	4.43	4.51	0.52	2.63	5.58	4.11	4.81	26489	NA	NA	Dry
Seasonal	WP_AMB2	Depth	NA	4.88	4.94	0.54	2.91	6.27	4.52	5.27	26058	NA	NA	Wet
Fiscal	WP_AMB2	Depth	NA	4.65	4.70	0.57	2.63	6.27	4.30	5.06	52547	NA	NA	NA
Monthly	WP_AMB4	Depth	1/7/2024	4.05	4.18	0.57	2.27	4.98	3.72	4.48	4463	Jul	2024	NA
Monthly	WP_AMB4	Depth	1/8/2024	3.90	3.98	0.54	2.43	4.84	3.55	4.31	4464	Aug	2024	NA
Monthly	WP_AMB4	Depth	1/9/2024	4.04	4.13	0.50	2.79	5.14	3.70	4.42	4318	Sep	2024	NA
Monthly	WP_AMB4	Depth	1/10/2024	3.94	4.01	0.50	2.53	4.96	3.61	4.32	4464	Oct	2024	NA
Monthly	WP_AMB4	Depth	1/11/2024	4.11	4.21	0.56	2.43	5.15	3.77	4.53	4318	Nov	2024	NA
Monthly	WP_AMB4	Depth	1/12/2024	4.53	4.63	0.60	2.92	5.58	4.15	5.00	4464	Dec	2024	NA
Monthly	WP_AMB4	Depth	1/1/2025	4.49	4.62	0.61	3.04	5.68	4.05	4.94	4461	Jan	2025	NA
Monthly	WP_AMB4	Depth	1/2/2025	4.25	4.21	0.66	2.64	5.78	3.78	4.74	4032	Feb	2025	NA
Monthly	WP_AMB4	Depth	1/3/2025	4.11	4.18	0.52	2.63	5.02	3.78	4.53	4461	Mar	2025	NA
Monthly	WP_AMB4	Depth	1/4/2025	4.29	4.42	0.49	2.69	5.36	3.95	4.65	4320	Apr	2025	NA
Monthly	WP_AMB4	Depth	1/5/2025	4.07	4.20	0.56	2.44	5.25	3.72	4.44	4463	May	2025	NA
Monthly	WP_AMB4	Depth	1/6/2025	4.35	4.49	0.57	2.60	5.40	4.01	4.72	4320	Jun	2025	NA
Seasonal	WP_AMB4	Depth	NA	4.06	4.14	0.56	2.27	5.40	3.70	4.46	26492	NA	NA	Dry
Seasonal	WP_AMB4	Depth	NA	4.30	4.36	0.60	2.43	5.78	3.90	4.73	26056	NA	NA	Wet
Fiscal	WP_AMB4	Depth	NA	4.18	4.24	0.59	2.27	5.78	3.80	4.59	52548	NA	NA	NA
Monthly	WP_AMB1	Depth_RMS	1/7/2024	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4462	Jul	2024	NA
Monthly	WP_AMB1	Depth_RMS	1/8/2024	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4464	Aug	2024	NA
Monthly	WP_AMB1	Depth_RMS	1/9/2024	0.01	0.01	0.00	0.00	0.05	0.01	0.01	4319	Sep	2024	NA
Monthly	WP_AMB1	Depth_RMS	1/10/2024	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4464	Oct	2024	NA
Monthly	WP_AMB1	Depth_RMS	1/11/2024	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4317	Nov	2024	NA

Monthly	WP_AMB1	Depth_RMS	1/12/2024	0.01	0.01	0.00	0.00	0.03	0.01	0.01	4464	Dec	2024	NA
Monthly	WP_AMB1	Depth_RMS	1/1/2025	0.01	0.01	0.00	0.00	0.03	0.00	0.01	4462	Jan	2025	NA
Monthly	WP_AMB1	Depth_RMS	1/2/2025	0.01	0.01	0.00	0.00	0.03	0.01	0.01	4032	Feb	2025	NA
Monthly	WP_AMB1	Depth_RMS	1/3/2025	0.01	0.01	0.00	0.00	0.04	0.00	0.01	4461	Mar	2025	NA
Monthly	WP_AMB1	Depth_RMS	1/4/2025	0.01	0.01	0.00	0.00	0.03	0.00	0.01	4320	Apr	2025	NA
Monthly	WP_AMB1	Depth_RMS	1/5/2025	0.01	0.01	0.00	0.00	0.03	0.00	0.01	4462	May	2025	NA
Monthly	WP_AMB1	Depth_RMS	1/6/2025	0.01	0.01	0.00	0.00	0.02	0.00	0.01	4320	Jun	2025	NA
Seasonal	WP_AMB1	Depth_RMS	NA	0.01	0.01	0.00	0.00	0.05	0.01	0.01	26491	NA	NA	Dry
Seasonal	WP_AMB1	Depth_RMS	NA	0.01	0.01	0.00	0.00	0.04	0.01	0.01	26056	NA	NA	Wet
Fiscal	WP_AMB1	Depth_RMS	NA	0.01	0.01	0.00	0.00	0.05	0.01	0.01	52547	NA	NA	NA
Monthly	WP_AMB2	Depth_RMS	1/7/2024	0.02	0.02	0.01	0.00	0.13	0.01	0.02	4462	Jul	2024	NA
Monthly	WP_AMB2	Depth_RMS	1/8/2024	0.02	0.02	0.01	0.00	0.08	0.01	0.02	4464	Aug	2024	NA
Monthly	WP_AMB2	Depth_RMS	1/9/2024	0.02	0.02	0.01	0.00	0.08	0.01	0.02	4317	Sep	2024	NA
Monthly	WP_AMB2	Depth_RMS	1/10/2024	0.02	0.01	0.01	0.00	0.08	0.01	0.02	4464	Oct	2024	NA
Monthly	WP_AMB2	Depth_RMS	1/11/2024	0.02	0.01	0.01	0.00	0.11	0.01	0.02	4319	Nov	2024	NA

Monthly	WP_AMB2	Depth_RMS	1/12/2024	0.04	0.02	0.04	0.00	0.34	0.01	0.05	4464	Dec	2024	NA
Monthly	WP_AMB2	Depth_RMS	1/1/2025	0.03	0.02	0.04	0.00	0.35	0.01	0.04	4462	Jan	2025	NA
Monthly	WP_AMB2	Depth_RMS	1/2/2025	0.10	0.08	0.07	0.01	0.43	0.04	0.15	4032	Feb	2025	NA
Monthly	WP_AMB2	Depth_RMS	1/3/2025	0.04	0.02	0.04	0.00	0.36	0.01	0.04	4461	Mar	2025	NA
Monthly	WP_AMB2	Depth_RMS	1/4/2025	0.03	0.02	0.04	0.00	0.44	0.01	0.03	4320	Apr	2025	NA
Monthly	WP_AMB2	Depth_RMS	1/5/2025	0.02	0.02	0.01	0.00	0.11	0.01	0.02	4462	May	2025	NA
Monthly	WP_AMB2	Depth_RMS	1/6/2025	0.02	0.02	0.01	0.00	0.09	0.01	0.03	4320	Jun	2025	NA
Seasonal	WP_AMB2	Depth_RMS	NA	0.02	0.02	0.01	0.00	0.13	0.01	0.02	26489	NA	NA	Dry
Seasonal	WP_AMB2	Depth_RMS	NA	0.04	0.02	0.05	0.00	0.44	0.01	0.05	26058	NA	NA	Wet
Fiscal	WP_AMB2	Depth_RMS	NA	0.03	0.02	0.04	0.00	0.44	0.01	0.03	52547	NA	NA	NA
Monthly	WP_AMB4	Depth_RMS	1/7/2024	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4463	Jul	2024	NA
Monthly	WP_AMB4	Depth_RMS	1/8/2024	0.01	0.01	0.00	0.00	0.05	0.00	0.01	4464	Aug	2024	NA
Monthly	WP_AMB4	Depth_RMS	1/9/2024	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4318	Sep	2024	NA
Monthly	WP_AMB4	Depth_RMS	1/10/2024	0.01	0.01	0.00	0.00	0.04	0.00	0.01	4464	Oct	2024	NA
Monthly	WP_AMB4	Depth_RMS	1/11/2024	0.01	0.01	0.00	0.00	0.05	0.00	0.01	4318	Nov	2024	NA

Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2024-2025

Monthly	WP_AMB4	Depth_RMS	1/12/2024	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4464	Dec	2024	NA
Monthly	WP_AMB4	Depth_RMS	1/1/2025	0.01	0.01	0.00	0.00	0.03	0.01	0.01	4461	Jan	2025	NA
Monthly	WP_AMB4	Depth_RMS	1/2/2025	0.01	0.01	0.00	0.00	0.05	0.01	0.02	4032	Feb	2025	NA
Monthly	WP_AMB4	Depth_RMS	1/3/2025	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4461	Mar	2025	NA
Monthly	WP_AMB4	Depth_RMS	1/4/2025	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4320	Apr	2025	NA
Monthly	WP_AMB4	Depth_RMS	1/5/2025	0.01	0.01	0.00	0.00	0.04	0.01	0.01	4463	May	2025	NA
Monthly	WP_AMB4	Depth_RMS	1/6/2025	0.01	0.01	0.00	0.00	0.03	0.00	0.01	4320	Jun	2025	NA
Seasonal	WP_AMB4	Depth_RMS	NA	0.01	0.01	0.00	0.00	0.05	0.01	0.01	26492	NA	NA	Dry
Seasonal	WP_AMB4	Depth_RMS	NA	0.01	0.01	0.00	0.00	0.05	0.01	0.01	26056	NA	NA	Wet
Fiscal	WP_AMB4	Depth_RMS	NA	0.01	0.01	0.00	0.00	0.05	0.01	0.01	52548	NA	NA	NA
Monthly	WP_AMB1	NTU	1/7/2024	11.88	6.97	16.90	1.24	376.81	3.62	15.14	4462	Jul	2024	NA
Monthly	WP_AMB1	NTU	1/8/2024	26.76	7.18	89.46	0.91	1088.98	3.30	17.64	4464	Aug	2024	NA
Monthly	WP_AMB1	NTU	1/9/2024	25.29	7.23	75.59	0.12	1086.47	2.99	17.30	4319	Sep	2024	NA
Monthly	WP_AMB1	NTU	1/10/2024	84.89	10.30	194.96	1.46	936.65	4.44	43.32	4464	Oct	2024	NA
Monthly	WP_AMB1	NTU	1/11/2024	135.3	15.50	266.40	0.38	1133.81	4.21	94.68	4316	Nov	2024	NA
				2										
Monthly	WP_AMB1	NTU	1/12/2024	44.02	15.34	127.10	1.15	1132.64	6.22	35.82	4379	Dec	2024	NA
Monthly	WP_AMB1	NTU	1/1/2025	51.51	15.98	140.79	0.01	1131.94	6.11	45.09	2953	Jan	2025	NA
Monthly	WP_AMB1	NTU	1/2/2025	NA	NA	NA	NA	NA	NA	NA	NA	Feb	2025	NA
Monthly	WP_AMB1	NTU	1/3/2025	8.78	4.55	11.40	0.56	87.03	2.25	10.04	2654	Mar	2025	NA

Monthly	WP_AMB1	NTU	1/4/2025	12.14	4.45	35.41	0.90	1010.45	2.31	9.92	4273	Apr	2025	NA
Monthly	WP_AMB1	NTU	1/5/2025	7.81	2.94	14.41	0.54	310.56	1.90	6.48	4461	May	2025	NA
Monthly	WP_AMB1	NTU	1/6/2025	10.22	5.75	10.17	0.89	140.14	3.48	13.83	4316	Jun	2025	NA
Seasonal	WP_AMB1	NTU	NA	27.92	6.23	97.45	0.12	1088.98	3.03	16.37	26486	NA	NA	Dry
Seasonal	WP_AMB1	NTU	NA	54.06	9.03	161.27	0.01	1133.81	3.36	28.26	18575	NA	NA	Wet
Fiscal	WP_AMB1	NTU	NA	38.70	7.14	128.33	0.01	1133.81	3.12	20.17	45061	NA	NA	NA
Monthly	WP_AMB2	NTU	1/7/2024	13.33	5.08	37.46	0.61	943.67	3.06	12.16	4462	Jul	2024	NA
Monthly	WP_AMB2	NTU	1/8/2024	3.91	3.03	3.20	0.59	51.27	2.05	4.50	4459	Aug	2024	NA
Monthly	WP_AMB2	NTU	1/9/2024	5.89	4.19	18.18	0.77	922.76	2.91	6.00	4314	Sep	2024	NA
Monthly	WP_AMB2	NTU	1/10/2024	7.64	3.62	33.33	0.49	891.50	2.45	5.92	4464	Oct	2024	NA
Monthly	WP_AMB2	NTU	1/11/2024	25.34	3.39	84.61	0.32	891.57	1.77	9.87	4317	Nov	2024	NA
Monthly	WP_AMB2	NTU	1/12/2024	95.47	15.85	180.32	0.44	897.49	2.81	90.33	4464	Dec	2024	NA
Monthly	WP_AMB2	NTU	1/1/2025	61.60	10.32	144.49	0.76	896.38	2.99	51.15	4462	Jan	2025	NA
Monthly	WP_AMB2	NTU	1/2/2025	72.48	35.05	108.75	0.34	863.40	5.71	92.88	4032	Feb	2025	NA
Monthly	WP_AMB2	NTU	1/3/2025	9.13	3.02	15.74	0.33	183.26	1.55	9.03	4461	Mar	2025	NA
Monthly	WP_AMB2	NTU	1/4/2025	10.07	3.36	20.74	0.64	286.00	2.21	7.12	4319	Apr	2025	NA
Monthly	WP_AMB2	NTU	1/5/2025	7.36	2.71	16.70	0.50	206.30	1.81	5.04	4460	May	2025	NA
Monthly	WP_AMB2	NTU	1/6/2025	11.02	3.30	46.67	0.36	1018.04	1.89	8.87	4320	Jun	2025	NA
Seasonal	WP_AMB2	NTU	NA	8.19	3.56	29.85	0.36	1018.04	2.28	6.41	26479	NA	NA	Dry
Seasonal	WP_AMB2	NTU	NA	45.56	5.53	115.59	0.32	897.49	2.22	32.66	26055	NA	NA	Wet
Fiscal	WP_AMB2	NTU	NA	26.72	4.04	86.16	0.32	1018.04	2.25	12.06	52534	NA	NA	NA
Monthly	WP_AMB4	NTU	1/7/2024	71.14	14.84	154.39	0.06	970.18	8.32	47.57	4463	Jul	2024	NA
Monthly	WP_AMB4	NTU	1/8/2024	38.61	9.75	106.23	1.34	967.97	5.35	22.57	4464	Aug	2024	NA
Monthly	WP_AMB4	NTU	1/9/2024	62.67	9.88	160.46	0.94	1011.94	5.33	29.29	4318	Sep	2024	NA
Monthly	WP_AMB4	NTU	1/10/2024	125.7	9.91	250.90	1.76	1012.23	5.29	93.06	4464	Oct	2024	NA
				1										
Monthly	WP_AMB4	NTU	1/11/2024	134.7	12.10	259.72	1.03	1049.10	5.13	102.2	4318	Nov	2024	NA
				1						4				
Monthly	WP_AMB4	NTU	1/12/2024	101.9	23.78	218.52	1.58	1047.67	10.43	61.05	4464	Dec	2024	NA
				1										

Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2024-2025

Monthly	WP_AMB4	NTU	1/1/2025	76.40	22.35	174.87	2.24	1046.52	13.35	50.68	4461	Jan	2025	NA
Monthly	WP_AMB4	NTU	1/2/2025	51.29	19.87	105.25	0.74	1027.96	8.54	52.84	4032	Feb	2025	NA
Monthly	WP_AMB4	NTU	1/3/2025	42.28	12.09	120.09	0.75	1024.24	5.27	34.78	4460	Mar	2025	NA
Monthly	WP_AMB4	NTU	1/4/2025	23.86	10.45	42.12	1.77	917.49	5.69	27.54	4320	Apr	2025	NA
Monthly	WP_AMB4	NTU	1/5/2025	31.95	9.23	97.52	1.04	1156.25	5.14	23.81	4463	May	2025	NA
Monthly	WP_AMB4	NTU	1/6/2025	142.8	28.00	265.95	2.13	1161.56	11.64	104.7	4320	Jun	2025	NA
				6						2				
Seasonal	WP_AMB4	NTU	NA	78.57	12.31	188.64	0.06	1161.56	6.22	40.15	26492	NA	NA	Dry
Seasonal	WP_AMB4	NTU	NA	72.00	16.80	174.58	0.74	1049.10	7.28	47.21	26055	NA	NA	Wet
Fiscal	WP_AMB4	NTU	NA	75.31	14.32	181.83	0.06	1161.56	6.69	44.19	52547	NA	NA	NA
Monthly	WP_AMB1	PAR	1/7/2024	12.12	0.33	30.68	-0.05	238.56	-0.01	5.25	4462	Jul	2024	NA
Monthly	WP_AMB1	PAR	1/8/2024	17.92	0.21	42.70	0.10	317.99	0.15	10.81	4464	Aug	2024	NA
Monthly	WP_AMB1	PAR	1/9/2024	19.02	0.21	42.77	-0.04	351.49	0.16	13.97	4319	Sep	2024	NA
Monthly	WP_AMB1	PAR	1/10/2024	26.05	0.29	48.18	-0.05	330.61	-0.02	31.71	4464	Oct	2024	NA
Monthly	WP_AMB1	PAR	1/11/2024	39.65	0.78	74.25	-0.05	466.99	0.00	46.18	4317	Nov	2024	NA
Monthly	WP_AMB1	PAR	1/12/2024	11.79	0.23	31.16	0.07	326.13	0.11	6.56	4380	Dec	2024	NA
Monthly	WP_AMB1	PAR	1/1/2025	6.21	0.14	17.39	0.09	157.78	0.12	1.99	2954	Jan	2025	NA
Monthly	WP_AMB1	PAR	1/2/2025	NA	NA	NA	NA	NA	NA	NA	NA	Feb	2025	NA
Monthly	WP_AMB1	PAR	1/3/2025	10.91	0.01	26.49	-0.04	244.59	-0.02	8.78	2656	Mar	2025	NA
Monthly	WP_AMB1	PAR	1/4/2025	8.83	-0.01	22.22	-0.07	173.50	-0.03	4.96	3859	Apr	2025	NA
Monthly	WP_AMB1	PAR	1/5/2025	16.55	0.08	36.40	-0.06	326.12	-0.01	15.51	3954	May	2025	NA
Monthly	WP_AMB1	PAR	1/6/2025	6.50	0.07	19.24	-0.01	167.86	0.04	1.56	4320	Jun	2025	NA
Seasonal	WP_AMB1	PAR	NA	16.40	0.18	38.44	-0.06	351.49	0.04	10.17	25983	NA	NA	Dry
Seasonal	WP_AMB1	PAR	NA	16.74	0.21	44.35	-0.07	466.99	0.00	9.52	18166	NA	NA	Wet
Fiscal	WP_AMB1	PAR	NA	16.54	0.20	40.98	-0.07	466.99	0.03	9.85	44149	NA	NA	NA
Monthly	WP_AMB2	PAR	1/7/2024	28.79	-0.03	63.99	-0.20	380.48	-0.12	22.03	4461	Jul	2024	NA
Monthly	WP_AMB2	PAR	1/8/2024	67.11	0.19	110.80	-0.06	687.72	-0.03	94.45	4464	Aug	2024	NA
Monthly	WP_AMB2	PAR	1/9/2024	59.29	0.46	101.20	-0.06	534.87	-0.03	80.95	4317	Sep	2024	NA
Monthly	WP_AMB2	PAR	1/10/2024	89.91	2.79	133.40	-0.08	612.61	-0.04	153.7	4464	Oct	2024	NA
										0				

Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2024-2025

Monthly	WP_AMB2	PAR	1/11/2024	106.3 7	6.03	159.93	-0.05	812.12	-0.01	174.3 0	4319	Nov	2024	NA
Monthly	WP_AMB2	PAR	1/12/2024	53.66	0.02	114.06	-0.03	697.20	0.00	42.49	4464	Dec	2024	NA
Monthly	WP_AMB2	PAR	1/1/2025	36.45	0.24	73.99	-0.03	520.29	0.02	34.01	4462	Jan	2025	NA
Monthly	WP_AMB2	PAR	1/2/2025	31.71	0.21	83.58	0.11	554.25	0.18	7.72	4032	Feb	2025	NA
Monthly	WP_AMB2	PAR	1/3/2025	68.93	0.66	124.15	-0.04	631.74	0.01	80.33	4460	Mar	2025	NA
Monthly	WP_AMB2	PAR	1/4/2025	40.07	0.05	76.27	-0.05	488.90	-0.01	43.19	4320	Apr	2025	NA
Monthly	WP_AMB2	PAR	1/5/2025	46.17	0.12	78.38	-0.08	502.89	-0.01	66.53	4462	May	2025	NA
Monthly	WP_AMB2	PAR	1/6/2025	34.86	0.12	72.01	0.05	609.35	0.09	32.78	4320	Jun	2025	NA
Seasonal	WP_AMB2	PAR	NA	54.44	0.12	98.66	-0.20	687.72	-0.03	65.35	26488	NA	NA	Dry
Seasonal	WP_AMB2	PAR	NA	56.41	0.24	112.85	-0.05	812.12	0.00	54.55	26057	NA	NA	Wet
Fiscal	WP_AMB2	PAR	NA	55.42	0.23	105.94	-0.20	812.12	-0.01	60.29	52545	NA	NA	NA
Monthly	WP_AMB4	PAR	1/7/2024	7.07	0.06	17.08	0.01	210.25	0.04	5.13	1239	Jul	2024	NA
Monthly	WP_AMB4	PAR	1/8/2024	19.58	0.08	40.78	0.00	265.65	0.05	16.84	4464	Aug	2024	NA
Monthly	WP_AMB4	PAR	1/9/2024	25.02	0.11	54.48	-0.02	488.15	0.05	22.29	4318	Sep	2024	NA
Monthly	WP_AMB4	PAR	1/10/2024	29.25	0.20	53.50	-0.03	336.79	0.01	36.51	4464	Oct	2024	NA
Monthly	WP_AMB4	PAR	1/11/2024	28.42	0.26	56.15	0.00	406.01	0.03	30.79	4318	Nov	2024	NA
Monthly	WP_AMB4	PAR	1/12/2024	8.06	0.20	24.11	0.14	227.95	0.18	2.79	4464	Dec	2024	NA
Monthly	WP_AMB4	PAR	1/1/2025	4.97	0.22	15.94	0.18	159.26	0.20	1.43	2939	Jan	2025	NA
Monthly	WP_AMB4	PAR	1/2/2025	7.23	0.12	13.20	0.03	74.31	0.10	8.39	2187	Feb	2025	NA
Monthly	WP_AMB4	PAR	1/3/2025	11.95	0.15	30.94	0.08	303.66	0.13	6.73	4461	Mar	2025	NA
Monthly	WP_AMB4	PAR	1/4/2025	8.58	0.15	20.38	0.10	207.63	0.14	5.70	4320	Apr	2025	NA
Monthly	WP_AMB4	PAR	1/5/2025	15.74	0.15	33.74	0.05	333.02	0.13	12.59	4463	May	2025	NA
Monthly	WP_AMB4	PAR	1/6/2025	5.11	0.08	13.29	0.03	126.77	0.07	2.74	4320	Jun	2025	NA
Seasonal	WP_AMB4	PAR	NA	18.35	0.14	41.92	-0.03	488.15	0.05	12.97	23268	NA	NA	Dry
Seasonal	WP_AMB4	PAR	NA	12.32	0.20	33.11	0.00	406.01	0.14	6.13	22689	NA	NA	Wet
Fiscal	WP_AMB4	PAR	NA	15.37	0.19	37.95	-0.03	488.15	0.08	9.29	45957	NA	NA	NA
Monthly	WP_AMB1	Temp	1/7/2024	25.17	25.67	1.08	23.17	26.84	24.16	26.18	4462	Jul	2024	NA
Monthly	WP_AMB1	Temp	1/8/2024	26.21	26.34	0.98	24.07	28.16	25.52	27.00	4464	Aug	2024	NA
Monthly	WP_AMB1	Temp	1/9/2024	26.91	26.72	0.91	25.63	29.79	26.14	27.46	4319	Sep	2024	NA

Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2024-2025

Monthly	WP_AMB1	Temp	1/10/2024	28.84	29.06	0.69	27.19	30.15	28.23	29.40	4464	Oct	2024	NA
Monthly	WP_AMB1	Temp	1/11/2024	29.76	29.91	0.61	28.31	30.89	29.29	30.23	4317	Nov	2024	NA
Monthly	WP_AMB1	Temp	1/12/2024	30.80	30.77	0.40	29.95	31.88	30.50	31.08	4464	Dec	2024	NA
Monthly	WP_AMB1	Temp	1/1/2025	31.16	31.15	0.44	29.95	32.46	30.88	31.43	4462	Jan	2025	NA
Monthly	WP_AMB1	Temp	1/2/2025	29.47	29.74	0.97	26.99	31.46	28.70	30.22	4032	Feb	2025	NA
Monthly	WP_AMB1	Temp	1/3/2025	30.86	30.77	0.58	29.47	32.41	30.46	31.27	4461	Mar	2025	NA
Monthly	WP_AMB1	Temp	1/4/2025	29.55	29.45	0.75	28.17	31.07	29.01	30.31	4320	Apr	2025	NA
Monthly	WP_AMB1	Temp	1/5/2025	28.16	28.21	0.41	27.11	29.30	27.97	28.43	4462	May	2025	NA
Monthly	WP_AMB1	Temp	1/6/2025	27.07	27.18	0.96	25.57	28.68	26.11	27.91	4320	Jun	2025	NA
Seasonal	WP_AMB1	Temp	NA	27.06	27.24	1.49	23.17	30.15	26.09	28.23	26491	NA	NA	Dry
Seasonal	WP_AMB1	Temp	NA	30.29	30.46	0.94	26.99	32.46	29.70	30.95	26056	NA	NA	Wet
Fiscal	WP_AMB1	Temp	NA	28.66	28.91	2.04	23.17	32.46	27.21	30.45	52547	NA	NA	NA
Monthly	WP_AMB2	Temp	1/7/2024	25.05	25.46	0.98	22.87	26.59	24.07	25.95	4462	Jul	2024	NA
Monthly	WP_AMB2	Temp	1/8/2024	25.88	26.05	0.86	24.13	27.83	25.08	26.52	4464	Aug	2024	NA
Monthly	WP_AMB2	Temp	1/9/2024	26.77	26.41	0.87	25.62	29.37	26.11	27.44	4317	Sep	2024	NA
Monthly	WP_AMB2	Temp	1/10/2024	28.64	28.79	0.74	26.98	29.94	28.01	29.30	4464	Oct	2024	NA
Monthly	WP_AMB2	Temp	1/11/2024	29.67	29.81	0.60	28.25	30.88	29.21	30.12	4319	Nov	2024	NA
Monthly	WP_AMB2	Temp	1/12/2024	30.81	30.80	0.40	30.06	31.96	30.48	31.09	4464	Dec	2024	NA
Monthly	WP_AMB2	Temp	1/1/2025	31.25	31.27	0.46	29.97	32.79	30.98	31.52	4462	Jan	2025	NA
Monthly	WP_AMB2	Temp	1/2/2025	29.58	29.82	0.72	27.92	31.00	28.86	30.12	4032	Feb	2025	NA
Monthly	WP_AMB2	Temp	1/3/2025	30.77	30.73	0.47	29.64	31.95	30.46	31.13	4461	Mar	2025	NA
Monthly	WP_AMB2	Temp	1/4/2025	29.57	29.41	0.73	28.31	31.00	28.97	30.31	4320	Apr	2025	NA
Monthly	WP_AMB2	Temp	1/5/2025	28.23	28.28	0.32	27.15	29.23	28.10	28.41	4462	May	2025	NA
Monthly	WP_AMB2	Temp	1/6/2025	26.96	26.95	0.86	25.58	28.91	26.19	27.65	4320	Jun	2025	NA
Seasonal	WP_AMB2	Temp	NA	26.92	26.84	1.48	22.87	29.94	25.99	28.20	26489	NA	NA	Dry
Seasonal	WP_AMB2	Temp	NA	30.30	30.41	0.90	27.92	32.79	29.72	30.95	26058	NA	NA	Wet
Fiscal	WP_AMB2	Temp	NA	28.60	28.81	2.09	22.87	32.79	26.80	30.41	52547	NA	NA	NA
Monthly	WP_AMB4	Temp	1/7/2024	25.05	25.43	1.17	21.41	26.77	23.95	26.07	4463	Jul	2024	NA
Monthly	WP_AMB4	Temp	1/8/2024	26.06	26.26	1.03	23.09	28.02	25.33	26.80	4464	Aug	2024	NA
Monthly	WP_AMB4	Temp	1/9/2024	26.79	26.56	0.93	24.39	29.59	26.10	27.46	4318	Sep	2024	NA

Port of Weipa Ambient Marine Water Quality Monitoring Program: Annual Report 2024-2025

Monthly	WP_AMB4	Temp	1/10/2024	28.80	28.91	0.74	26.82	30.86	28.21	29.40	4464	Oct	2024	NA
Monthly	WP_AMB4	Temp	1/11/2024	29.87	29.93	0.72	28.07	31.68	29.34	30.41	4318	Nov	2024	NA
Monthly	WP_AMB4	Temp	1/12/2024	30.96	30.91	0.44	29.91	32.07	30.62	31.28	4464	Dec	2024	NA
Monthly	WP_AMB4	Temp	1/1/2025	31.22	31.22	0.46	29.60	32.71	30.97	31.48	4461	Jan	2025	NA
Monthly	WP_AMB4	Temp	1/2/2025	29.48	29.73	1.07	26.61	31.45	28.64	30.34	4032	Feb	2025	NA
Monthly	WP_AMB4	Temp	1/3/2025	30.99	30.85	0.67	29.48	33.01	30.53	31.45	4461	Mar	2025	NA
Monthly	WP_AMB4	Temp	1/4/2025	29.61	29.44	0.81	28.09	32.66	29.04	30.39	4320	Apr	2025	NA
Monthly	WP_AMB4	Temp	1/5/2025	28.17	28.23	0.50	26.72	29.69	27.85	28.49	4463	May	2025	NA
Monthly	WP_AMB4	Temp	1/6/2025	26.98	27.02	1.01	24.61	29.14	26.04	27.80	4320	Jun	2025	NA
Seasonal	WP_AMB4	Temp	NA	26.98	27.09	1.56	21.41	30.86	25.98	28.20	26492	NA	NA	Dry
Seasonal	WP_AMB4	Temp	NA	30.38	30.56	1.01	26.61	33.01	29.71	31.10	26056	NA	NA	Wet
Fiscal	WP_AMB4	Temp	NA	28.66	28.90	2.15	21.41	33.01	27.05	30.55	52548	NA	NA	NA

APPENDIX B QUALITY CONTROL

To support the ongoing use of high-resolution in-situ loggers within the NQBP ambient monitoring program, a standardised and science-based quality control (QC) framework has been applied consistently across recent reporting years. This QC process is derived from internationally recognised Real-Time Oceanographic Data Quality Control (QARTOD) procedures (NOAA, 2020), which are widely adopted by CSIRO, IMOS and AIMS. The same framework has now been embedded in the program for several years, providing a robust and repeatable approach to ensuring confidence in long-term logger datasets.

Logger data undergo both automated and manual QC steps. The automated workflow applies 12 objective tests (Table A6), which evaluate sensor performance, environmental plausibility, stability, and instrument integrity. Each result is assigned a QC flag: ‘good data’ (green), ‘probably good data’ (blue), ‘probably bad data’ (yellow), or ‘bad data’ (red). These flags allow users to make transparent, reproducible decisions about data suitability for different applications.

Table A- 1 QC tests applied to logger data

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

Each logger includes four core sensors—temperature, depth, tilt, and either turbidity (NTU) or photosynthetically active radiation (PAR). For every 10-minute interval, the ‘worst’ QC flag from tests 1–12 is retained for that sensor, providing a conservative assessment of data reliability. Figures A 1 – A4 presents the QC-flagged datasets for the current reporting period, while Figure A-5 summarises the proportion of records in each QC category for every parameter.

For most analyses, ‘good’ and ‘probably good’ data are considered fit-for-purpose, while ‘probably bad’ data may be usable with caution depending on context. ‘Bad’ data should be excluded. Data with specific QC categories can be easily filtered or masked in Excel, R, Python, or other data management platforms. Figure A-3 shows the

A full technical description of the QC methodology, test definitions and implementation is provided in the TropWATER technical report (Iles et al., 2023), available on the TropWATER website.

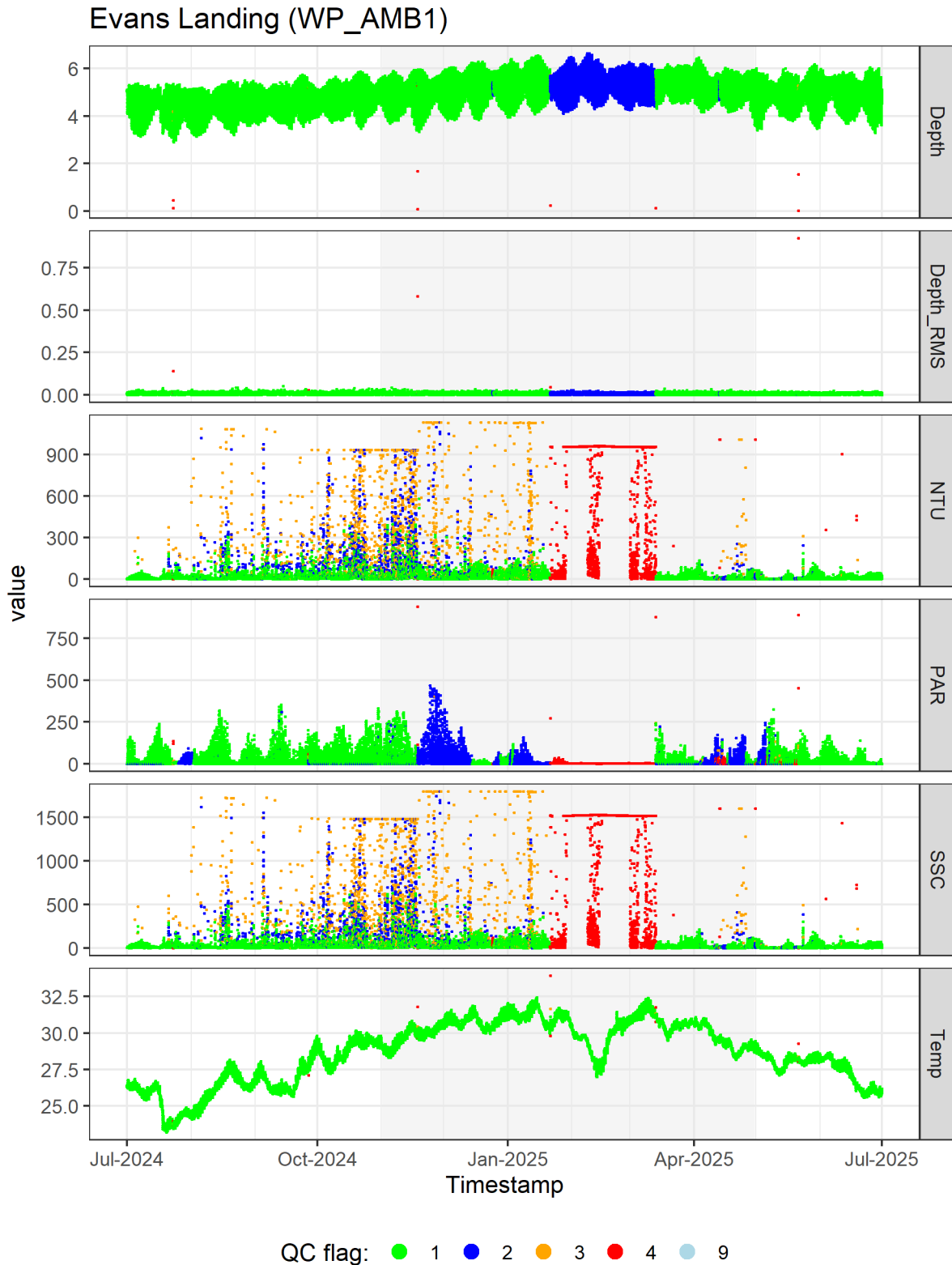


Figure A- 1 Raw data collected at Evans Landing with IMO loggers. Passed through automated and manual quality control (QC) steps. Symbol colour indicates QC flag designation where: 1 (green) = Good data, 2 (blue) = Probably good data, 3 (orange) = Suspect data, 4 (red) = Bad data, 9 (light blue) = Missing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

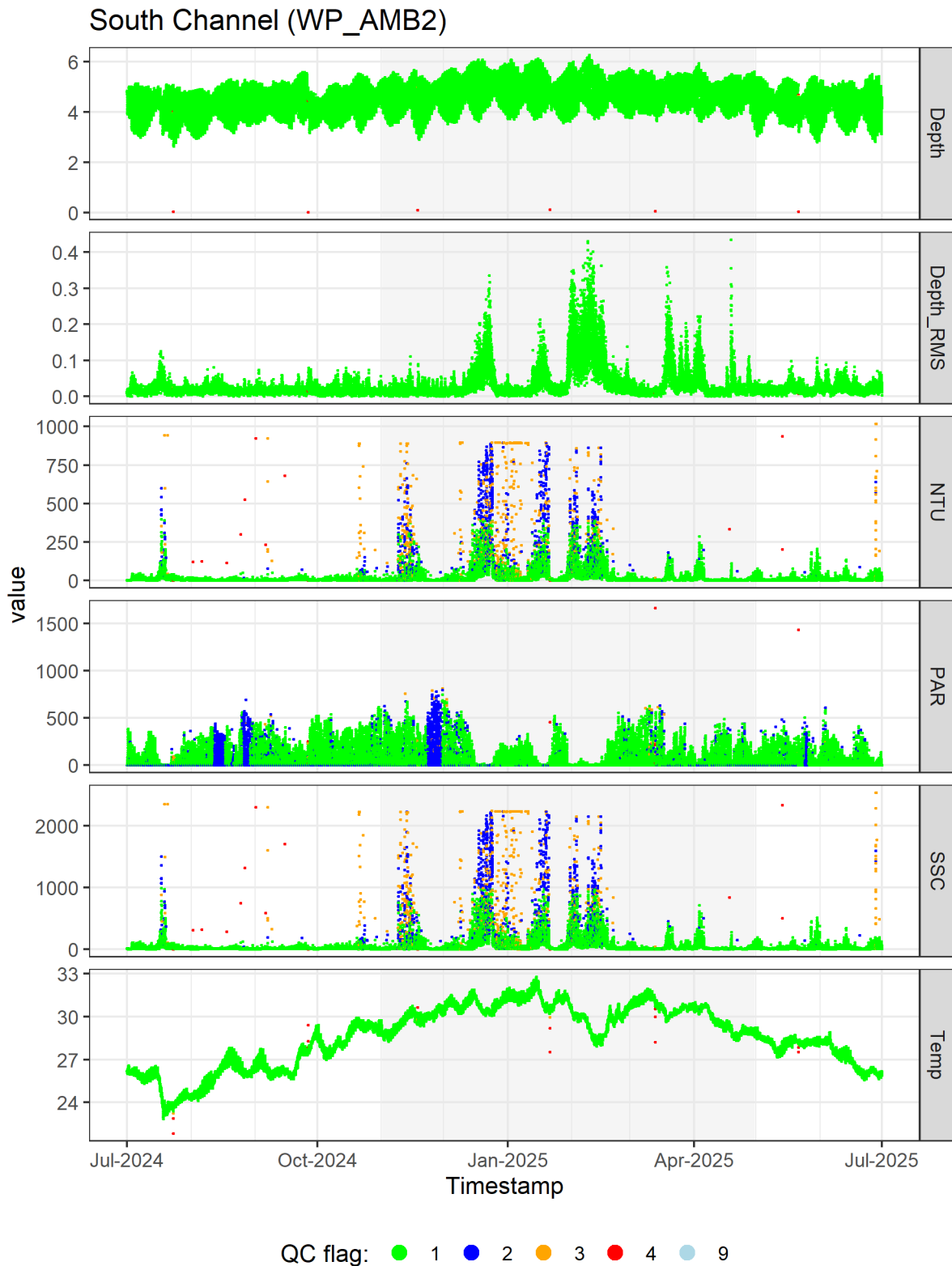


Figure A-2 Raw data collected at South Channel with IMO loggers. Passed through automated and manual quality control (QC) steps. Symbol colour indicates QC flag designation where: 1 (green) = Good data, 2 (blue) = Probably good data, 3 (orange) = Suspect data, 4 (red) = Bad data, 9 (light blue) = Missing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

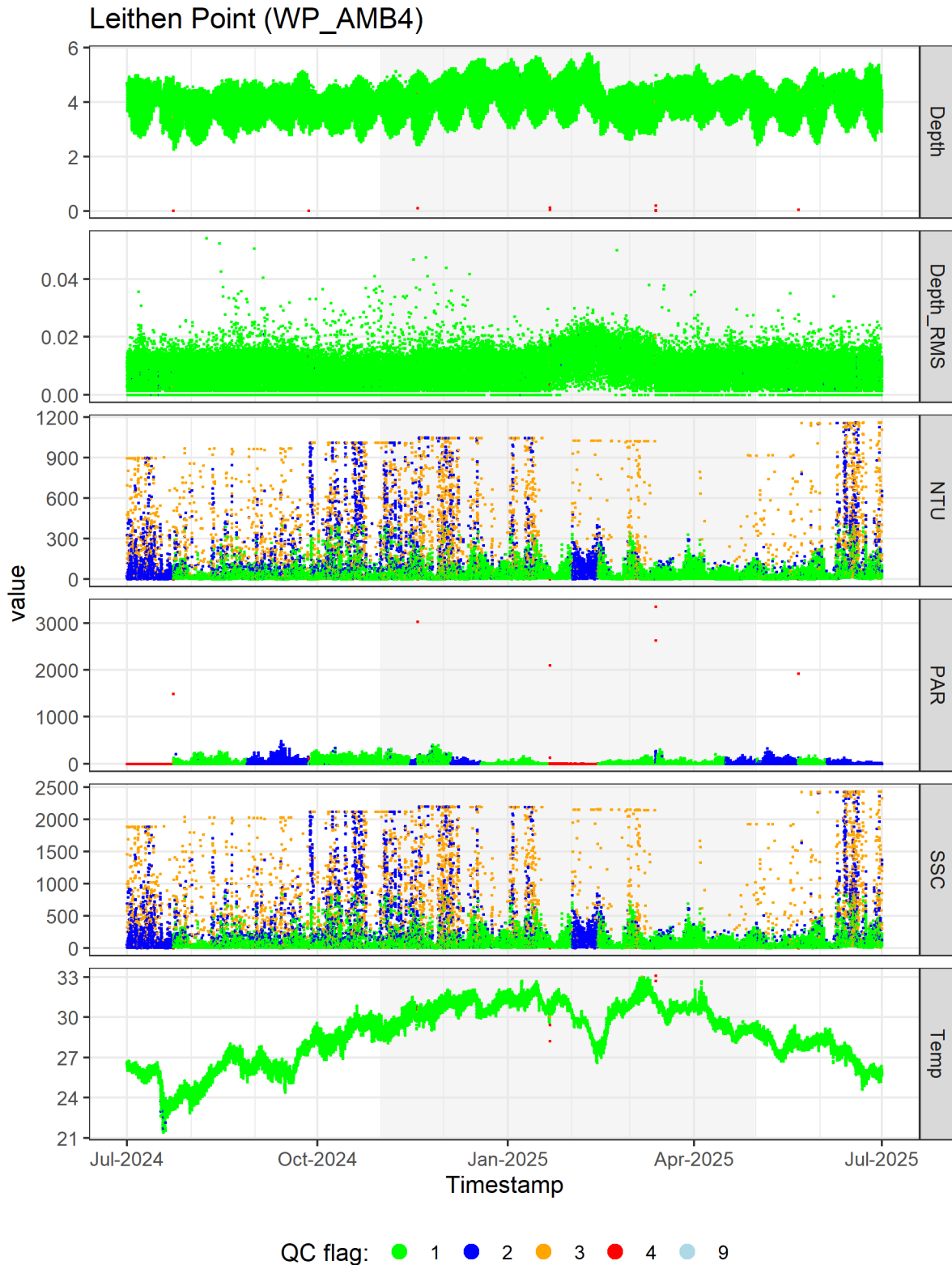


Figure A-3 Raw data collected at Leithen Point with IMO loggers. Passed through automated and manual quality control (QC) steps. Symbol colour indicates QC flag designation where: 1 (green) = Good data, 2 (blue) = Probably good data, 3 (orange) = Suspect data, 4 (red) = Bad data, 9 (light blue) = Missing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

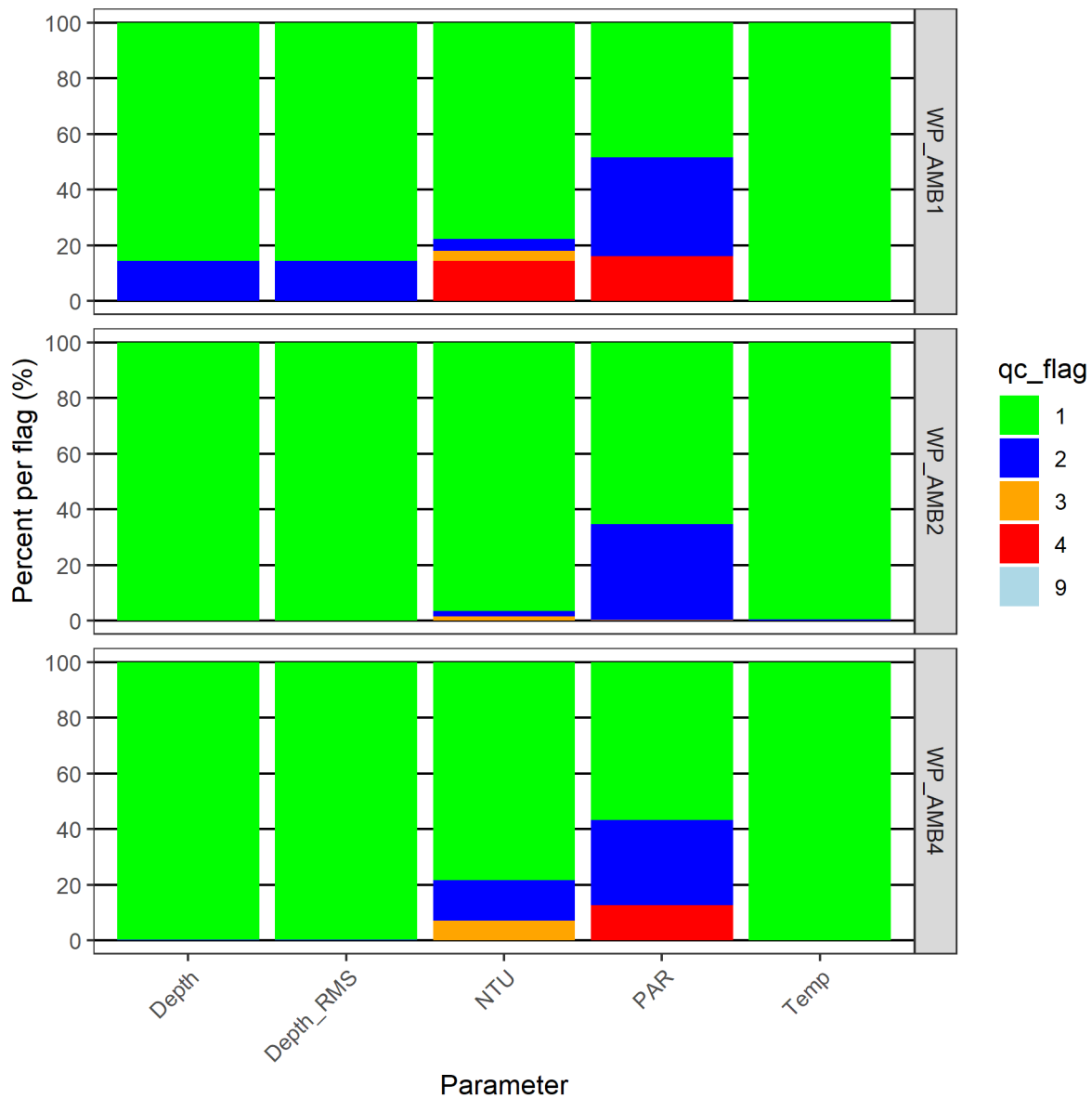


Figure A-4 Logger data recovery statistics for the Weipa monitoring sites over the reporting period.

APPENDIX C GAMM MODELS OUTPUTS

Table A-1 Summary of Generalised Additive Mixed Model (GAMM) results for chlorophyll-a, showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```

Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.37878    0.09918   3.819 0.000194 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
      edf Ref.df    F p-value
s(Month) 2.52     3 12.414 <2e-16 ***
s(Time)   1.00     1  1.436  0.233
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.149
Scale est. = 0.28848 n = 158
      k'    edf k-index p-value
s(Month)  3 2.520332 1.0034663  0.53
s(Time)   19 1.000000 0.7101112  0.00

```

Table A-2 Summary of Generalised Additive Mixed Model (GAMM) results for Phaeophytin-a, showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```

Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept) -1.39055    0.07218 -19.27 <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
      edf Ref.df    F p-value
s(Month) 1.311     3  1.048  0.0881 .
s(Time)   1.000     1  2.290  0.1323
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.0166
Scale est. = 0.81795 n = 158
      k'    edf k-index p-value
s(Month)  3 1.310572 0.9573165  0.5375
s(Time)   19 1.000000 0.7997021  0.0350

```

Table A-3 Summary of Generalised Additive Mixed Model (GAMM) results for conductivity, showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) 10.76742    0.01398   770.3   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df      F p-value
s(Month)  2.76      3 37.475 <2e-16 ***
s(Time)   1.00      1  3.122  0.0792 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.425
Scale est. = 0.011893 n = 158
              k'      edf  k-index p-value
s(Month)  3 2.760310 0.7215054      0
s(Time)   19 1.000001 0.7423495      0
```

Table A-4 Summary of Generalised Additive Mixed Model (GAMM) results for particulate nitrogen (PN), showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.76801    0.06554   57.49   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df      F p-value
s(Month) 0.3095      3 0.121 0.31537
s(Time)   1.0000      1 7.799 0.00589 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.0407
Scale est. = 0.67016 n = 157
              k'      edf  k-index p-value
s(Month)  3 0.3095443 0.8250806 0.0850
s(Time)   19 1.0000001 0.8899946 0.2775
```

Table A-5 Summary of Generalised Additive Mixed Model (GAMM) results for total dissolved nitrogen (TDN), showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept)  4.80477    0.02127   225.9  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
      edf Ref.df    F p-value
s(Month)  1.531   3.00 1.470 0.00284 **
s(Time)   12.641  12.64 6.626 < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.464
Scale est. = 0.029703 n = 158
      k'    edf k-index p-value
s(Month)  3  1.531437 0.7958719 0.0025
s(Time)   19 12.641047 0.8097287 0.0075
```

Table A-6 Summary of Generalised Additive Mixed Model (GAMM) results for total nitrogen (TN), showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept)  5.09742    0.03224   158.1  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
      edf Ref.df    F p-value
s(Month)  2.109    3  6.119 8.48e-05 ***
s(Time)   1.000    1 16.814 6.73e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.16
Scale est. = 0.050801 n = 155
      k'    edf k-index p-value
s(Month)  3  2.109473 0.7868869 0.01
s(Time)   19 1.000001 0.7505275 0.00
```

Table A- 7 Summary of Generalised Additive Mixed Model (GAMM) results for particulate phosphorous (PP), showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.67537    0.09577   17.49  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df      F p-value
s(Month)  0.9568      3 0.558  0.174
s(Time)   1.0000      1 0.818  0.367

R-sq.(adj) = 0.0085
Scale est. = 0.48064 n = 158
              k'      edf k-index p-value
s(Month)    3 0.9568367 0.9905198  0.565
s(Time)    19 1.0000002 0.7725844  0.005
```

Table A- 8 Summary of Generalised Additive Mixed Model (GAMM) results for total dissolved phosphorous (TDP), showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  2.12161    0.02996   70.81  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df      F p-value
s(Month)  2.595  3.000 13.079 <2e-16 ***
s(Time)   2.354  2.354  4.286  0.012 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.227
Scale est. = 0.14093 n = 158
              k'      edf k-index p-value
s(Month)    3 2.594770 0.9141345  0.15
s(Time)    19 2.354491 0.5822641  0.00
```

Table A- 9 Summary of Generalised Additive Mixed Model (GAMM) results for total phosphorous (TP), showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  2.63713    0.03261   80.86  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df    F  p-value
s(Month)  2.561   3.000 9.863 1.94e-06 ***
s(Time)   1.934   1.934 2.370   0.11
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.18
Scale est. = 0.11108  n = 158
              k'    edf  k-index p-value
s(Month)   3 2.560677 0.8638891   0.05
s(Time)   19 1.933890 0.5485867   0.00
```

Table A- 10 Summary of Generalised Additive Mixed Model (GAMM) results for total suspended solids (TSS), showing the fitted smooth terms for month (seasonality) and time (long-term trend).

```
Family: Gamma
Link function: log

Formula:
value ~ s(Month, fx = FALSE, bs = "cc", k = 5) + s(Time, fx = FALSE,
  bs = "tp", k = 20)

Parametric coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.6480    0.1217   13.54  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df    F  p-value
s(Month)  1.455    3 1.288  0.0692 .
s(Time)   1.000    1 1.318  0.2534
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0108
Scale est. = 0.53534  n = 116
              k'    edf  k-index p-value
s(Month)   3 1.454624 0.9399482  0.2675
s(Time)   19 1.000000 0.8008601  0.0175
```