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Great Barrier Reef MARINE MONITORING PROGRAM



Annual Report INSHORE WATER QUALITY MONITORING

2020-21



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Front cover image: Satellite imagery showing flood plumes entering the central Great Barrier Reef from the Herbert and Tully Rivers, 23 February 2021. Imagery from the NASA Worldview application (<https://worldview.earthdata.nasa.gov/>), part of the NASA Earth Observing System Data and Information System (EOSDIS), downloaded by C. Petus, James Cook University (TropWATER).

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Commonly used abbreviations, acronyms, definitions and units

Abbreviations, acronyms and definitions

AIMS	Australian Institute of Marine Science
Authority	Great Barrier Reef Marine Park Authority
BoM	Bureau of Meteorology
CDOM	colour dissolved organic matter
Chl- <i>a</i>	chlorophyll <i>a</i>
CTD	Conductivity Temperature Depth profiler
CYWMP	Cape York Water Monitoring Partnership
DIN	dissolved inorganic nitrogen
DOC	dissolved organic carbon
DON	dissolved organic nitrogen
DOP	dissolved organic phosphorus
ENSO	El Nino – Southern Oscillation cycle
GAMM	generalised additive mixed effect model
GV	guideline value
JCU	James Cook University
K_D	light attenuation coefficient
LOD	limit of detection
MMP	Marine Monitoring Program
Marine Park	Great Barrier Reef Marine Park
MODIS	Moderate Resolution Imaging Spectroradiometer
NH ₃	ammonia
NO _x	nitrogen oxides
NRM	natural resource management
PN	particulate nitrogen
PO ₄	phosphate (dissolved inorganic phosphorus)
POC	particulate organic carbon
PP	particulate phosphorus
PSII herbicide	photosystem II inhibiting herbicide
QA/QC	quality assurance/quality control
QLUMP	Queensland Land Use Mapping Program
Reef	Great Barrier Reef
Reef 2050 WQIP	Reef 2050 Water Quality Improvement Plan
Reef Plan	Reef Water Quality Protection Plan
Reef 2050 Plan	Reef 2050 Long-Term Sustainability Plan
SDD	Secchi disk depth
TSS	total suspended solids

WS colour scale	wet season colour scale
WQ Index	Water Quality Index

Units

GL	gigalitre
m	metre
mm d ⁻¹	millimetres per day
mg L ⁻¹	milligram per litre
ML	megalitre
km	kilometre
km.h ⁻¹	kilometres per hour
kt	kilotonne
t	tonne
µg L ⁻¹	microgram per litre

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Executive summary

The water quality component of the Great Barrier Reef Marine Monitoring Program reports on the annual and long-term condition in inshore water quality of the Great Barrier Reef with reference to data over more than 15 years.

The program design includes the collection of samples along transects in the Cape York, Wet Tropics, Burdekin and Mackay-Whitsunday regions year-round, with higher frequency sampling during the wet season to better characterise this period of episodic river discharge. Satellite imagery and modelling are linked with *in situ* monitoring data to estimate the exposure of inshore areas to end-of-catchment loads from rivers for all Great Barrier Reef catchment regions.

Trends in key inshore water quality indicators

Key water quality indicators were used to derive a Water Quality Index which communicates the long-term trend (insensitive to year-to-year variability) and annual condition (sensitive to year-to-year variability) of water quality relative to guideline values (Figure i).

The long-term Index showed that long-term inshore water quality trend has:

- **declined** gradually in the Wet Tropics region from 2008–2018 and is showing signs of **improving** in recent years
- **declined** gradually in the Burdekin region since 2010 and stabilised in recent years
- **declined** steadily in the Mackay-Whitsunday region since 2008 but stabilised in recent years and showing early signs of improvement this year.

Cape York trends are not assessed yet as there is not enough data for a robust assessment.

The annual condition index showed that the annual condition for inshore water quality (Figure i) in 2020–21 was:

- **moderate** in the Wet Tropics and Burdekin regions, worse than in 2019–20
- **moderate** in the Mackay-Whitsunday, the same as in 2019–20
- **moderate** in Cape York, the first year it has been reported

Declines in annual Index scores relative to 2019–20, are most likely related to the below-average river discharge during 2019–20.

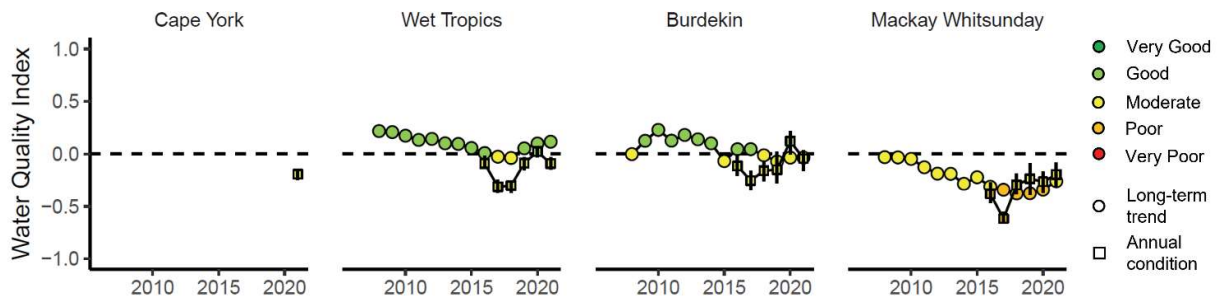


Figure i: Water Quality Index scores from 2008 to 2021 for the Cape York, Wet Tropics, Burdekin and Mackay-Whitsunday regions. The Index is calculated to show the long-term trend in water quality since the start of monitoring (circles), where seasonal and short-term variability signals are removed. An updated Index version communicating annual condition is calculated from 2015 onwards (squares) that includes increased temporal and spatial sampling and relates water quality values to wet and dry season Reef water quality guidelines. The Index includes five variables: water clarity, concentrations of nitrate/nitrite, particulate nitrogen, particulate phosphorus, and chlorophyll *a*. Long-term data are not available for Cape York. Details of calculations are in Appendix B.

Individual water quality indicators are monitored for trends and compared against water quality guideline values. In general, concentrations of chlorophyll *a* and dissolved inorganic phosphorus are improving, while total suspended solids concentrations are stable or improving and all three parameters met guideline values in most regions in the 2020–21 year. Particulate phosphorus and

Secchi depth values were generally stable across all regions and particulate phosphorous was just meeting guideline values in most regions in the 2020–21 year. In contrast these parameters exceeded guideline values in most or all regions during 2020–21:

- Nitrate/nitrite
- Particulate nitrogen
- Secchi depth (a proxy for water clarity).

In Cape York chlorophyll *a* and particulate phosphorus met the water quality guideline values at most sites for all sub-regions while NO_x and Secchi depth were not meeting the guideline values at most sites and sub-regions. Total suspended solids, phosphorus and particulate nitrogen comparisons against guideline values were mixed, with some sites and sub-regions meeting the GVs.

Changes in nutrient concentrations are related to changes in nutrient sources (i.e., inputs) and sinks (i.e., outputs) in the Reef lagoon and potentially changes in the rates of key ecological processes (such as primary production). The spatial and temporal variability in the *in situ* water quality discussed in this report highlights the combination of complex factors including river discharge, biogeochemical processes, and physical forcing that drive water quality.

Drivers and pressures

Environmental conditions over the 2020–21 wet season involved rainfall and river discharge close to the long-term median, with the rivers south of the Don River catchment below the long-term median. There was limited cyclone impact on the Reef with four cyclones that either weakened in Reef areas or tracked offshore.

End-of-catchment sediment and nutrient load estimates showed distinct variations between the focus areas, with the highest dissolved inorganic nitrogen exports from the Herbert and Burdekin-Haughton basins, followed by the Tully-Murray and Russell-Mulgrave-Johnstone basins. This finding was largely due to the relatively low discharges from all focus areas. Loads of total suspended solids and particulate nitrogen were dominated by the Burdekin-Haughton basins.

River-derived nutrient and sediment loads dispersion was similar to other years with discharges close to or slightly above the long-term median. Comparison with modelled pre-development conditions identified anthropogenic influence mostly confined to the coastal waterbody in 2020–21, with the strongest influence in the region affected by discharge from the Burdekin River.

For the first time the high resolution Sentinel-3 satellite images of the reef were used to map Reef optical water types. Water types are classified depending on water colour and linked to water quality characteristics; primary waters are brownish (enriched in sediment and dissolved organic matter), secondary waters are greenish (enriched in algae and dissolved organic matter), and tertiary waters have low risk of detrimental ecological effects. There was a high frequency of exposure to the primary water type in inshore areas, with mid-shelf to offshore areas most frequently exposed to the tertiary water type only. In the midshelf and offshore water bodies, this water type is often the result of marine processes such as upwelling rather than direct influence of catchment discharge. The area exposed to a water quality potential risk in 2020–21 was spatially limited relative to the scale of the Great Barrier Reef, although the area of the Reef in the highest risk categories is almost 10,000km². Eighty-five percent of the Great Barrier Reef was exposed to no or very low potential risk.

Conclusion

While this report presents some positive results for inshore water quality in the Great Barrier Reef for the 2020–21 sampling period, broad reaching and sustained improvements in the marine water quality of the inshore reef have not yet been observed. The complexity of the relationship between land-based runoff and water quality, the influence of inter-annual variability and external drivers and pressures, the progress of changed management practice adoption, and the expected slow response timeframes between land-based changes and marine water quality all contribute to this lack of observed change.

1 Introduction

1.1 The Great Barrier Reef

The Great Barrier Reef (the Reef) is the most extensive reef system in the world, comprising over 2900 km² of coral reefs. It also includes large areas of seagrass meadows, estimated to be over 43,000 km² or ~12.5% of the total area of the Great Barrier Reef Marine Park (the Marine Park) (Great Barrier Reef Marine Park Authority, 2019). The Reef catchment is divided into six natural resource management (NRM) regions, each with differing land use, biophysical and socio-economic characteristics.

1.2 Water quality monitoring in the Reef

The management of water quality remains a priority for the Great Barrier Reef Marine Park Authority (the Authority) because good water quality supports the health and resilience of coastal and inshore ecosystems of the Reef (Great Barrier Reef Marine Park Authority, 2019).

In response to concerns about the impact of land-based run-off on water quality, the *Reef 2050 Water Quality Improvement Plan* (Reef 2050 WQIP; Australian and Queensland governments, 2018a) was updated by the Australian and Queensland governments in 2017, and integrated as a major component of the Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia, 2018)¹, which provides a framework for the integrated management of the Great Barrier Reef World Heritage Area.

A key deliverable of the Reef 2050 WQIP is the *Paddock to Reef Integrated Monitoring, Modelling and Reporting Program* (Australian and Queensland governments, 2018b), which is used to evaluate the efficiency and effectiveness of the implementation of the Reef 2050 WQIP, and report on progress towards goals and targets. The Great Barrier Reef Marine Monitoring Program (MMP) forms an integral part of the *Paddock to Reef Integrated Monitoring, Modelling and Reporting Program*. The MMP has the following three components: inshore water quality, coral, and seagrass. Ecological components of the MMP (seagrass and coral health) are published in separate annual reports detailing the condition and trend of these ecosystems in relation to multiple stressors, including water quality presented in this report (for example, McKenzie *et al.*, 2021; Thompson *et al.*, 2021). In previous years, inshore pesticide monitoring has been presented in a separate report (for example, Thai *et al.*, 2020). Loads of sediments, nutrients, and pesticides within rivers are monitored by the Catchment Loads Monitoring Program (Ten Napel *et al.*, 2019).

The overarching objective of the inshore water quality monitoring program is to ‘Assess temporal and spatial trends in inshore marine water quality and link pollutant concentrations to end-of-catchment loads’ (Australian and Queensland governments, 2018b). Water quality monitoring has been delivered by the Australian Institute of Marine Science (AIMS), James Cook University (JCU) and the Authority since 2005; the Cape York Water Monitoring Partnership (CYWMP) was added as a collaborator in 2017. Pesticide monitoring has also been conducted by the University of Queensland.

1.3 Structure of the report

The following Section presents a summary of the program’s methods. Section 3 describes the factors influencing marine water quality, referred to as drivers and pressures in the Driver-Pressure-State-Impact-Response (DPSIR) framework (Figure 1-1). Water quality results from satellite imagery and hydrodynamic modelling are presented in Section 4 at Reef and regional scales. Detailed results from focus areas are presented in Section 5, including monitoring results, indices, and catchment

¹ <http://www.environment.gov.au/marine/gbr/reef2050>

loading. At the request of the Authority, the pesticide monitoring results for the Mackay-Whitsunday region are included in the regional results. An overall Discussion and Conclusions are given in Sections 6 and 7, respectively. Detailed tables and figures of monitoring data are included in Appendix C.

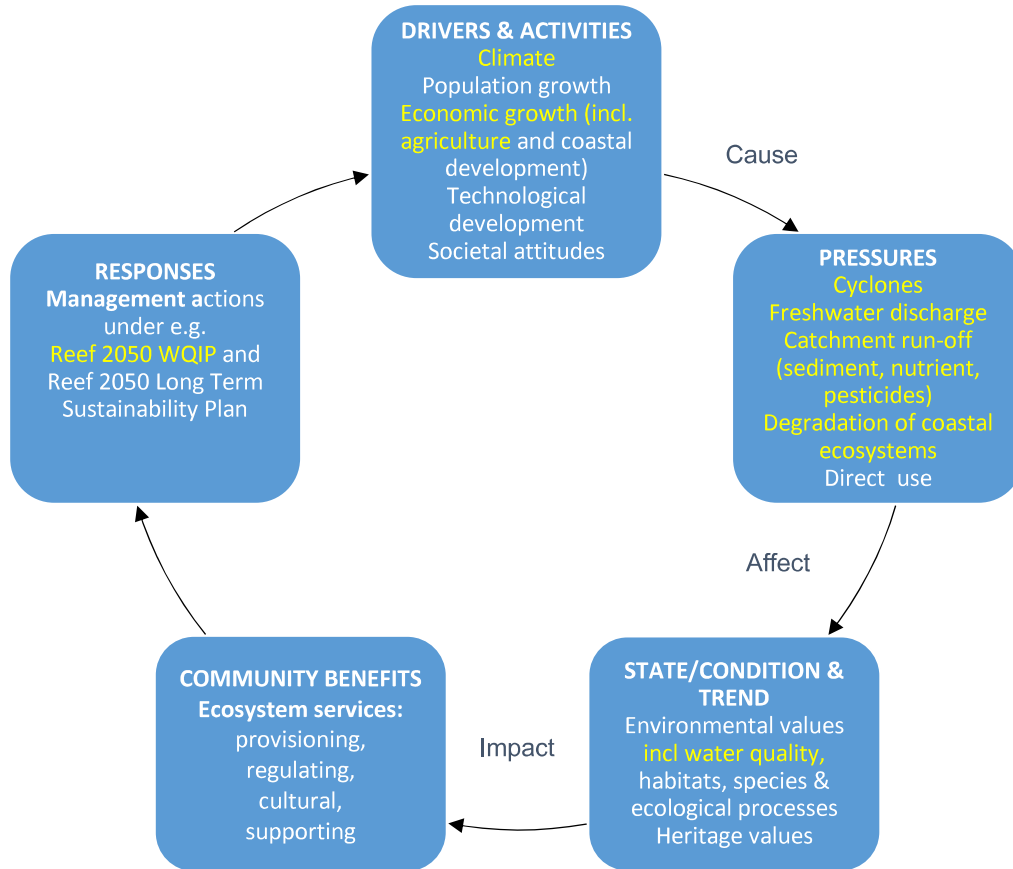


Figure 1-1: DPSIR framework used to guide the structure of the MMP derived from the Great Barrier Reef Strategic Assessment (Great Barrier Reef Marine Park Authority, 2014). The aspects highlighted in yellow are included in this report.

2 Methods

This Section provides an overview of the sampling design and indicators that are monitored as part of the MMP. More details are presented in Appendix A, B and C, and in a separate quality assurance/quality control (QA/QC) report published annually (Great Barrier Reef Marine Park Authority, 2021).

2.1 Sampling design

The MMP inshore water quality monitoring program is designed to measure the annual condition and long-term trends in coastal water quality. Tropical waters are characterised by high seasonal variability in river discharge, as rainfall from low pressure systems causes river flood plumes to extend into the coastal ocean, while river discharge becomes negligible during low rainfall periods. Water quality monitoring by the MMP is thus conducted during both ambient conditions and discharge events.

Ambient monitoring refers to routine sampling during the wet and dry seasons outside of major flood events. It has been conducted since 2005 under the MMP, although the program design (site location, site number, monitoring frequency) has changed over time.

Event-based monitoring occurs in response to major flood events to capture conditions within flood plumes; event-based monitoring occurs at the ambient site locations, plus additional sites, and the monitoring frequency depends on the number of flood events each year.

The program currently covers four NRM regions including Cape York, the Wet Tropics, Burdekin and Mackay-Whitsunday, chosen based on previous water quality risk assessments (Brodie *et al.*, 2013). Monitoring site locations were selected along expected water quality gradients related to exposure to land-based runoff. This was largely determined by increasing distance from a river mouth in a northerly direction to reflect the predominantly northward flow of surface water driven by the prevailing south-easterly winds (Brinkman *et al.*, 2011).

From 2005 to 2014, monitoring occurred ~3 times per year at 3 sites in the regions listed above and additionally in the Fitzroy region (discontinued in 2015). An independent statistical review of the MMP in 2014 (Kuhnert *et al.*, 2015) showed that additional sites and higher sampling frequency would provide additional statistical power. The current program design was implemented in February 2015 and includes most of the sampling sites in the pre-2015 design, allowing for the continuation of the long-term time-series, and inclusion of additional sites.

The program currently includes nine focus areas, each with 5 to 6 sites measured routinely: Pascoe, Normanby-Kennedy, Annan-Endeavour and Stewart Rivers (in the Cape York NRM, all added in 2017); Barron-Daintree, Russell Mulgrave and Tully Rivers (in the Wet Tropics NRM); Burdekin and Mackay-Whitsunday. The frequency of ambient water quality monitoring was increased in 2015, and sites are now visited 3–10 times annually, depending on the focus region.

This report also presents results from water quality monitoring along the Cairns Transect in the Barron-Daintree focus region of the Wet Tropics. AIMS has been monitoring the 6 Cairns Transect sites 3 times annually since 1989, making this dataset one of the world's longest tropical water quality datasets. In 2005, monitoring at the Cairns Transect sites became part of the MMP.

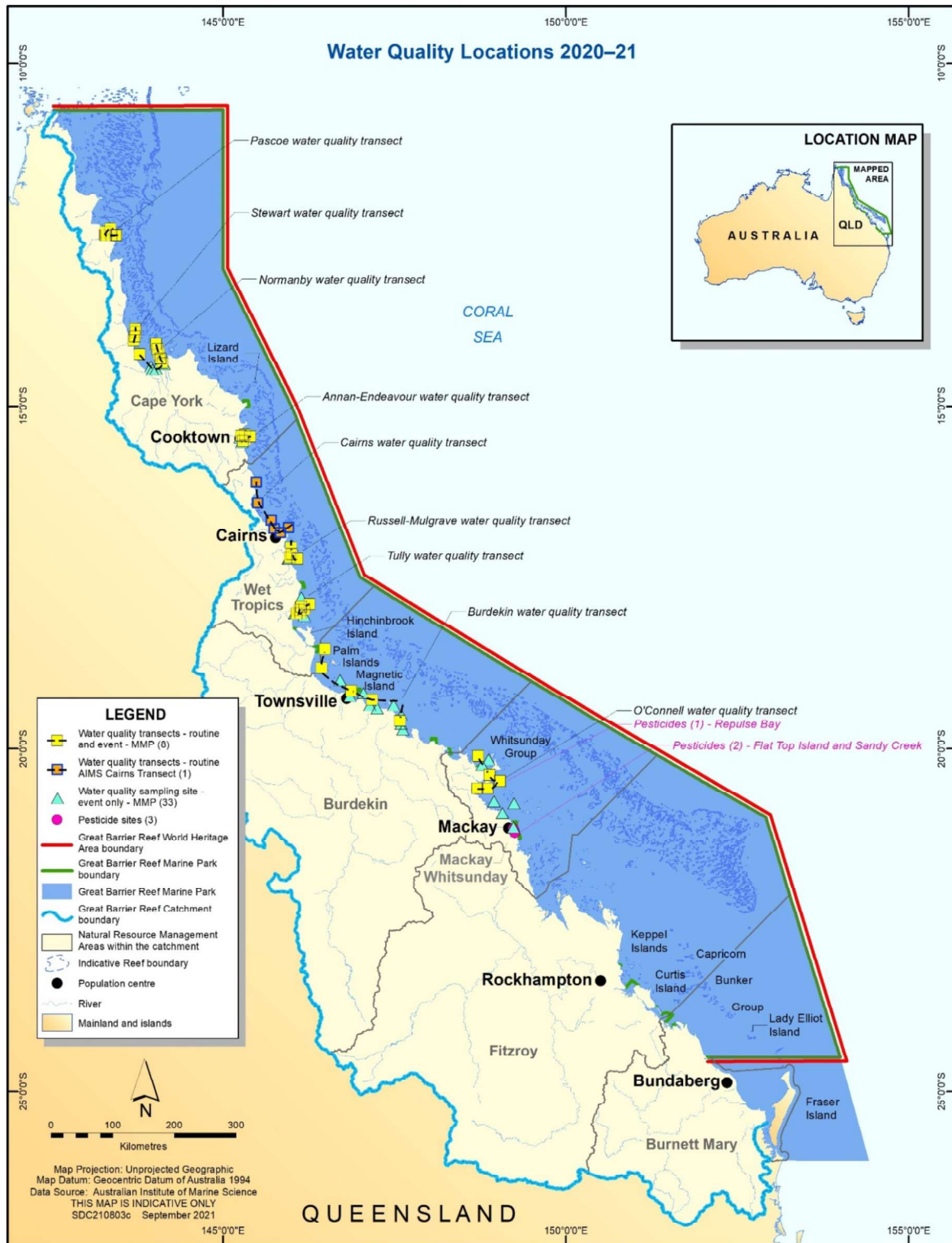


Figure 2-1: Sampling locations of the water quality monitoring sampled from 2015 onwards. Note that the Cape York transects were added in 2017.

The list of parameters sampled in the MMP is provided in Table 2-1 and includes:

- continuous measurement of salinity and temperature at seven sites
- continuous measurement of chlorophyll and turbidity at 16 sites
- 49 ambient sites with more frequent sampling during the wet season
- 33 event-based sites identified for sampling during flood conditions.

Table 2-1: List of parameters measured during the ambient and event-based water quality monitoring. Note that +/- signs identifying the charge of the nutrient ions were omitted for brevity.

Condition	Parameter	Abbreviation	Units of Measure
Physico-chemical	Salinity	Salinity	
	Temperature	Temperature	Celsius degree
	Light attenuation coefficient ¹	K_D	m^{-1}
	Secchi depth	Secchi	m
	Total suspended solids	TSS	$mg L^{-1}$
	Coloured dissolved organic matter	CDOM	m^{-1}
	Turbidity	Turb	NTU
Nutrients	Ammonia	NH_3	$\mu g L^{-1}$
	Nitrite ²	NO_2	$\mu g L^{-1}$
	Nitrate ²	NO_3	$\mu g L^{-1}$
	Dissolved inorganic phosphorus	PO_4	$\mu g L^{-1}$
	Silica	Si	$\mu g L^{-1}$
	Particulate nitrogen	PN	$\mu g L^{-1}$
	Particulate phosphorus	PP	$\mu g L^{-1}$
	Total dissolved nitrogen	TDN	$\mu g L^{-1}$
	Total dissolved phosphorus	TDP	$\mu g L^{-1}$
	Particulate organic carbon	POC	$\mu g L^{-1}$
	Dissolved organic carbon	DOC	$\mu g L^{-1}$
Biological	Chlorophyll <i>a</i>	Chl- <i>a</i>	$\mu g L^{-1}$

¹ Derived from vertical profiles of photosynthetically active radiation and not sampled at all sites
² NO_x is the sum of NO_2 and NO_3

2.2 Water quality sampling

At each of the sampling locations (Figure 2-1, Appendix A), vertical profiles of water salinity and temperature were measured with a Conductivity Temperature Depth (CTD) profiler (Sea-Bird Electronics SBE19plus). CTD profiles are used to characterise the water column and to identify its state of vertical mixing. Some CTD profiles included measurements of photosynthetically active radiation (PAR), which were used to derive the light attenuation coefficient (K_D). See the QA/QC report for a detailed description of CTD data processing (Great Barrier Reef Marine Park Authority, 2021).

Immediately following the CTD cast, discrete water samples were collected with Niskin bottles. Samples collected at ambient sites were from the surface (~0.5 m below water surface) and bottom (~1 m above the seabed) of the water column, whereas for some event-based sampling only surface water samples were collected. Samples from the Niskin bottles were taken in duplicate and were analysed for a broad suite of water quality parameters (Table 2-1). Detailed descriptions of analytical chemistry techniques can be found in the QA/QC report (Great Barrier Reef Marine Park Authority,

2021). Values of water quality variables presented in this report are depth-weighted means calculated using surface and bottom samples.

Below is a brief description of each of the main water quality variables measured as part of the MMP. These definitions are not all-encompassing but are meant to provide a short description of what aspects of water quality they measure and what processes influence the variables:

- **Total Suspended Solids (TSS)** is a measure of the suspended particulate material in the water column. These solids include suspended sediments (sand, silt, and clay), living plankton, and detrital (non-living organic) material. TSS concentrations are affected by oceanographic processes including primary production and resuspension, as well as inputs from other sources such as dredging and land-based run-off.
- **Secchi depth** is a visual measure of water clarity and proxy for light penetration, which is measured using a high-contrast black and white patterned disc called a Secchi disc. The Secchi depth is the average of the vertical disappearance and reappearance depths of the disc, where clarity increases with increasing Secchi depth. Secchi depth is a simple method that has been used for over 150 years, so is excellent for assessing long-term change and for cross-system comparisons.
- **Turbidity** is a measure of light scattering caused by fine suspended particles, such as sediment, detritus, and plankton. Turbidity is affected by a wide range of factors including oceanographic processes such as resuspension of bottom sediments by wind, waves and currents, river discharge, and anthropogenic factors such as dredging.
- **Chlorophyll a (Chl-a)** concentration is a measure of phytoplankton biomass in a water body. Phytoplankton grow quickly in response to nutrient availability, so elevated values of Chl-a can indicate increased nutrient loading.
- **Dissolved inorganic nutrients (NH₃, NO_x, PO₄ and Si)** measure the amount of readily available nutrients for plankton growth in water samples. Inorganic nitrogen (NH₃, NO_x) and phosphate (PO₄) represent around 1% of the nutrient pools in the Reef. The inorganic nutrient pools are affected by a complex range of biogeochemical processes including both natural (for example, plankton uptake, upwelling, nitrogen fixation, and remineralisation) and anthropogenic (for example, dredging and nutrient inputs from changed land use) processes.
- **Particulate nutrients (POC, PN and PP)** are a measure of the suspended material retained on a filter with a pore size of approximately 0.7 µm. This material consists of a minor fraction of living biomass (for example, bacteria, phytoplankton) and a major fraction of detritus (for example, dead cells, faecal pellets). Particulate nutrient concentrations are affected by oceanographic processes (primary production, bacterial production, resuspension, and remineralisation) as well as sources such as dredging and land-based run-off.
- **Dissolved organic carbon (DOC)** is a measure of organic carbon concentrations passing through a filter with a pore size of 0.45 µm. DOC has a complex chemical composition and is used by bacteria as a source of energy. The DOC pool is affected by a range of production and degradation pathways. The sources include primary production by phytoplankton, zooplankton grazing, resuspension events, river runoff, and abiotic breakdown of POC. DOC can be degraded by sunlight.
- **Pesticides** the suite of chemicals monitored included 13 photosystem II (PSII) inhibiting herbicides (such as diuron, atrazine (and its metabolites), ametryn, hexazinone, tebuthiuron), which all affect photosynthesis, and are commonly detected due to their high usage in adjacent catchments, and their high solubility. The twelve other pesticides monitored include those that have non-photosynthetic effects (such as metolachlor), non-

selective or ‘knockdown’ herbicides (such as 2,4-D) and insecticides (such as imidacloprid) (Thai *et al.*, 2020).

Pesticides at fixed monitoring sites are sampled using Empore Disk™ (ED) passive samplers deployed for approximately one month in the wet season (Thai *et al.*, 2020; Great Barrier Reef Marine Park Authority, 2022). Polydimethylsiloxane (PDMS) passive samples (used previously to detect the relatively more hydrophobic pesticides propiconazole, pendimethalin, chlorpyrifos and trifluralin) were not deployed in the 2020–21 wet season. Passive samplers were deployed at three fixed monitoring sites located in the Mackay-Whitsunday region at Repulse Bay, Flat Top Island and Sandy Creek (Appendix C-7 Table C-9). Following retrieval, samplers were analysed for pesticides as described previously (Thai *et al.*, 2020), and a flow-weighted average of pesticide concentration over the period of deployment was derived.

Time-averaged estimates of pesticide concentration data were evaluated in two ways (Great Barrier Reef Marine Park Authority, 2022):

- Individual estimates of concentration were checked against relevant water quality guidelines and exceedances noted (ANZG, 2018)
- Measured concentrations in a given sample were assessed against a pesticide exposure risk metric which predicts the percentage of species that may be affected by mixtures of pesticides detected. The risk metric used was the multi-substance potentially affected fraction (ms-PAF method) (Traas *et al.*, 2002) and the calculations were performed by the Queensland Department of Environment and Science, developed and used by the Catchment Loads Monitoring Program.

Similar to previous reporting periods, the presence of non-detectable pesticides or concentration measurements below the Limit of Reporting (LOR) were treated by replacing LOR values with zeros.

2.3 *In situ* loggers

Continuous *in situ* Chl-*a* fluorescence and turbidity were measured using WET Labs ECO FLNTUSB Combination Fluorometer and Turbidity Sensors located at 16 sites (Appendix A), which were deployed 3 m (Cape York region) or 5 m (all other regions) below the surface, and sampled at 10 min intervals. Water samples for analyses of Chl-*a* and TSS were collected three times per year to calibrate logger fluorescence and turbidity to *in situ* conditions. Diver-operated Niskin bottles were used to sample close to the moored loggers. Samples were preserved and analysed in the same manner as ship-based water samples.

Daily averages of the chlorophyll and turbidity collected by the ECO FLNTUSB instruments are presented as time-series graphs in Appendix C Figure C-1. Annual means and medians of turbidity were also calculated for each site based on the ‘water year’ (1 October to 30 September) and compared with the guideline value (GV) (Appendix C Table C-3).

Salinity and temperature loggers (Sea-Bird Electronics SBE37) were deployed at seven locations, with four of these being placed on fixed moorings near the O’Connell, Russell-Mulgrave, Tully and Burdekin River mouths (Figure 2-1; Appendix A). See the QA/QC report (Great Barrier Reef Marine Park Authority, 2021) for detailed descriptions of logger pre- and post-deployment procedures. Site-specific time-series from these loggers can be found in Appendix C Figure C-2.

2.4 Data analyses – Summary statistics and trends

Concentrations of water quality parameters at each sampling occasion were calculated as depth-weighted means by trapezoidal integration of the data from all sampling depths. At most sites, only two vertical points are sampled (i.e., surface and bottom samples), and this method averages these

values to derive the depth-weighted mean. Measurements falling below the analytical detection limit were represented as half the detection limit. Summary statistics for all water quality variables are presented for all monitoring sites in Appendix C. Concentrations were compared to site-specific GVs (Appendix C Table C-9), which are defined for Chl-a, PN, PP, TSS, Secchi depth, NO_x, and PO₄. Concentrations of water quality parameters are presented along the sampling transects for each focus region with distance from river mouths. Trends in water quality are represented with generalised additive models, fitted with a maximum of five knots and modelled with a gamma-distributed response and log-link function.

Temporal trends in key water quality variables (Chl-a, TSS, Secchi depth, turbidity, NO_x, PN, PP, DOC, and POC) since 2005 are reported for all focus regions except Cape York. Only open coastal and mid-shelf sites are used for these analyses because GVs for enclosed coastal waters are derived differently and are not available for all variables, creating statistical imbalance.

Generalised additive mixed effects models (GAMMs) were used to decompose each irregularly spaced time-series into its trend cycles (long-term) and periodic (seasonal) components (Wood, 2006). GAMMs are an extension of additive models that allow flexible modelling of non-linear relationships by incorporating penalised regression spline types of smoothing functions into the estimation process. The degree of smoothing of each smooth term (and by extension, the estimated degrees of freedom of each smoother) is treated as a random effect and thus estimable via its variance as with other effects in a mixed modelling structure (Wood, 2006).

For each water quality variable within each focus region, the variable was modelled against a thin-plate smoother for date and a cyclical cubic regression spline (maximum of 5 knots) over months within the year. Spatial and temporal autocorrelation in the residuals was addressed by including sampling locations as a random effect and imposing a first-order continuous-time auto-regressive correlation structure (Pinheiro and Bates, 2000). All GAMMs were fitted using the *mgcv* (Wood 2006, 2011) package in R 3.6.1 (R Core Team, 2019).

In order to provide a more quantitative assessment of trend, linear change in values of GAMMs was measured from the present sampling year to five years prior (a five-year period). This period was chosen as it incorporates the MMP re-design, which began in 2015, and using earlier data would unbalance this analysis as the amount of sampling greatly changed in 2015. As GAMMs are detrended to remove the effects of seasons, tides, and wind, this analysis aims to quantify trends occurring outside of these cycles.

Trend analysis results are presented for each focus region in Section 5.

2.5 Data analyses – Water Quality Index

The Water Quality Index (WQ Index) is an interpretation tool developed by AIMS to visualise trends in the suite of water quality variables measured, and to compare monitored water quality to existing Water Quality Guidelines (Department of Environment and Resource Management, 2009; Great Barrier Reef Marine Park Authority, 2010). The WQ Index uses a set of five key indicators:

- Water clarity (TSS concentrations, Secchi depth, and turbidity measurements by FLNTUSB instruments, where available)
- Chl-a concentrations
- PN concentrations
- PP concentrations
- NO_x concentrations.

These five indicators are a subset of the comprehensive suite of water quality variables measured in the MMP inshore water quality program. They have been selected because GVs are available for these measures and they can be considered as relatively robust indicators that integrate a number of bio-physical processes in the coastal ocean.

For each monitoring site, these indicators are compared to GVs, scored based on performance relative to guidelines, and averaged to give an overall site-specific score. Sites are then averaged over a region or focus region to give a regional score (see Appendix B for details of Index calculation). Results are presented in Section 5.

The WQ Index is calculated using two different methods due to the objectives of the program needing to report both the long-term trend in water quality condition, and the annual condition to which that ecosystems are exposed. Both affect the response of those ecosystems but in different ways. Changes in the MMP design that occurred in 2015 also needed to be accommodated. The changes in design included increased number of sites, increased sampling frequency and a higher sampling frequency during December to April to better represent wet season variability. Thus, statistical comparisons between MMP data from 2005–15 to 2015–onwards must account for these changes. The two versions of the WQ Index have different purposes:

- 1. Long-term trend:** This version is based on the pre-2015 MMP sampling design and uses only the original sites (open coastal water body) and three sampling dates per year. This sampling design had low temporal and spatial resolution and was aimed at detecting long-term trends in inshore water quality. Key aspects of this version are:
 - annual water quality GVs are used for scoring monitoring data (Appendix B Table B-1)
 - only AIMS monitoring data are used
 - a four-year running mean is applied to data to reduce the effect of sampling time on the Index
 - the Index is an average of scores for five indicators (water clarity, Chl-*a*, NO_x, PN, and PP weighted equally).
- 2. Annual condition:** This version is based on the post-2015 MMP sampling design and uses all sites (except enclosed coastal sites) and sampling dates per year. Key aspects of this version are:
 - seasonal site-specific water quality GVs are used for scoring monitoring data (i.e., wet season data are compared to a wet season GV and dry season data are compared to a dry season GV) (Appendix C Table C-9)
 - both AIMS and JCU monitoring data are used
 - a running mean is not applied
 - the Index is a hierarchical combination of scores for five indicators [water clarity, productivity (combined score of Chl-*a* and NO_x), and particulate nutrients (combined score of PN and PP) are weighted equally].

A water quality Index (Annual condition version) was produced for Cape York focus regions for the first time in 2020–21. The methods for this are the same as those detailed above, although results are not presented in a time-series format like other regions. Details of Index calculation are in Appendix B.

2.6 Data analyses – Remote sensing monitoring products

2.6.1 Mapping Reef water types

Trends in Reef marine water composition during the wet season have been successfully monitored over the last decade using a combination of Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite imagery and the water quality variables measured. Using a “wet season” colour scale specifically developed for the Reef (Alvarez-Romero *et al.*, 2013), MODIS satellite pixels are reclassified into six colour classes, then three distinct water types: the primary (corresponding to colour classes 1 to 4), secondary (colour class 5) and tertiary (colour class 6) wet season water types (Figure 2-2a and Table 2-2).

These water types represent typical colour and water quality gradients encountered in the Reef during the wet season (December to April), including river plumes. Catchment run-off in sediment-laden river discharge appears in satellite images as brownish flood plumes, while productive waters

appear with a greenish colour, and ambient (clear) marine waters are a bluish colour. Brownish-green waters also appear when sediments are re-suspended by wind or tide, and it is impossible to fully separate the direct influence of riverine plume from wind- and wave-driven sediment resuspension (some of which may have been originally derived from the Reef rivers discharge) in optical satellite images. Therefore, the term “wet season waters” refers to flood river plumes, associated resuspension and marine processes occurring in the Reef during the wet season.

Several monitoring products are then derived each wet season from the satellite water type maps to report on water quality trends. They focus on the wet season period (December to April) and aim to:

- map Reef optical water types (hereafter water types) and water quality gradients during the wet season and assess the extent of river flood plumes during high flow conditions
- characterise the composition of the Reef wet season water types (mean long-term TSS, Chl-a, CDOM, DIN, DIP, PP and PN concentrations and SDD values) and identify where mean long-term concentrations of TSS, Chl-a, PP, and PN are likely to be above wet season GVs. Wet season GVs for the whole of the Reef (hereafter Reef-wide GVs) are derived from De'ath and Fabricius (2008) (Appendix B Table B-3)
- assess the exposure of coral reefs and seagrass ecosystems to potential risk from land-sourced pollutants.

These products are used to illustrate wet season conditions for every wet season and to compare seasonal trends with baseline reference trends in water composition (long-term, typical wet year and dry year conditions, over a documented recovery period for coral reefs).

However, MODIS sensors are ageing (MODIS-Aqua was launched in 2002) and the quality of the MODIS imagery is declining. The use of Sentinel-3 Ocean Land Colour Instrument (OLCI) satellite imagery and another colour scale (the Forel-Ule (FU) colour scale) was proposed for the continuous mapping of Reef waters (Petus *et al.*, 2019). The FU colour scale is an historical colour scale standard to determine the colour and classifies worldwide bodies of water (Novoa *et al.*, 2013). It is composed of 22 colours; going from indigo blue to ‘cola’ brown, and is applicable for all natural waters (inland, estuarine, inshore and offshore) and all environmental conditions, including wet and dry season conditions (Wernand *et al.*, 2012, 2013; Van der Woerd *et al.*, 2016; Van der Woerd and Wernand, 2018). The FU satellite algorithm converts satellite normalised multi-band reflectance information into a discrete set of FU numbers using uniform colourimetric functions (Van der Woerd *et al.*, 2016, Van der Woerd and Wernand, 2018). The derivation of the colour of natural waters is based on the calculation of Tristimulus values of the three primaries (X, Y, Z) that specify the colour stimulus of the human eye. The algorithm is validated by a set of hyperspectral measurements from inland, coastal and marine waters (Van der Woerd *et al.*, 2016, Van de Wored and Wernand, 2018). Technical details about the FU scale algorithm are synthesised through the European citclops (URL: <http://www.citclops.eu/>) and Eye on Water project webpages (<https://www.eyeonwater.org/>). The methods are described in further detail in Appendix B. MODIS-Aqua WS and Sentinel-3 FU colour class maps showed very similar patterns over the 2017–18 wet season in a case study focusing on Wet Tropics and Burdekin regions of the Reef (Petus *et al.*, 2019 and Figure 2-2b and Table 2-2). Further comparisons are presented in Appendix E.

For this report, Sentinel-3 images of the Reef and the FU colour scale were used to produce water type maps instead of the MODIS imagery. Equivalent FU water types were defined by grouping the FU colour classes 1–3 (equivalent to marine waters in the wet season scale), FU colour classes 4–5 (equivalent to Tertiary water type), FU colour classes 6–9 (equivalent to the Secondary water type) and $FU \geq 10$ (equivalent to the primary water type), as defined in Petus *et al.* (2019) (Table 2-2) (see following Sections and Appendix B for description of the wet season water types and colour classes).

Available satellite data are biased toward clear, non-cloudy days, and may underrepresent water quality conditions in regions of higher rainfall and cloudiness like the Wet Tropics and Cape York. Reef wet season water types are characterised by different colour and concentrations of optically active components (e.g., TSS, CDOM, and Chl-a, see section below), which influence light attenuation (Petus *et al.*, 2018), as well as different pollutant concentrations (Devlin *et al.*, 2015; Petus *et al.*, 2019). These characteristics vary the impact on the underlying ecological systems.

2.6.2 Characterising composition of Reef water types

To assess the water quality characteristics of each water type, the colour class category and water type corresponding to the location and week of acquisition of each water quality sample were extracted (see method in Appendix B). This allows the water quality parameters measured during this wet season (2020–21) and previous wet seasons (2002–03 to 2019–20) to be associated with a wet season water type (and colour class) category, i.e., to primary (colour classes 1 to 4), Secondary (colour class 5) or Tertiary (colour class 6) water types. The transport and transformation of water quality parameters as well as the pollutant concentrations relative to the Reef-wide wet season GVs derived from De'ath and Fabricius (2008) (Appendix B Table B-3) were investigated by plotting mean long-term and boxplots of water quality concentration and Secchi disk depth against their water type and colour class categories.

To minimise data loss due to the dense cloud cover in the Reef, match ups between field water quality data and MODIS colour class/water type categories were made using the weekly wet season water type composites (see Section 2.6.3). The long-term water quality concentrations were calculated using all surface data (<0.2 m) collected between December and April by JCU (since 2004), and since the 2016–17 reporting, included the AIMS and the CYWMP data. The mean TSS, Chl-*a*, PP and PN concentrations were assessed against wet season GVs as a relative measure to assign potential risk grading for each water type (see Section 2.6.3 Exposure maps).

Long-term water quality values are now reviewed and updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure that the water type characterisation remains appropriate, and to improve its accuracy as more field data are collected every wet seasons. The last update was in 2019 (Gruber *et al.*, 2020), using field data collected from 2003–04 to 2018–19. Wet season water type (and colour class) categories for all these sites and sampling weeks were extracted from the archive of weekly wet season water type composite (2002–03 to 2018–19). Long-term mean DIN, PP and PN concentrations were calculated as $DIN = \text{nitrite} + \text{nitrate} + \text{ammonia}$, $PP = \text{Total Phosphorus} - \text{Total Dissolved Phosphorus}$ and $PN = \text{Total Nitrogen} - \text{DIN}$, respectively. Note that PN/PP definitions changed in 2018–19 to be direct measurements as defined in the QA/QC report.

2.6.3 Wet season water type, frequency and exposure maps

Several summary maps were produced including weekly panel maps of environmental and marine wet season conditions, frequency maps of occurrence of wet season water types and exposure maps. The area (km²) and percentage (%) of coral reefs and seagrass meadows affected by different relative categories of exposure (or potential risk) was tabled. Details are in Appendix B.

Wet season water type maps were produced using daily Sentinel-3 OLCI Level 2 (hereafter, Sentinel-3 or S3) imagery reclassified to 21 distinct colour classes defined by their colour properties and using the FU colour classification scale. Sentinel-3 imagery of the study area was downloaded on the EUMETSAT Data centre (URL: <https://www.eumetsat.int/eumetsat-data-centre>). Sentinel-3 are atmospherically corrected and were processed with the FU Satellite Toolbox implemented in the Sentinel Application Platform (SNAP, URL: <https://step.esa.int/main/toolboxes/snap/>) and using automated tools (python scripts and ArcGIS toolboxes) developed through MMP funding.

Weekly wet season water type composites were created to minimise the image area contaminated by dense cloud cover and intense sun glint (Álvarez-Romero *et al.*, 2013). The maximum FU value of each pixel/week was used to keep the colour class with the highest turbidity level for each wet season week. The weekly composite maps were cleaned to remove single or small clusters of cells sometimes misclassified by the FU satellite algorithm in the offshore regions of the Reef (including, for example, around coral reefs due to bottom interference and residual glint contamination). The method involved sequentially infilling contiguous areas one FU class at a time from FU1 through to FU21 then replacing nearshore pixels in FU classes ≥ 10 with the original pixels using Python 2.7.3 (Python Software Foundation, 2012) and ArcGIS 10.2 (ESRI, 2013). In order to produce weekly primary, secondary and tertiary-equivalent maps, marine waters were clustered by

grouping the FU colour classes 1–3 (FU 1-3), tertiary waters as FU4-5, secondary waters as FU6-9 and primary waters as FU≥10.

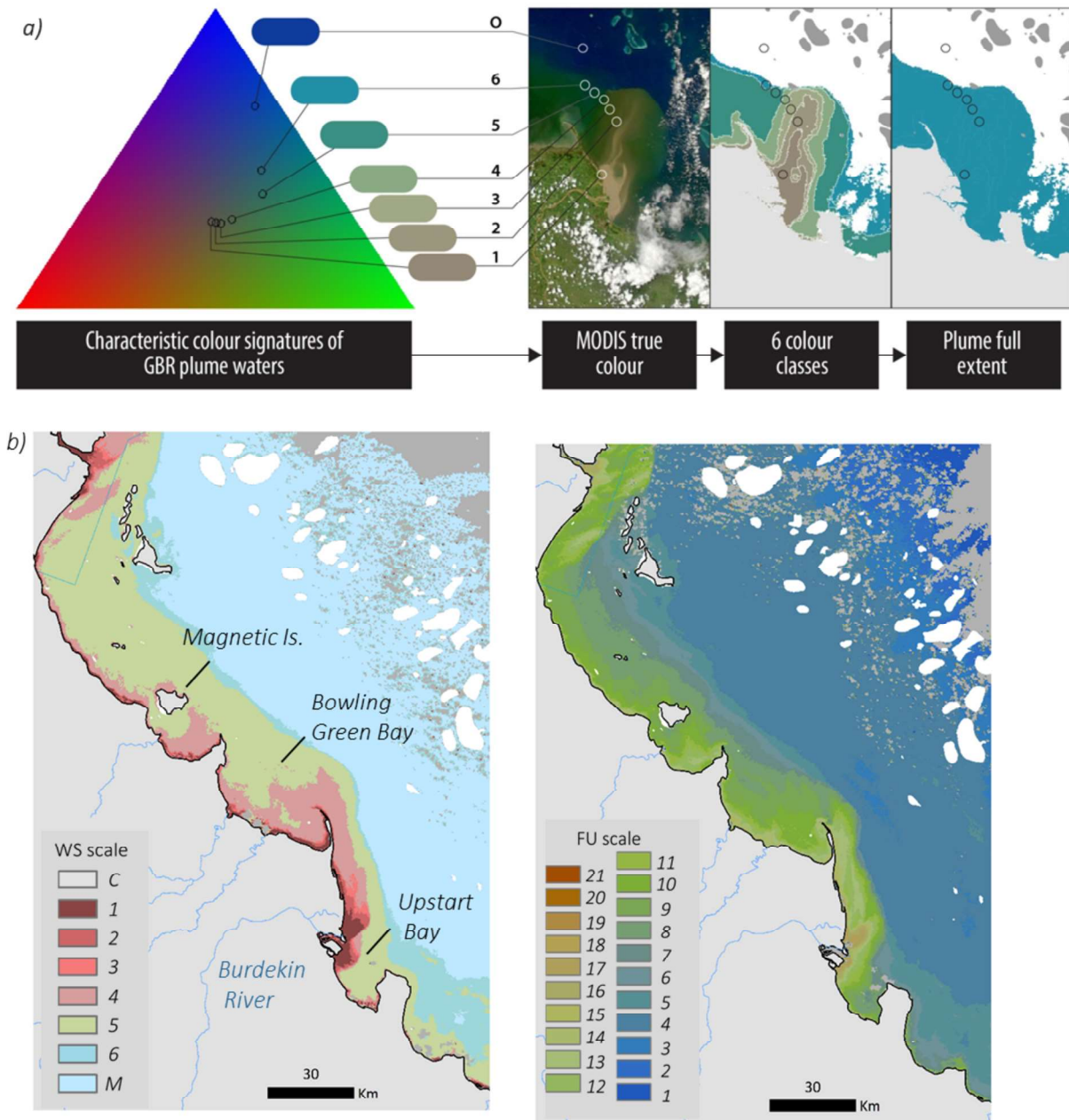


Figure 2-2: a) Triangular colour plot showing the characteristic colour signatures of the wet season water types in the Red-Green-Blue (RGB or true colour) space b) Illustration of the very similar colour patterns between the (left) MODIS wet season and (right) Sentinel-3 Forel-Ule colour class maps: Burdekin River plume, 14 March 2018. Álvarez-Romero *et al.* (2013) developed a method to map these characteristic coastal water masses in the Reef using a supervised classification of MODIS true colour data (modified from Devlin *et al.*, 2015).

Table 2-2: Description of the MODIS wet season water types and groupings of colour classes and comparison with the Sentinel-3 Forel-Ule equivalent water types and grouping of water types (modified from Petus *et al.*, 2019).

MODIS-Aqua wet season water types			Sentinel-3 Forel Ule wet season water types		
Water types	Colour classes	Description	Water types	Colour classes	Description
Primary	1-4	<i>Brownish to brownish-green turbid waters typical of inshore regions of the Reef that receive land-based discharge and have high concentrations of resuspended sediments during the wet season.</i> <i>These water bodies in flood waters typically contain high nutrient and phytoplankton concentrations but are also enriched in sediment and dissolved organic matter resulting in reduced light levels</i>	Primary-equivalent	FU ≥ 10	<i>Waters with high phytoplankton levels and increasing sediment and dissolved organic matter</i>
Secondary	5	<i>Greenish to greenish-blue turbid water typical of coastal waters rich in algae (Chl-a) and containing dissolved organic matter and fine sediment. This water body is found in open coastal waters of the Reef as well as in the mid-water plumes where relatively high nutrient availability and increased light levels due to sedimentation favour coastal productivity (Bainbridge <i>et al.</i>, 2012).</i>	Secondary-equivalent	FU 6-9	<i>Waters with colour still dominated by algae, but increased dissolved organic matter and some sediment may be present</i>
Tertiary	6	<i>Greenish-blue waters correspond to waters with slightly above ambient suspended sediment concentrations. Tertiary waters are typical of areas towards the open sea. This water type includes offshore regions of river flood plumes, fine sediment resuspension around reefs and islands and marine processes such as upwelling. Tertiary waters are associated with low land-sourced contaminant concentrations and the ecological relevance of these conditions is likely to be minimal although not well researched. The Tertiary areas have a low magnitude score in the Reef exposure assessment.</i>	Tertiary-equivalent	FU 4-5	<i>Waters with high light penetration</i>
Marine	No number	<i>Ambient waters with high light penetration</i>	Marine-equivalent	FU 1-3	<i>Waters with high light penetration</i>

Frequency maps were produced to predict the areas affected by the three wet season water types (primary, secondary and tertiary water types) individually (i.e., of the brownish, greenish and greenish-blue waters, respectively) and the primary and secondary water types combined (previously a combination of all water types, this has been modified to recognise that the ecological relevance of the water quality concentrations in the tertiary water type is not well understood but expected to be relatively minor)..

Average frequency maps were produced for several periods intending to represent the most relevant reference periods for comparison of the results for the current year:

- (i) for this reporting wet season (2020–21),
- (ii) over the long-term (2002–03 to 2017–18: 16 wet seasons), and
- (iii) over a documented recovery period for coral reefs (2012–2017; Thompson *et al.*, 2019) intended to represent a favourable exposure scenario.

Composite frequency maps were also produced to represent typical wet year and dry year conditions, taking into account the wettest and driest years for each NRM region. This is explained further in Appendix B. Except for the ‘coral recovery period’, reference maps (long-term, Wet and Dry frequency maps) are now updated or reviewed every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure they remain appropriate and to improve their accuracy as more satellite data are available. The last update was in the 2018–19 reporting (Gruber *et al.*, 2020).

The presence and spatial extent of each wet season water type is the result of the complex physico-chemical transformations occurring within river plumes, but also of resuspension, transport and other hydrodynamic processes. As a result, the extent of the Secondary and Tertiary water type frequencies is rarely attributed to an individual river and is usually merged into one heterogeneous area.

Exposure maps were produced for the whole of the Reef, for all focus regions and over the same timeframes as those reported for the frequency maps (above). The maps were produced using an exposure assessment framework developed through a collaborative effort between the MMP monitoring providers (JCU water quality and seagrass teams and the AIMS coral monitoring team) and modified from Petus *et al.* (2016). These are also updated or reviewed every 4 years (and/or in the case of extremely wet year or specific event patterns) with the last update in the 2018–19 reporting (Gruber *et al.*, 2020).

In this *magnitude × likelihood* framework, the ‘potential risk’ corresponds to an exposure to above Reef-wide wet season GV concentrations of land-sourced pollutants during the wet season and focuses on TSS, Chl-*a*, PP and PN concentrations. The ‘*magnitude of the exposure*’ corresponds to the mean long-term wet season concentration of pollutants (the proportional exceedance of the Reef-wide wet season GV) mapped through the primary, secondary and tertiary water types (section 2.6.2). The ‘*likelihood of the exposure*’ is estimated by calculating the frequency of occurrence of each wet season water type mapped through the frequency maps (see above). The exposure for each of the water quality parameters defined is the proportional exceedance of the GV multiplied by the likelihood of exposure in each of the wet season water types.

1. **Calculation of the exposure (magnitude) scores:** The long-term mean concentrations of water quality parameters (Reef-wide) measured across the wet season water types (Section 2.6.2) are assessed against Reef-wide wet season GVs to calculate magnitude scores for TSS, Chl-*a*, PP and PN. The GVs were calculated based on annual GVs (Great Barrier Reef Marine Park Authority, 2010) that were seasonally adjusted as described in De’ath and Fabricius (2008) (see Appendix B Table B-3). Mean long-term water quality concentrations include samples collected from the enclosed coastal zone, where high TSS, Chl-*a*, PN, and PP concentrations are likely to contribute to exceedances of the Reef-wide GVs (see Appendix B Table B-4). The only GV presently available for Secchi depth is an annual mean, and thus comparison with wet season Secchi depth data was not possible.

3. **Production of the exposure maps:** The magnitude scores were used in combination with the seasonal, long-term, coral recovery, wet-year and dry-year frequency maps (described above) to derive seasonal, long-term, coral recovery, wet-year and dry-year exposure maps, respectively. Exposure from each map produced was then grouped into potential risk categories (I to IV) based on a “Natural Break (or Jenks)” classification² (Appendix B-3). The exposure classes were defined by applying the Jenks classification to the mean long-term (2003–2018) exposure map, because this map presented the highest number of observations (16 wet seasons). Category I and areas not exposed were re-grouped into a unique category corresponding to no or very low exposure to a potential risk. Magnitude scores per se. have no ecological significance but are used in the risk framework as a relative measure to assign potential risk grading for each water type.
4. **Exposure assessment:** Exposure maps were overlaid with information on the spatial distribution of coral reefs and surveyed seagrass meadows to identify areas and percentages of these ecosystems that may experience exposure to pollutants during the wet season. The area (km²) and percentage (%) of coral reefs and seagrass meadows affected by the different categories of exposure (I to IV) was calculated in the Reef and marine NRM regions. Exposure maps are presented in the context of the long-term reference period (average of 16 wet seasons), the representative coral recovery period (2012–2017), and typical wet-year and dry-year composites. Areas and percentages of exposure are presented in the context of the long-term reference period.

The methods are described in further detail in Appendix B. The ‘potential risk’ is influenced by the available satellite data on cloud-free days, with the likelihood of exposure likely to be underestimated in higher rainfall and areas with high cloud cover like the Wet Tropics and Cape York regions.

2.7 River discharge and catchment loads

River flow is reported annually and can be derived from several sources. In many cases, river flow gauges that measure discharge (and constituent loads) are located well upstream of the river mouth and only capture a certain proportion of the catchment/basin area. Such disparities mean that river gauge data should not be directly compared across basins and NRM regions. For example, the Daintree and Barron Basins within the Wet Tropics region contain a similar area (2,100–2,200 km²); however, the Daintree River at Bairds and the Bloomfield River at China Camp gauges collectively only measure 56% of the Daintree Basin whereas the Barron River at Myola gauge captures 89% of the Barron Basin. If gauge data are used to compare discharge between these basins, the gauge on the Barron Basin is covering a much larger proportion of the area compared to the gauges on the Daintree Basin. A scaling factor is used on these data so that discharge (and constituent loads) can be directly compared across basins and NRM regions.

To account for these differences, the relevant discharge data for each basin were compiled, where available (Table 2-3; Department of Regional Development, Manufacturing and Water [DRMW], 2021). The total annual discharge for each gauge was then up scaled using the best information available including the use of the Bureau of Meteorology’s G2G model (covering basins from the Normanby to Mary: Bureau of Meteorology [BoM], 2017; Wells *et al.*, 2018). Where a flow gauge did not exist in a basin (for example, Jacky Jacky Creek, Lockhart River, Jeannie River, Proserpine River, Styx River, Shoalwater Creek and Boyne River—marked with an asterisk), the gauge from the nearest neighbouring basin was used coupled with the correction factor informed by either area (northern Cape York basins) or the BoM G2G model. The calculation of the long-term medians for each basin has been anchored to cover the 30-year period from 1986–87 to 2015–16 water years.

² Jenks is a statistical procedure, embedded in ArcGIS that analyses the distribution of values in the data and finds the most evident breaks in it (i.e., the steep or marked breaks; Jenks and Caspall 1971).

Table 2-3. The 35 basins of the Reef catchment, the gauges used to examine flow, and the corrections required to upscale flows to provide annual discharge estimates.

NRM Region	Basin	AWRC No.	Basin area (km ²)	Relevant gauges	Percentage of Basin covered by key gauges	Correction factor
Cape York	Jacky Jacky Creek	101	2,963	Jardine River at Monument*	0	1.2
	Olive Pascoe River	102	4,180	Pascoe River at Garraway Creek	31	3.0
	Lockhart River	103	2,883	Pascoe River at Garraway Creek*	0	1.9
	Stewart River	104	2,743	Stewart River at Telegraph Road	17	5.8
	Normanby River	105	24,399	Normanby River at Kalpowar Crossing (from 2005/06; previous upscale using Battle Camp gauge)	53	1.9
	Jeannie River	106	3,638	Endeavour River at Flaggy*	0	10.0
	Endeavour River	107	2,182	Endeavour River at Flaggy + Annan at Beesbike (from 1989/90 previous upscale from Endeavour at Flaggy)	27	3.7
Wet Tropics	Daintree River	108	2,107	Daintree River at Bairds + Bloomfield River at China Camp	56	1.3**
	Mossman River	109	473	Mossman River at Mossman	22	3.2**
	Barron River	110	2,188	Barron River at Myola	89	1.2**
	Mulgrave-Russell River	111	1,983	Mulgrave River at Peets Bridge + Russell River at Bucklands	42	1.4**
	Johnstone River	112	2,325	South Johnstone River at Upstream Central Mill + North Johnstone at Tung Oil	57	1.5**
	Tully River	113	1,683	Tully River at Euramo	86	1.1**
	Murray River	114	1,107	Murray River at Upper Murray	14	2.2**
Burdekin	Herbert River	116	9,844	Herbert River at Ingham	87	1.1
	Black River	117	1,057	Black River at Bruce Highway + Bluewater Creek at Bluewater	32	2.2**
	Ross River	118	1,707	Ross River at Aplins Weir + Alligator Creek at Allendale (from 2001–02 previous upscale from Alligator and Bohle)	52	1.9
	Haughton River	119	4,051	Haughton River at Powerline + Barratta at Northcote	62	1.2**
	Burdekin River	120	130,120	Burdekin River at Clare	100	1.0
Mackay-Whitsunday	Don River	121	3,736	Don River at Reeves + Elliot River at Guthalungra + Euri Creek at Koonandah (from 1998/99 previous Don + Elliot)	46	2.2
	Proserpine River	122	2,494	O'Connell River at Staffords Crossing*	0	2.5**
	O'Connell River	124	2,387	O'Connell River at Staffords Crossing + Andromache River at Jochheims + St Helens Creek at Calen	29	1.7**
	Pioneer River	125	1,572	Pioneer River at Dumbleton Weir T/W	95	1.1
Fitzroy	Plane Creek	126	2,539	Sandy Creek at Homebush + Carmila Creek at Carmila	16	1.8**
	Styx River	127	3,013	Waterpark Creek at Byfield*	0	2.4**
	Shoalwater Creek	128	3,601	Waterpark Creek at Byfield*	0	2.0**
	Water Park Creek	129	1,836	Waterpark Creek at Byfield	12	1.5**
	Fitzroy River	130	142,552	Fitzroy River at The Gap	95	1.0

NRM Region	Basin	AWRC No.	Basin area (km ²)	Relevant gauges	Percentage of Basin covered by key gauges	Correction factor
Burnett-Mary	Calliope River	132	2,241	Calliope River at Castlehope	57	1.7
	Boyne River	133	2,496	Calliope River at Castlehope*	0	0.43
	Baffle Creek	134	4,085	Baffle Creek at Mimdale	34	1.7**
	Kolan River	135	2,901	Kolan River at Springfield + Gin Gin Creek at Brushy Creek	37	1.3**
	Burnett River	136	33,207	Burnett River at Figtree Creek	92	1.1
	Burrum River	137	3,362	Gregory River at Leasons + Elliott River at Dr Mays Crossing + Isis River at Bruce Highway	40	2.5
	Mary River	138	9,466	Mary River at Home Park	72	1.2**

*Gauges used which are not in the basin area

**informed using the BoM G2G model

Current annual and pre-development TSS, DIN and PN load estimates were calculated for all basins using a systematic approach. The DIN loads for the basins of the Wet Tropics and Haughton Basin were calculated using the model originally developed in Lewis *et al.* (2014), which uses a combination of the annual nitrogen fertiliser applied in each basin coupled with basin discharge (calculated as per previous description). DIN loads for the Burdekin, Pioneer and Fitzroy basins were taken from those reported in the Great Barrier Reef Catchment Loads Monitoring Program. If the measured data for the most recent years in these basins were unavailable, a mean of the long-term annual mean concentration from the previous monitoring data was coupled with the discharge to calculate a load. DIN loads for the remaining basins were calculated using an annual mean concentration which was multiplied by the corresponding basin discharge calculations. The annual mean concentration for each basin was informed using a combination of available monitoring data and Source Catchments model outputs. The pre-development DIN loads were calculated using a combination of the estimates from the Source Catchments model as well as available monitoring data from 'pristine' locations.

The TSS and PN loads were similarly determined through a step-wise process. For the basins where the Great Barrier Reef Catchment Loads Monitoring Program captured >95% of the basin area (for example, Burdekin, Pioneer and Fitzroy) the measured/reported TSS and PN loads were used. If the measured data for the most recent years were unavailable, a mean of the long-term annual mean concentration from the previous monitoring data was coupled with the discharge to calculate a load. For other basins with monitoring data, the range of annual mean concentrations were compiled and compared with the latest Source Catchment modelling values. From these data a 'best estimate' of an annual mean concentration was produced and applied with the annual discharge data to calculate loads. Finally, for the basins that have little to no monitoring data, the annual mean concentration from the Source Catchments data was examined along with nearest neighbour monitoring data to determine a 'best estimate' concentration to produce the load. The pre-development TSS and PN loads were calculated using a combination of the annual mean concentrations from the Source Catchments model and available monitoring data from 'pristine' locations. The corresponding discharge was used as calculated previously to produce a simulation of the pre-development load for the water year.

2.8 Load mapping

Hydrodynamic models are a valuable tool for identifying, quantifying, and communicating the spatial impact of discharges from various rivers into the Reef lagoon. These models can simulate the three-dimensional transport and fate of material delivered to the marine environment. The models can also deliver benefits over traditional static observations of river plume distributions especially in relation to the scale and frequency at which they can operate. While remote sensing can track the visual extent of river plumes, it is generally difficult to quantify the contribution of individual rivers to the

overall observed spatial impact. The impact of the rivers is often confounded by a number of factors including plumes from adjacent rivers that spatially overlap and mix, and inputs of low salinity tropical water advected from the north and low surface salinity due to rainfall, which is rapidly mixed. Numerical models provide a number of solutions to this problem. During flood events, discharges of freshwater are resolved by the model's salinity solution. Passive tracers overcome the problems of using salinity alone as a tracer, as they allow the freshwater from the individual rivers to be tagged and assessed. Passive tracers act as virtual markers and are conservatively advected and diffused. Simulation of the transport of unique tracers 'released' from different rivers enables the identification of marine regions influenced by discharges from individual catchments and provides insight into the mixing and retention of river water along various regions within the Reef lagoon.

As part of the eReefs project (<http://ereefs.org.au/ereefs>), a regional implementation of a three-dimensional, baroclinic hydrodynamic model has been developed for the Reef lagoon. Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracers for each river, mixing coefficients, and sea level. The model is described in detail by Schiller *et al.* (2015). The MMP used outputs from the regional ~4 km horizontal spatial resolution model.

Hindcast simulations were performed over the period 1 October until 1 May of the following year to capture all potential river discharge that occurred during that water year. River-tagged passive tracers were modelled as being released from each of the major gauged rivers discharging into the Reef lagoon. The influence of 22 rivers was examined, including the Normanby, Russel-Mulgrave, Johnstone, Herbert, Burdekin, Fitzroy, Mary, Daintree, Barron, Tully, Houghton, Don, O'Connell, Pioneer, Burnett, Fly, Calliope, Boyne, Caboolture, Logan, Pine, and Brisbane Rivers. The discharge concentration of each river's unique tracer was set at 1.0 at the river mouth, while the starting tracer concentration in the Reef lagoon (time = 0 for each wet season) was set to 0.

In 2018–19 a revised approach was developed for estimating the dispersion of river-derived DIN, TSS and PN loads into the Reef lagoon, improving the method developed in previous reports by using the eReefs marine models (Margvelashvili *et al.*, 2018; Skerratt *et al.*, 2019; Steven *et al.*, 2019) to estimate river dispersion (Gruber *et al.*, 2020).

Cumulative exposure index

A cumulative exposure index was defined that integrates the tracer concentration above a defined threshold. It is a cumulative measurement of the exposure concentration and duration of exposure to dissolved inputs from individual river sources. It is expressed as Concentration × Days (Conc.Days). For example, if a grid cell was exposed to concentrations of 5% river water for 2 days, this gives an exposure index of 0.1 (0.05 × 2). If a grid cell was exposed to concentrations of 50% river water for 10 days, this gives an exposure index of 5 (0.5 × 10). Whenever river water concentration is greater than 1%, the exposure index is calculated and added to all other exposures in that wet season (i.e., it is cumulative). This index provides a consistent approach to assessing relative differences in exposure of Reef shelf waters to inputs from various rivers.

The mathematical formulation that expresses this concept is given below:

$$\text{Conc.Days} = \sum_{t=0}^T \text{Conc}_{\text{exceedance}} * t$$

where,

$$\text{Conc}_{\text{exceedance}} = \begin{cases} \text{Conc}(t) - \text{Conc}_{\text{threshold}}, & \text{where } \text{Conc}(t) > \text{Conc}_{\text{threshold}} \\ 0, & \text{where } \text{Conc}(t) \leq \text{Conc}_{\text{threshold}} \end{cases}$$

and $Conc_{threshold}$ is defined here as 1% of the river concentration, $Conc(t)$ represents the time-varying tracer concentration, and t is time in days from the beginning of the wet season ($t_0 = 1$ October), and $T_{end\ of\ wet\ season} = 1$ May. Cumulative exposure is calculated for each grid point in the model domain.

The first step involved generation of tracer maps, which followed the same method as described above for the cumulative exposure index. By taking the cumulative sum of each river tracer concentration over the course of a water year (1 October to 30 September), the cumulative exposure of each map location to water from each river in that year was estimated.

A preliminary GIS analysis was then used to generate the loading maps. In this step, the end-of-catchment load for fine sediment, DIN or PN was dispersed for each river assuming a direct relationship between pollutant and tracer concentration (conservative mixing). Thus, surface load of fine sediment, DIN or PN per km^2 was calculated as:

$$Surf.load = \frac{tracer}{pixel} \times \frac{[total\ load]}{[sum\ of\ tracer]} \times \frac{pixel}{km^2}$$

The total Reef surface load was calculated by summing the surface load outputs for the 17 rivers for which tracer data were available: Normanby, Daintree, Barron, Russell-Mulgrave, Johnstone, Tully, Herbert, Haughton, Burdekin, Don, O'Connell, Pioneer, Fitzroy, Calliope, Boyne, Burnett, and Mary.

The difference between the estimated wet season fine sediment, DIN, and PN loadings (tonnes km^2) in the Reef lagoon for the 2020 water year (1 October 2019 to 30 September 2020) was calculated and compared to the pre-development loads derived from the Source Catchments model, which have a degree of uncertainty (refer to McCloskey *et al.*, 2021). This can be interpreted as 'anthropogenic' fine sediment, DIN or PN loadings, highlighting the areas of greatest change with current land use characteristics.

3 Drivers and pressures influencing water quality in 2020–21

3.1 Coastal development including agriculture

The Wet Tropics, Burdekin, and Mackay-Whitsunday regions are characterised by a variety of land uses including agricultural (sugarcane, grazing, cropping and other horticulture), mining, and urban development. Parts of the Cape York region are less developed than other Reef catchments. Land-based activities in this region are assumed to have a reduced impact on marine ecosystems (Waterhouse *et al.*, 2017a) despite a history of widespread grazing and mining impacts. Specifically:

- Cape York
 - The Pascoe River has an area of 2,088 km² with a high proportion (84%) of nature/conservation land use with some (15%) closed grazing (QLUMP, 2015). However, locals advise that there is no longer any active grazing within the Pascoe catchment (Polglase pers. comm. November 2018). Feral cattle and pigs, fire, and road erosion are the main pressures affecting water quality. These impacts are considered to be minimal in this focus region relative to other Reef catchments (Cape York NRM and South Cape York Catchments, 2016).
 - The Stewart River catchment has an area of 2770 km² and is mostly nature/conservation land use (94%) with approximately 2% grazing (QLUMP, 2015). Current and historic cattle grazing and road erosion are current pressures affecting sediment loads within the catchment.
 - The Normanby Basin is 24,550 km² and has a high proportion of nature/conservation land use (46%) and grazing (52%) (QLUMP, 2015). Additional lands have shifted from grazing to conservation since 2015, resulting in ~53% conservation land use and ~47% grazing. Horticulture accounts for only 1% of land use but has been expanding in the Laura and West Normanby sub-catchments. Current and historic cattle grazing, post-European initiation and acceleration of gully erosion, agricultural land clearing, and road construction are the primary pressures affecting water quality across the Normanby catchment (Brooks *et al.*, 2013; Shellberg and Brooks, 2013; Cape York NRM and South Cape York Catchments, 2016; Spencer *et al.*, 2016). Horticulture in the Laura sub-catchment has also increased nutrient concentrations in the Laura River (Howley, 2020).
 - The Endeavour and Annan River Basin is 2186 km² and has a high proportion of nature/conservation land use (52% as of 2015) and closed grazing (40%) (QLUMP, 2015). Additional grazing land has been converted to conservation land use since 2015 and approximately 80% of the Annan catchment is now under conservation or Aboriginal freehold. Sources of pollution in the Endeavour catchment include urban run-off from the township of Cooktown, cattle grazing, horticulture, and road erosion. Historic mining disturbances, cattle grazing impacts (current and historic), and road erosion are the primary sources of pollution to the Annan River (Shellberg *et al.*, 2016).
- Wet Tropics
 - The Barron Daintree focus region is primarily influenced by discharge from the Daintree, Mossman, and Barron catchments and (to a lesser extent) by other Wet Tropics rivers south of the focus region (Brodie *et al.*, 2013; Waterhouse *et al.*, 2017a). The Daintree catchment is 2,107 km² and has a high proportion of protected areas (56% natural/minimal use lands and 32% forestry). The remaining area consists of 7% grazing and, to a lesser extent, sugarcane and urban areas. The Mossman catchment is 479 km² and consists of 76% natural/minimal use lands, 10% sugarcane, and smaller areas of grazing and urban land uses. The Barron catchment has an area of 2189 km² and consists of 29% natural/minimal use lands, 31% grazing,

18% forestry, 11% cropping (including bananas and sugarcane), and smaller areas of dairy and urban land uses (Terrain NRM, 2015). The Barron River is the most hydrologically modified river in the Wet Tropics region and is heavily regulated by water supply infrastructure.

- The Russell-Mulgrave Basins contain a high proportion of upland National Park and forest (72%), with 13% of the area used for sugarcane production on the coastal floodplain (Terrain NRM, 2015). The Johnstone Basin is 2,326 km² and has a relatively high proportion of natural/minimal use lands (55%). The remaining area has 16% grazing, 12% sugarcane, and smaller areas of dairy (in the upper catchment), bananas and other crops, and urban land uses (Terrain NRM, 2015).
- The Tully River Basin is 1,685 km² and has a high proportion of natural/minimal use lands (75%). The remaining area is comprised of 12% sugarcane, 4% bananas, 5% grazing, and smaller areas of forestry, other crops and urban land uses. The Murray River Basin has an area of 1115 km² and has a high proportion of natural/minimal use lands (64%). The remaining area is comprised of 14% sugarcane, 10% forestry, 6% grazing and smaller areas of bananas, other crops and urban land uses. The Herbert River Basin is 9,842 km² and consists of 27% natural/minimal use lands, 56% grazing, 8% sugarcane, and smaller areas of forestry.
- The Burdekin region is one of the two large dry tropical catchment regions adjacent to the Reef, with cattle grazing as the primary land use on over 95% of the catchment area (NQ Dry Tropics, 2016). There is also intensive irrigated sugarcane on the floodplains of the Burdekin and Haughton Rivers. Fluctuations in climate and cattle numbers greatly affect the state and nature of vegetation cover and, therefore, the susceptibility of soils to erosion and off-site transport of suspended sediments and associated nutrients.
- The Mackay-Whitsunday region has a wet or mixed wet and dry tropical climate with the catchment land use dominated by agriculture broadly divided into grazing in the upper catchments (43%), sugarcane cultivation on the coastal plains (19%) and dispersed areas of nature conservation (19%) (Folkers *et al.*, 2014). In addition, there are expanding urban areas along the coast.

3.2 Climate and cyclone activity

Climate is a major driver of the condition of water quality and ecosystems and can vary substantially between years. It is heavily driven by the El Niño Southern Oscillation (ENSO) cycle. Climate models predict continued warming, increasing intensity of extreme rainfall events, fewer but more intense tropical cyclones, and more frequent and extreme La Niña and El Niño events (Schaffelke *et al.*, 2017).

During the 2020–21 wet season, there were four Tropical (or ex-tropical) Cyclones that influenced the Reef. These included cyclone Imogen in early January (1 to 6 January 2021) that formed in the Gulf of Carpentaria before weakening to a rain depression and causing considerable rainfall along the central catchments of the Reef. In mid-January cyclone Kimi (16 to 19 January 2021) briefly formed over the central Reef but did not make landfall. Similarly, to cyclone Imogen, cyclone Lucas formed in the Gulf of Carpentaria and moved eastwards across the Queensland mainland over the northern sections of the Reef catchments. Finally, Severe Tropical Cyclone Niran formed in the central section of the Reef in late February (27 February to 5 March 2021) and caused elevated wind/wave conditions and rainfall along the Wet Tropics coast, although it then moved further offshore and did not make landfall (Figure 3-1).

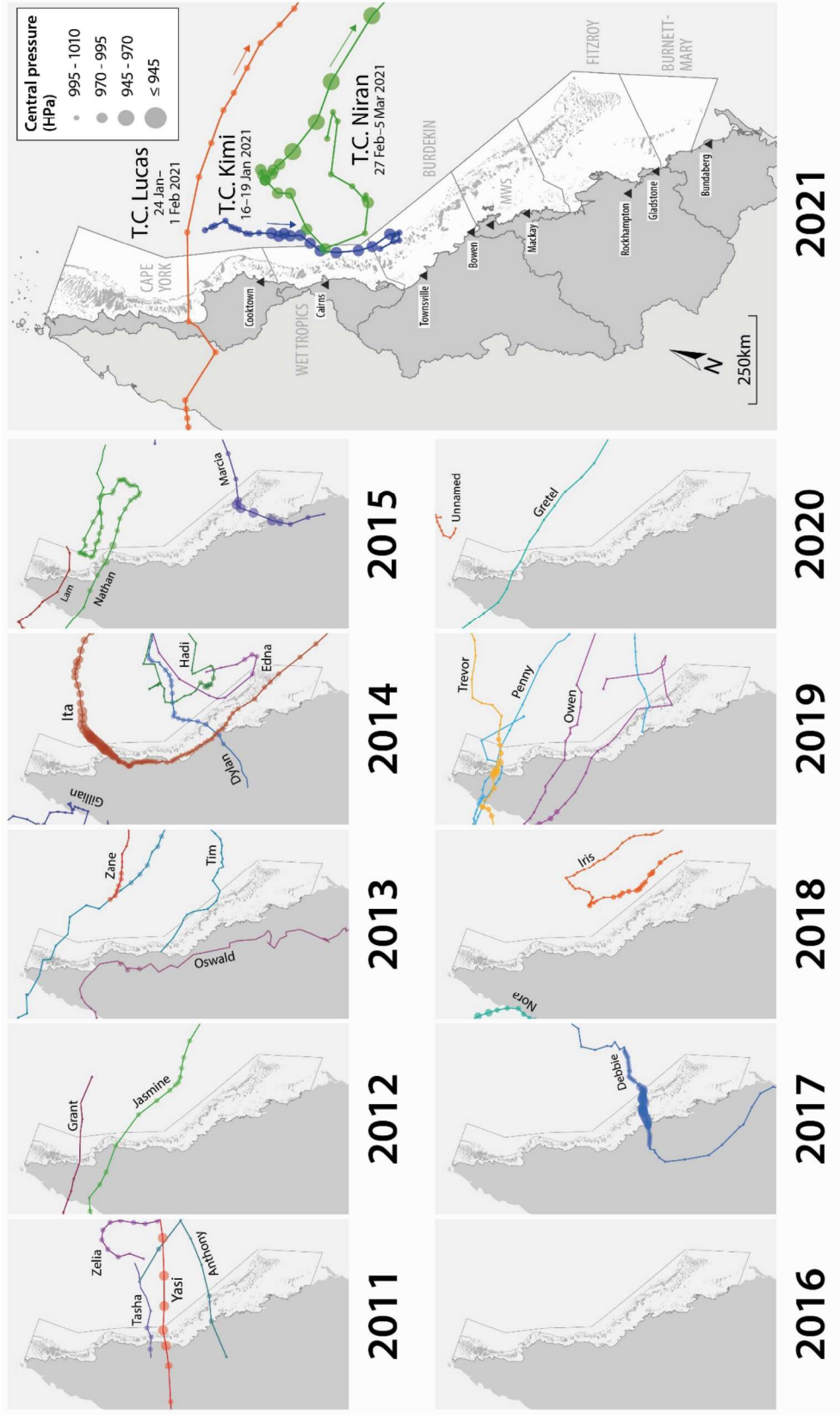


Figure 3-1: Trajectories of tropical cyclones affecting the Reef in 2020–21 and in previous years (2011 to 2020).

3.2.1 Rainfall for the Reef, NRM regions and basins

Queensland rainfall is highly variable on seasonal, inter-annual, and decadal timescales. Wet season rainfall in 2020–2021 was generally above average for the basins from the Burdekin northwards (with the exception of Jacky Jacky, Endeavour and Daintree Basins) and below average for all of the basins from the Don Basin southward relative to the long-term average of wet seasons from 1961–1990 (Figure 3-2 and Figure 3-3). In the focus regions including those within the Cape York, Wet Tropics and Burdekin NRM regions, 2020–21 was wetter than 2019–20 (Figure 3-2 and Figure 3-3).

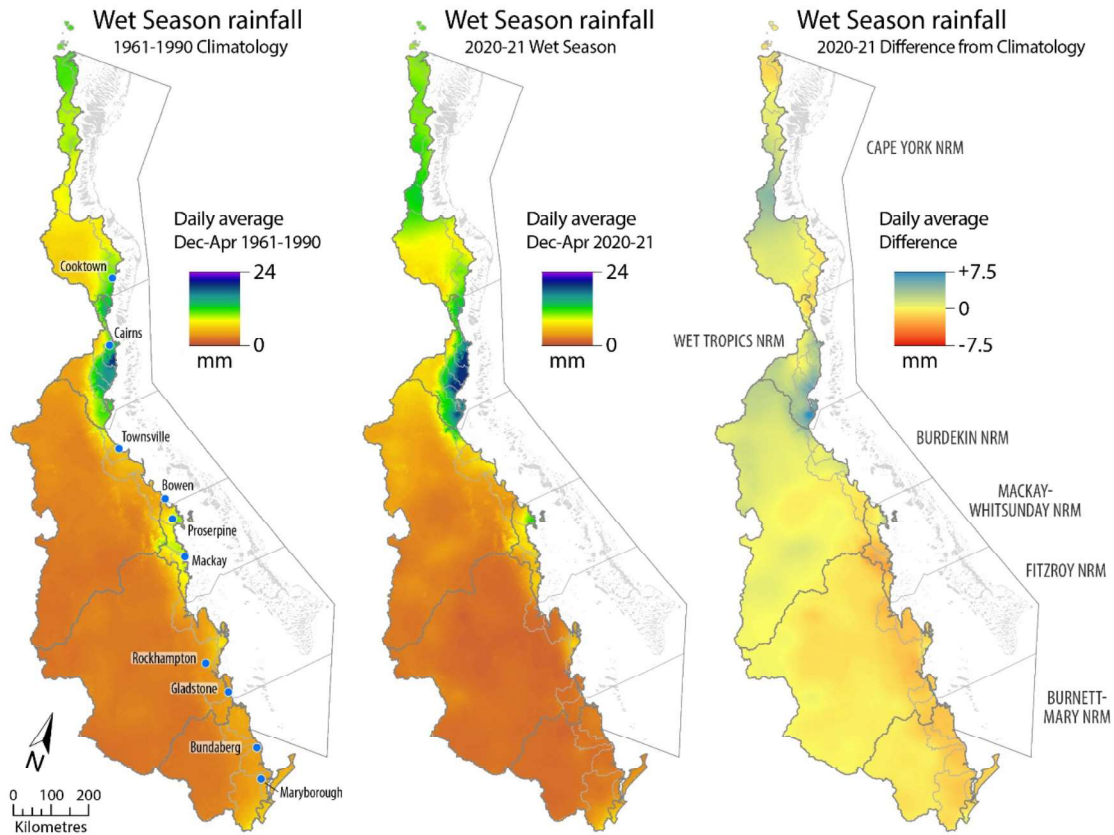


Figure 3-2: Average daily wet season rainfall (mm d^{-1}) in the Reef catchment: (left) long-term daily average (1961–1990; time period produced by BoM), (centre) 2020–21 and (right) the difference between the long-term average and 2020–21 rainfall. Source data: Bureau of Meteorology (2021).

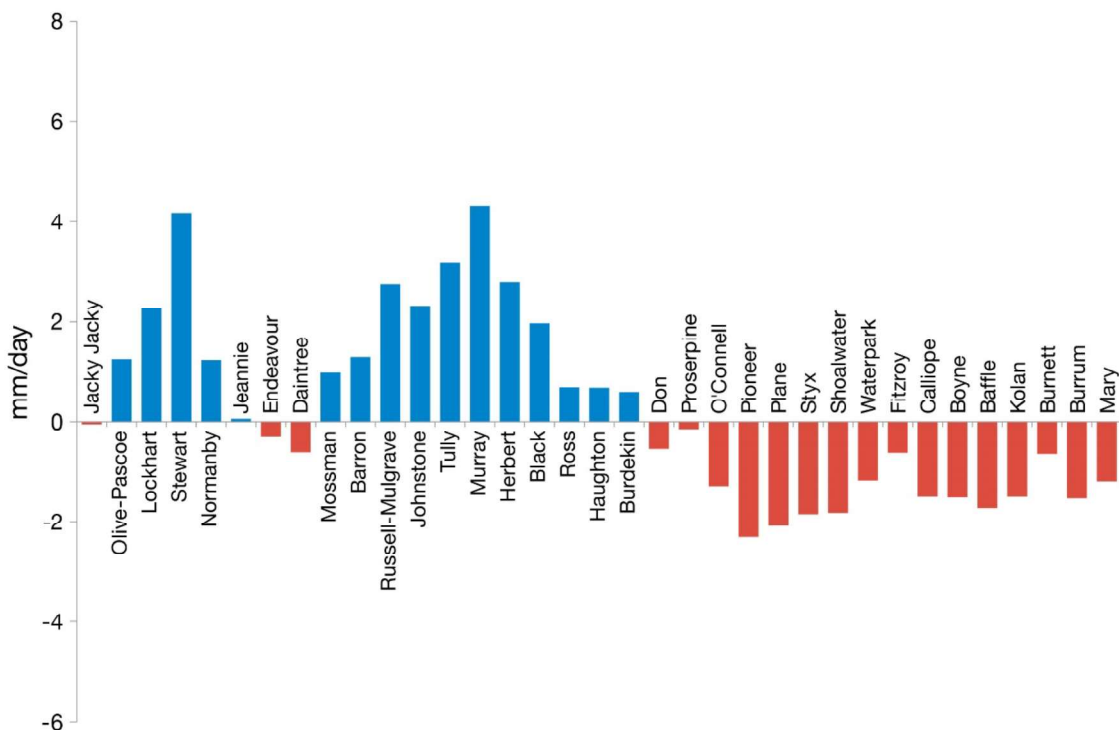


Figure 3-3: Difference between daily average wet season rainfall (December 2020–April 2021) and the long-term wet season rainfall average (from 1961–1990). Red and blue bars (none shown in this period) denote basins with rainfall below and above the long-term average, respectively. Note that the basins are ordered from north to south (left to right). Source data: Bureau of Meteorology (2021).

3.2.2 Freshwater discharge for the Reef, NRM regions and basins

Freshwater discharge volumes into the Reef lagoon are closely related to rainfall during the wet season and have a significant influence on coastal water quality. The total annual freshwater discharge for all of the Reef basins relative to long-term medians (based on water year, calculated using the methods described in Section 2.7) is shown in Figure 3-4. Discharge at the regional level is shown in Figure 3-5.

In 2020–21, the overall Reef catchment area had discharge just above the long-term average (1.1 times the long-term median). On a regional basis, the most northern three NRM regions had above average discharge including the Cape York (1.7 times higher than long-term median), Wet Tropics (1.3 times higher) and Burdekin (1.7 times higher) NRM regions. In comparison, the most southern three NRM regions had well below average discharge, all recording less than 50% of their long-term median values.

Annual discharge for each of the 35 Reef basins in 2020–21 is shown in Table 3-1 and compared to long-term median annual flows. Of these basins, Jacky Jacky, Olive-Pascoe, Lockhart and Stewart (Cape York NRM), Murray, Herbert (Wet Tropics NRM), Black, Burdekin (Burdekin NRM) and Styx, Shoalwater and Waterpark (Fitzroy NRM) had values above their long-term median.

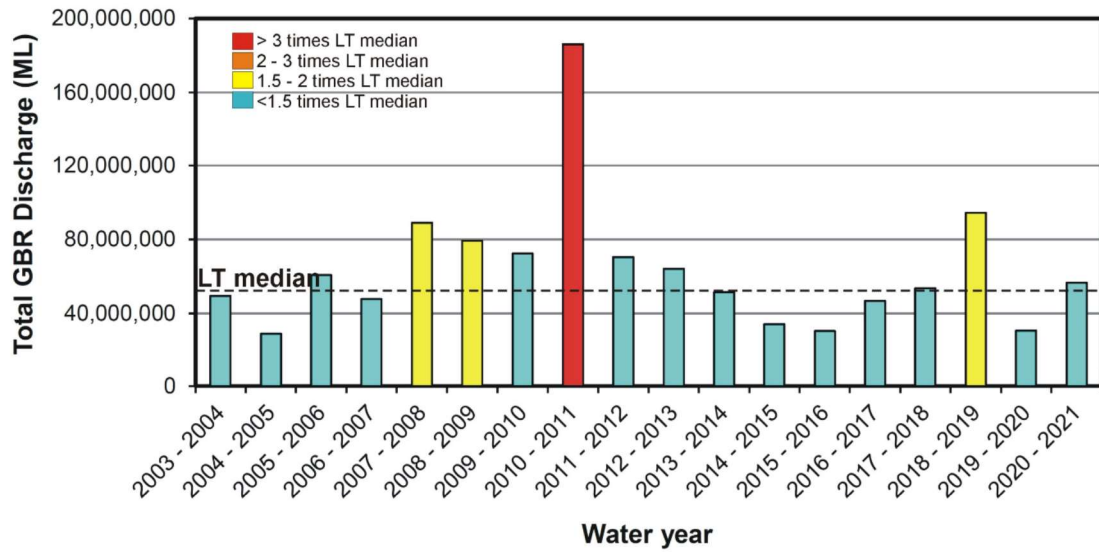


Figure 3-4: Long-term total discharge in ML (water year: 1 October to 30 September) for the 35 main Reef basins. Source : DRMW, <https://water-monitoring.information.qld.gov.au/>.

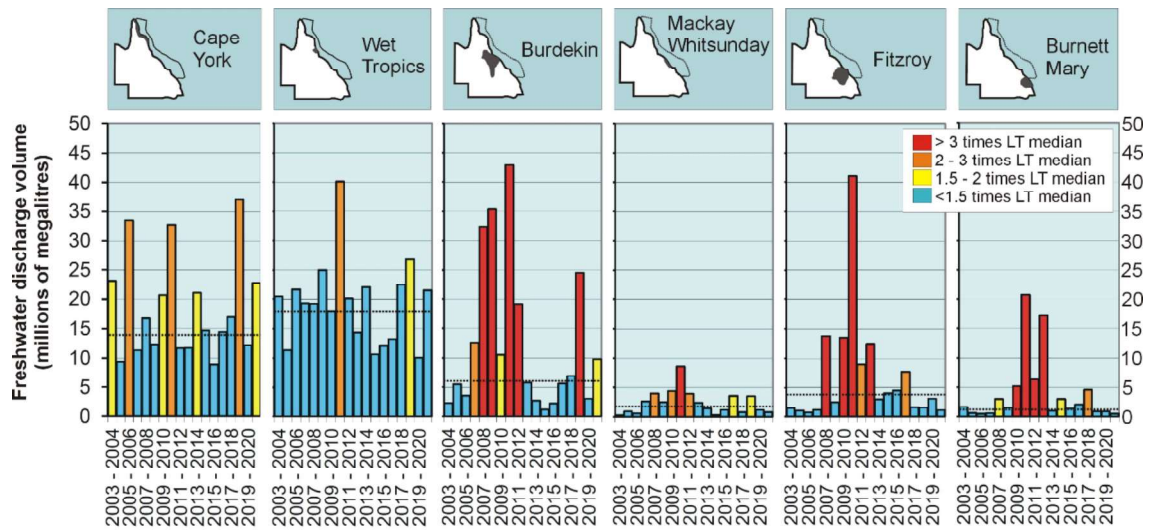


Figure 3-5: Corrected annual water year (1 October to 30 September) discharge from each NRM region (using the correction factors in Table 2-3) for 2003–04 to 2020–21 (in ML per year). Data derived from DRMW (2021).

Table 3-1: Annual water year discharge (ML) of the 35 main Reef basins (1 October 2017 to 30 September 2021, inclusive) and 30-year long-term (LT) median discharge (1986–87 to 2015–16). Colours indicate levels above the long-term median: yellow for 1.5 to 2 times, orange for 2 to 3 times and red greater than 3 times.

Basin	LT median	2017 - 2018	2018 - 2019	2019 - 2020	2020 - 2021
Jacky Jacky Creek	2,047,129	2,689,450	3,124,009	1,920,007	3,324,787
Olive Pascoe River	2,580,727	3,424,596	6,992,798	3,189,195	5,361,951
Lockhart River	1,634,460	2,168,911	4,428,772	2,019,824	3,395,902
Stewart River	674,618	826,499	3,109,052	584,988	1,470,654
Normanby River	4,159,062	4,333,023	12,102,053	2,792,858	5,928,821
Jeannie River	1,263,328	1,721,175	3,350,682	932,300	1,782,930
Endeavour River	1,393,744	1,796,913	3,847,478	773,315	1,552,254
Daintree River	1,512,054	1,439,220	4,752,327	901,248	1,490,754
Mossman River	858,320	1,069,336	1,885,921	555,280	910,701
Barron River	574,567	946,635	1,535,892	320,056	615,937
Mulgrave-Russell River	2,600,465	3,359,834	3,550,093	1,694,470	3,025,022
Johnstone River	3,953,262	4,950,329	4,774,747	2,743,805	4,485,038
Tully River	3,241,383	3,883,954	4,020,452	2,200,744	4,123,338
Murray River	380,472	521,465	519,739	199,630	592,702
Herbert River	3,556,376	6,385,655	5,707,209	1,472,338	6,271,988
Black River	208,308	386,030	965,544	102,296	304,652
Ross River	377,011	83,113	2,371,556	133,165	72,975
Haughton River	419,051	598,668	2,363,209	251,321	446,782
Burdekin River	4,406,780	5,542,306	17,451,417	2,203,056	8,560,072
Don River	508,117	321,875	1,356,004	398,312	441,329
Proserpine River	284,542	174,183	837,962	205,680	148,928
O'Connell River	478,097	260,937	1,223,297	279,585	253,873
Pioneer River	692,342	249,530	1,158,768	383,506	235,359
Plane Creek	309,931	75,052	351,879	299,502	125,665
Styx River	155,384	218,115	109,376	225,782	280,934
Shoalwater Creek	129,487	181,763	91,147	188,152	234,112
Water Park Creek	97,115	136,322	68,360	141,114	175,584
Fitzroy River	2,852,307	954,533	1,339,964	2,533,631	397,027
Calliope River	152,965	141,438	2,682	80,255	25,097
Boyne River	38,691	35,775	678	20,300	6,348
Baffle Creek	215,446	1,081,646	930	47,143	12,271
Kolan River	52,455	325,578	4,958	5,304	114
Burnett River	230,755	849,051	202,436	332,366	118,241
Burrum River	79,112	715,449	63,972	70,928	14,743
Mary River	981,183	1,630,741	658,014	472,580	360,779
Sum of basins	51,812,207	53,479,101	94,323,378	30,674,035	56,547,662

4 Modelling and mapping marine water quality

This section presents results from satellite remote sensing of wet season water quality as well as outputs from eReefs model simulations of cumulative exposure to river discharge and estimated dispersal of nutrient and sediment loads.

4.1 Satellite remote sensing of wet season water types

To illustrate wet season influence on coastal water quality and identify potential risk to ecosystems, satellite-derived map products were produced for the Reef, including frequency maps predicting the areas affected by the combined primary and Secondary water types combined (Figure 4-1) or the three wet season water types individually (Figure 4-2) from December 2020 to April 2021.

4.1.1 Areas affected

The extent and frequency of the occurrence of combined primary and secondary water types was variable across regions, cross-shelf and between years, reflecting the concentrations and intensity of the river discharge and resuspension events (Figure 4-1). The maps illustrate a well-documented inshore to offshore gradient (for example, Devlin *et al.*, 2013, 2015), with coastal areas experiencing the highest frequency of primary water types and mid-shelf and offshore areas less frequently exposed to primary waters (Figure 4-2).

Frequency of occurrence: The frequencies of occurrence of the combined primary and secondary water types were consistent with previous years, and indicated similar conditions to mean long-term conditions, or in the Mackay-Whitsunday region, to those characteristics of drier years. The frequencies of occurrence measured across the Tully and Burdekin transects in 2020–21 (Figure 4-1f) were below the frequencies extracted from the typical wet-year composite and above the frequencies extracted from the typical dry-year composite. In the Tully transect, the frequencies of occurrence were similar to the long-term average and slightly above the representative coral recovery period. In the Burdekin transect, the frequencies of occurrence were above both long-term average and the representative coral recovery period. The frequencies measured across the Pioneer transect were similar to the typical dry-year composite.

Reef area exposed: In 2020–21: only 3% of the Reef was exposed to primary waters, 16% of the Reef was exposed to secondary waters and 57% of the Reef was exposed to tertiary waters (Table 4-1).

The area exposed to primary waters was similar to both the long-term and coral recovery period percentages and only the enclosed coastal and open coastal Reef waters were exposed (90% and 17% of the enclosed coastal and open coastal waterbody areas, respectively). The area exposed to secondary waters was similar to both the long-term and coral recovery period percentages (16% of the Reef) and 82% of the open coastal Reef waters were exposed.

Table 4-1: Areas (km²) (and percentages, %) of the Reef lagoon (total 348,839 km²) and division by waterbodies (WB: enclosed coastal, OC: Open coastal, Mid = mid-shelf and Off = offshore) affected by the primary and secondary wet season water types combined, and the three wet season water types individually during the current wet season and for a range of reference periods

Water type	Water -body (WB)	Area of Reef affected in km ² and %									
		2020-21 wet season		Long-term average		Average of coral recovery period: 2012–2017		Typical Wet-year composite		Typical Dry-year composite	
		km ²	% Reef (% WB)	km ²	% Reef (% WB)	km ²	% Reef (% WB)	km ²	% Reef (% WB)	km ²	% Reef (% WB)
Combined primary + secondary (CC1-5)	Reef	56,984	16%	60,768	17%	58,870	17%	87,660	25%	42,366	12%
	EC	6,376	2% (99%)	6,054	2% (94%)	39,911	2% (94%)	6,058	2% (94%)	6,059	2% (94%)
	OC	29,007	8% (83%)	33,852	10% (97%)	39,911	10% (97%)	34,516	10% (99%)	29,438	8% (85%)
	Mid	17,146	5% (21%)	18,045	5% (22%)	16,296	5% (20%)	35,290	10% (43%)	6,291	2% (8%)
	Off	4,455	1% (2%)	2,818	1% (1%)	2,664	1% (1%)	11,797	3% (5%)	577	0% (0%)
Primary	Reef	11,721	3%	10,381	3%	10,140	3%	19,501	6%	7,127	2%
	EC	5,813	2% (90%)	5,681	2% (88%)	5,635	2% (87%)	5,925	2% (92%)	5,117	1% (79%)
	OC	5,780	2% (17%)	4,700	1% (14%)	4,501	1% (13%)	11,174	3% (32%)	2,009	1% (6%)
	Mid	118	0% (0%)	-	0% (0%)	4	0% (0%)	2,402	1% (3%)	-	0% (0%)
	Off	11	0% (0%)	-	0% (0%)	-	0% (0%)	-	0% (0%)	-	0% (0%)
Secondary	Reef	55,326	16%	56,797	16%	55,074	16%	81,921	23%	39,742	11%
	EC	5,055	1% (78%)	4,800	1% (75%)	4,637	1% (72%)	5,056	1% (78%)	4,401	1% (68%)
	OC	28,977	8% (83%)	33,616	10% (97%)	33,688	10% (97%)	34,493	10% (99%)	29,251	8% (84%)
	Mid	16,866	5% (21%)	15,647	4% (19%)	14,387	4% (18%)	31,592	9% (39%)	5,513	2% (7%)
	Off	4,428	1% (2%)	2,734	1% (1%)	2,363	1% (1%)	10,782	3% (5%)	577	0% (0%)
Tertiary	Reef	197,282	57%	165,460	47%	165,582	47%	195,072	56%	136,990	39%
	EC	457	0% (7%)	21	0% (0%)	27	0% (0%)	82	0% (1%)	5	0% (0%)
	OC	29,202	8% (84%)	26,485	8% (76%)	25,684	7% (74%)	27,151	8% (78%)	25,586	7% (74%)
	Mid	77,062	22% (94%)	70,255	20% (86%)	71,728	21% (87%)	76,350	22% (93%)	54,679	16% (67%)
	Off	90,562	26% (41%)	68,700	20% (31%)	68,143	20% (31%)	91,489	26% (41%)	56,721	16% (25%)

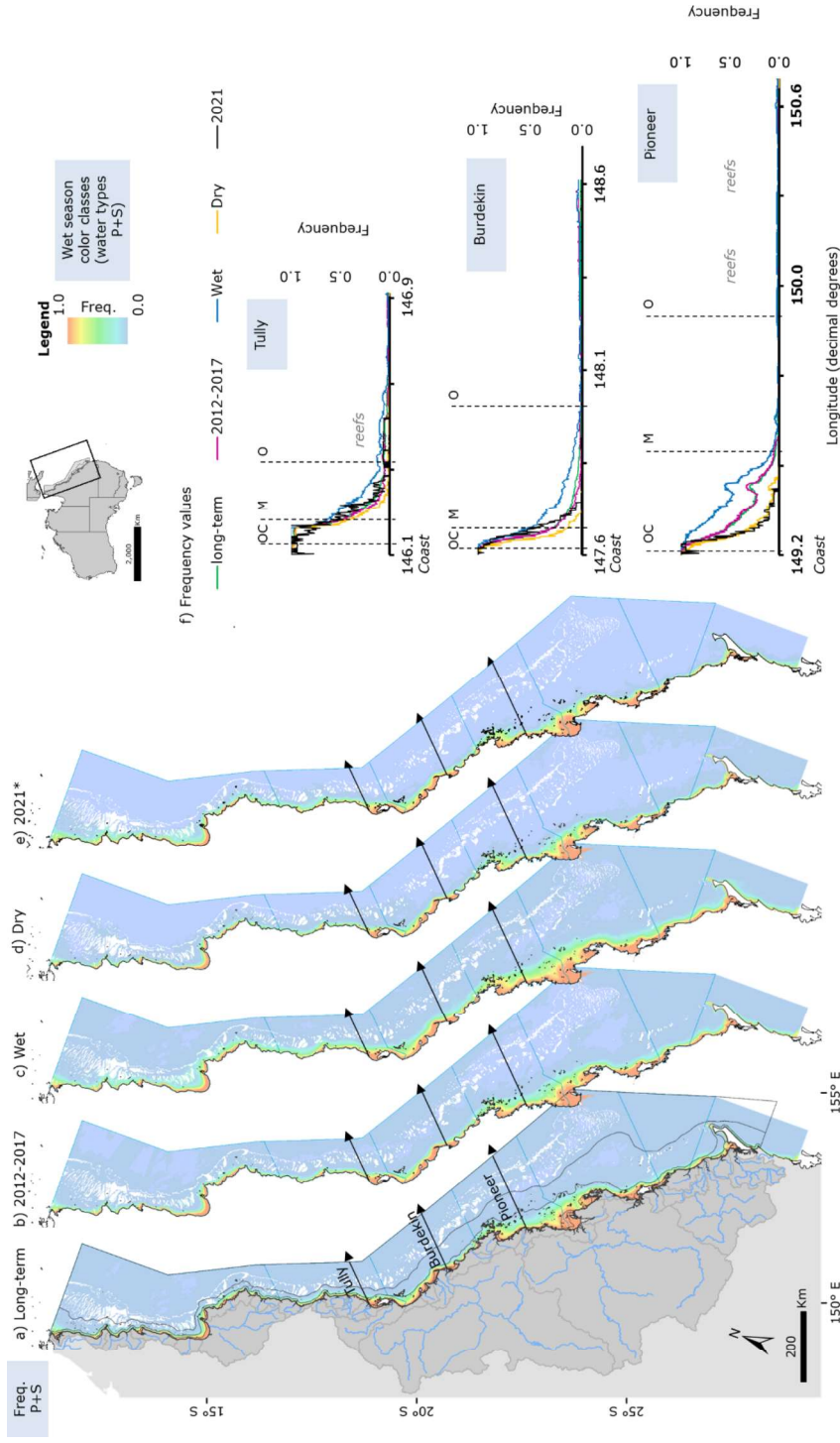


Figure 4-1: Map showing the frequency of primary (CC1–4) and secondary (CC5) water types combined in the a) long-term (16 wet seasons since 2003–04) b) representative coral recovery period (2011–12 to 2016–17, 6 wet seasons or 132 weeks), c) typical dry-year wet season composites and d) typical dry-year wet season (22 weeks). * The 2020–21 frequency maps were produced using Sentinel-3 images and the FU colour scale. Previous wet seasons and reference period composites have been produced using MODIS satellite imagery and the wet season colour scale (Waterhouse *et al.*, 2021). Except for the coral recovery period, reference maps (long-term, Wet and Dry frequency maps) are updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure they remain valid as a representative period and to improve their accuracy as more satellite data are available. Last update was in 2019. The highest frequency is shown in orange and the lowest frequency is shown in blue. f) Plots on the right show the frequency values recorded along three transects extending from the Tully, Burdekin and Pioneer Rivers to the external boundaries of the Marine Park and illustrate the differences in the spatial distribution and frequency of occurrence between the different representative periods. OC: open coastal, M: mid-shelf and O: Offshore marine water body boundaries.

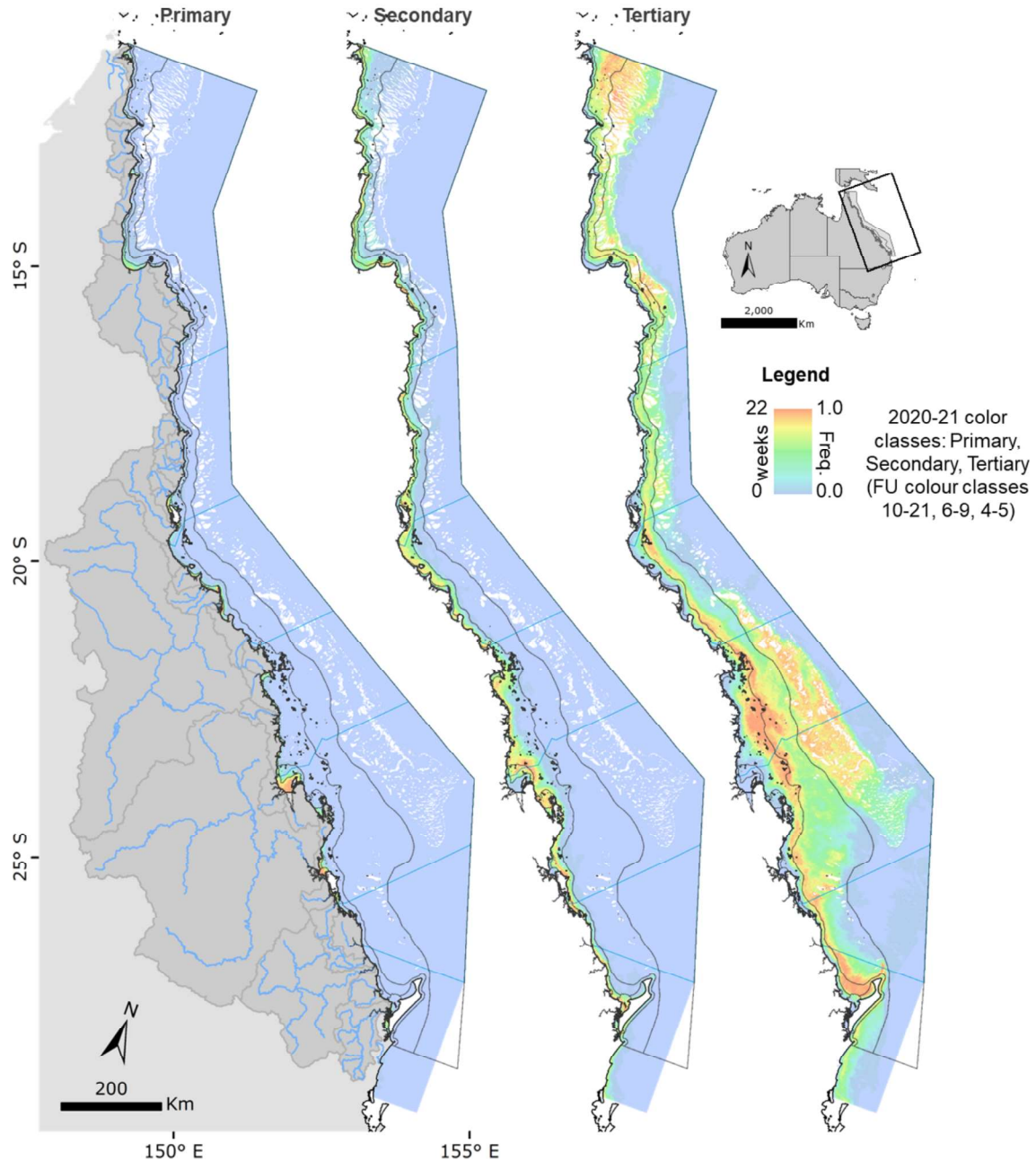


Figure 4-2: Map showing the frequency of primary, secondary and tertiary wet season water types in the 2020–21 wet season (22 weeks). The highest frequency is shown in orange and the lowest frequency is shown in blue. These maps are used in the exposure assessment to represent the spatial likelihood of exposure of each of the wet season water types in 2020–21.

Similar to last year, the Reef area exposed to tertiary waters was unexpectedly large (57% of the Reef, 70% in 2019–20) and covered a larger area than all reference periods, including the 'wet' years (56% of the Reef). This result is related to anomalously large tertiary areas measured in the midshelf and offshore Reef (94% and 26% of the midshelf and offshore waterbody area) This result is not fully understood but is likely an indication of offshore upwelling in the central and southern Reef areas. Image classification by optical type does not directly elucidate the cause of variations in water colour, and the tertiary water type in particular (but also, to some extent, the primary and secondary water types in some coastal

areas) is often due to processes not influenced by catchment discharges. This upwelling hypothesis should be further investigated in a future case study by comparing the tertiary maps with sea surface temperature climatology (for example, Wijffels *et al.*, 2018). Furthermore, major reprocessing of the MODIS and Sentinel 3-OLCI radiance has been made in 2018 (Lee *et al.*, 2019) and 2021, respectively. This could have had a partial effect on the results of the classification of the colour classes, particularly for the clearest waters. Tertiary waters are associated with low land-sourced contaminant concentrations or the influence of marine processes and have a low magnitude score in the Reef exposure assessment (Figure 4-3 and Figure 4-4). While tertiary areas were larger than in the reference periods, this did not result in increasing the potential risk offshore: 99% of the offshore areas were classified as no/very low potential risk in the 2020–21 risk assessment (Figure 4-5).

4.1.2 Composition of water types

Boxplots of long-term water quality parameters in the wet season water types and six colour classes are shown in Figure 4-3 and Figure 4-4, respectively. Detailed summaries of water quality parameters for the long-term period (16 wet seasons) and reporting year are provided in Appendix C. Long-term water quality values are now reviewed and updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure the water type characterisation remain valid as a representative period, and to improve its accuracy as more field data are collected every wet seasons. The last update was in the 2018–19 reporting year (Gruber *et al.*, 2020), using field data collected from 2004 to 2019. Note also that the long-term water quality concentrations are presented rather than the seasonal mean concentrations in each colour class that were reported before 2018–19 which were considered to be potentially biased by the wet season sampling effort. The latter figures are still presented in Appendix C for consistency.

Boxplots of water quality concentrations for every water type followed published patterns (for example, Devlin *et al.*, 2015; Petus *et al.*, 2019) with TSS, Chl-*a*, CDOM, DIN, DIP, PP and PN decreasing from the primary water type (colour classes 1–4) to the tertiary water type (colour class 6). High TSS, Chl-*a* and CDOM concentrations were at levels expected to decrease light availability (for example, Petus *et al.*, 2018) and the Secchi depth was logically lowest in the primary water types and increased from the primary to the tertiary water types (Figure 4-3). The primary water type had the larger interquartile range for all parameters, illustrating a greater variability in water quality concentrations measured in this most turbid water type.

While Devlin *et al.* (2012) reported higher Chl-*a* concentrations in secondary than in primary water types, the long-term wet season was characterised by higher mean Chl-*a* concentrations in the primary water type ($1.61 \pm 2.37 \mu\text{g L}^{-1}$) than in the secondary water type ($0.80 \pm 0.84 \mu\text{g L}^{-1}$). However, when distinguishing individual colour classes (Figure 4-4c), Chl-*a* concentrations were higher in colour class 3 ($2.28 \pm 2.98 \mu\text{g L}^{-1}$) than in colour classes 1 ($2.20 \pm 3.41 \mu\text{g L}^{-1}$) and 2 ($1.48 \pm 1.12 \mu\text{g L}^{-1}$). Thus, the sub-classification into colour classes may better describe fine-scale coastal processes and supports the findings of Devlin *et al.* (2013) that Chl-*a* concentrations peak in transition zones between the primary and secondary water types. This peak is hypothesised to be driven by factors that control phytoplankton production including light attenuation, nutrient inputs, and salinity (Carstensen *et al.*, 2015). Mean long-term water quality concentrations decreased exponentially across the six colour classes and, except for DIN and DIP, mean long-term concentrations were two (PN and CDOM) to three (TSS and PP) times higher in CC1 than in CC2 or CC3 (Figure 4-4 and see Appendix C-4 for the concentration values). The number of samples collected in CC1 ($n=117$) and CC2 ($n=104$) was however limited in comparison to, for example CC5 ($n=926$, Appendix C-4). It would be interesting to collect extra samples inshore in the future to further characterise concentrations in the more turbid regions of flood plumes.

Mean long-term concentrations of water quality parameters showed similar patterns between focus regions (Figure 4-5), with maximum concentrations measured in the primary water type

and minimum concentrations in the tertiary water type (Figure B-2 in Appendix B). However, there were distinct differences in the concentrations of individual pollutants across regions. Across years, the frequency of sampling in flood events as well as the location, timing, and number of samples historically collected in each region is a major influence on these results. Thus, the *magnitude scores* for the exposure maps (Section 4.1.3) are calculated using the mean long-term water quality concentrations across the whole of the Reef (Figure 4-5).

Mean water quality concentrations for TSS, Chl-*a*, PP and PN were compared against Reef-wide wet season GVs (Figure 4-5). Long-term mean Secchi depths (<7 m in all water types) did not meet the annual mean value (10 m), although the ecological significance of this is not clear. The following patterns were identified for the three water types:

- Primary: the long-term mean TSS, Chl-*a*, PP, and PN concentrations were above the Reef-wide wet season GVs (Figure 4-5). However, it is important to note that water quality parameters in primary waters are highly variable (Figure 4-3)
- Secondary: the long-term mean TSS, Chl-*a* concentrations were above, and the PP and PN concentrations slightly above, the Reef-wide wet season GVs
- Tertiary: the long-term mean TSS concentration was above the wet season GV. Concentrations of Chl-*a*, PP, and PN were below Reef-wide wet season GVs.

Using this data, magnitude scores in the exposure mapping were finally calculated as the proportional exceedance of the GVs, and negative magnitude scores capped to zero (Figure 4-5). Magnitude scores *per se.* have no ecological significance but are used in the risk framework as a relative measure to assign potential risk grading for each water type (refer Section 4.1.3).

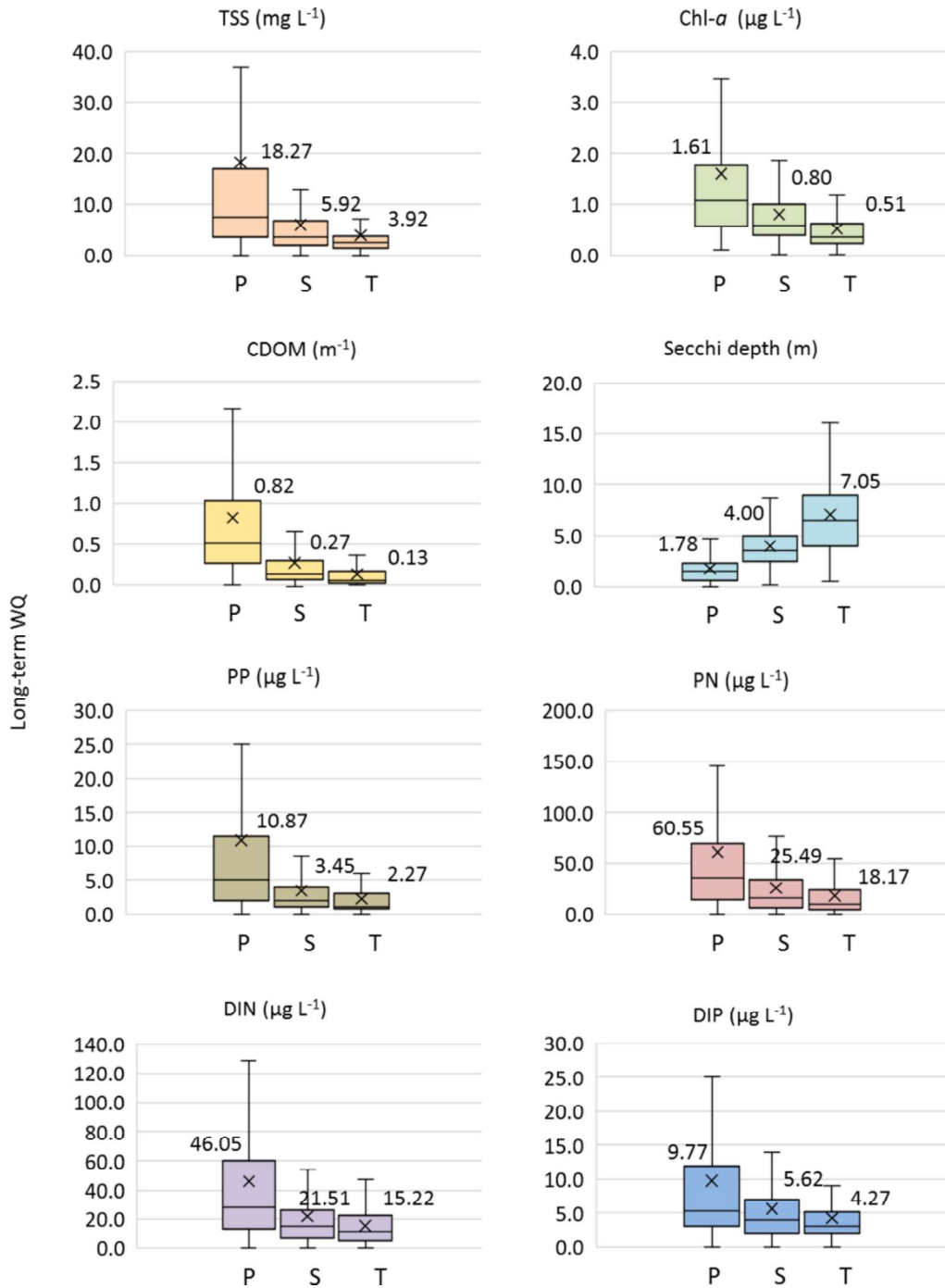


Figure 4-3: Long-term water quality (WQ) concentration and Secchi disk depth boxplots for each wet season water type (P = primary, S = secondary, T = tertiary). The mean is plotted as a cross, and its numerical value is indicated. The interquartile range is delimited by the box and the median by the line inside the box. Whiskers indicate variability outside the upper and lower quartiles. Data beyond the whiskers range are considered outliers and are not plotted. Long-term WQ values are reviewed and updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure the water type characterisation remains valid as a representative period, and to improve its accuracy as more field data are collected every wet seasons. Last update was in 2019, using all field data available (from 2004 to 2019).

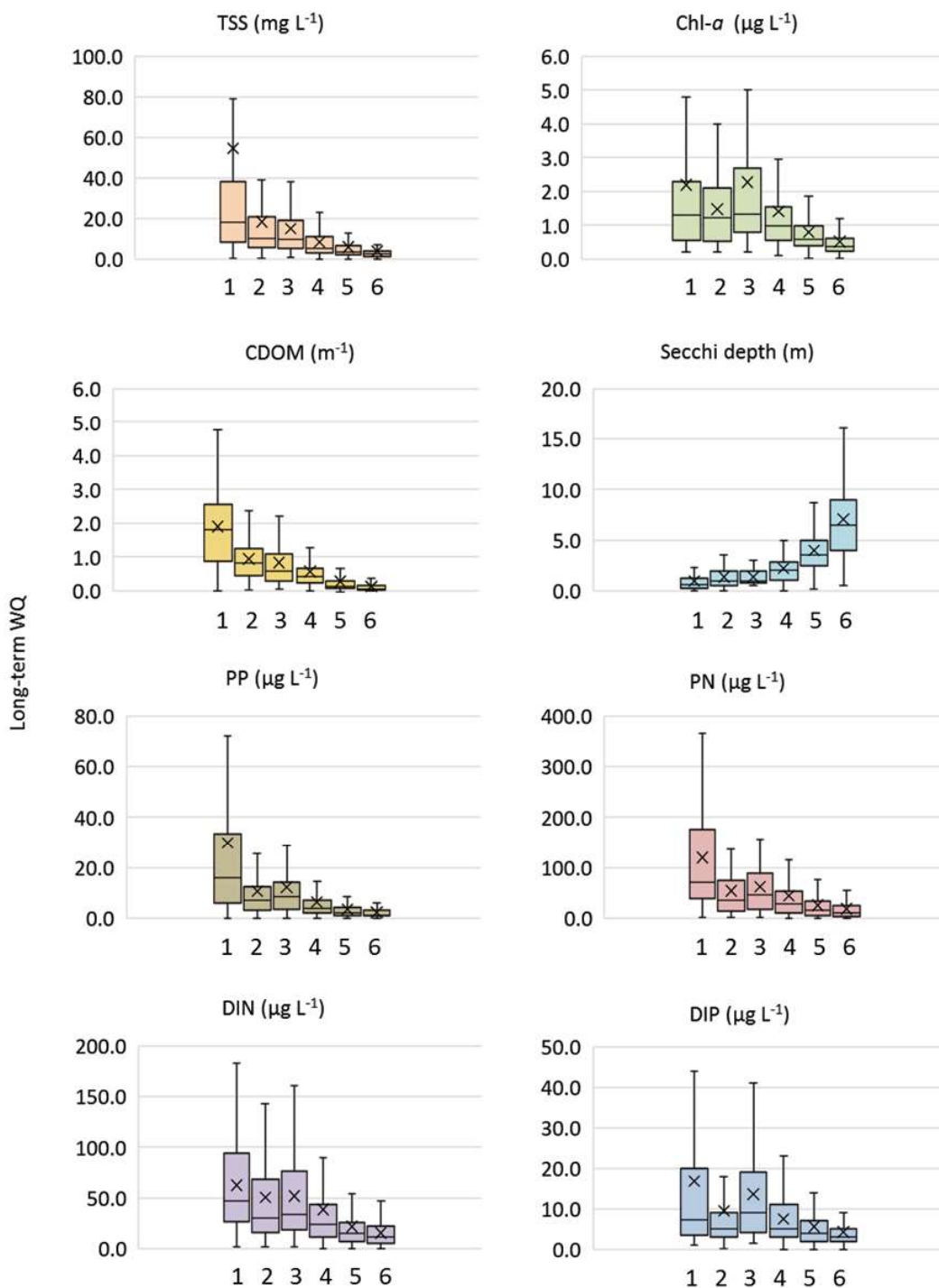


Figure 4-4: Long-term water quality (WQ) concentration and Secchi disk depth boxplots for each wet season colour class. The mean is plotted as a cross, and its numerical value is indicated. The interquartile range is delimited by the box and the median by the line inside the box. Whiskers indicate variability outside the upper and lower quartiles. Data beyond the whiskers range are considered outliers and are not plotted. Long-term water quality values are reviewed and updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure the water type characterisation remains valid as a representative period, and to improve its accuracy as more field data are collected every wet seasons. Last update was in 2019, using all field data available (from 2004 to 2019).

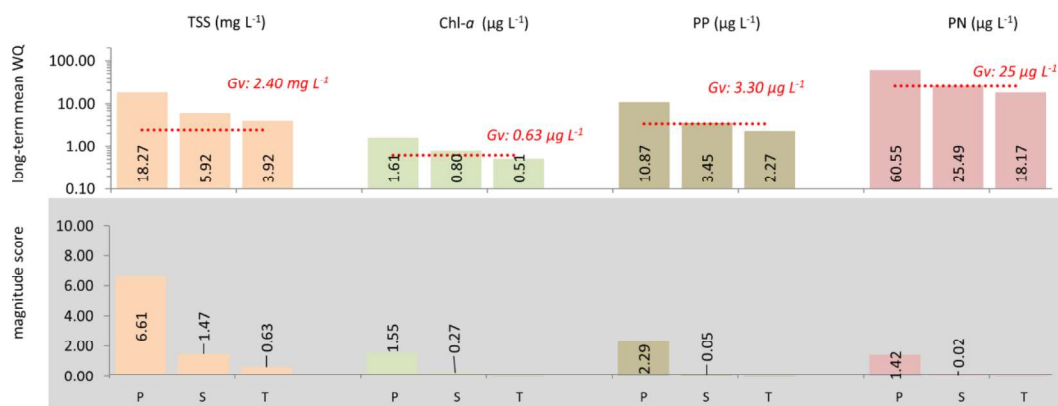


Figure 4-5: (top) Mean long-term water quality concentrations and (bottom) magnitude score across the three wet season water types. Red lines show the Reef-wide wet season GV (Appendix B Table B-3). Magnitude scores are calculated as the proportional exceedance of the guideline: $magnitude_{water\ type} = ([Poll.]_{water\ type} - GV)/GV$ and $Poll. = TSS, Chl-a, PP$ or PN . Negative Magnitude score are scored as zero. Mean long-term water quality concentrations and Magnitude score are re-calculated every 4 years as additional field data is collected (and/or in the case of extremely wet year or specific event patterns). Mean long-term water quality concentrations include samples collected from the enclosed coastal water type where high concentrations are likely to contribute to exceedances of the Reef-wide GV, particularly for primary waters.

4.1.3 Potential exposure risk to Reef ecosystems

This section presents the area (km²) and percentage (%) of coral reefs and seagrass meadows affected by different categories of exposure (or potential risk) based on satellite-derived wet season water types.

The exposure categories are not validated against ecological health data and at this stage represent relative potential risk categories for seagrass and coral reef ecosystems. The areas and percentages of ecological communities affected by the different categories of exposure were calculated as a relative measure between regions and the long-term average.

Reef-wide: The area exposed to a potential risk in 2020–21 was spatially limited relative to the scale of the Reef with 88% exposed to no or very low potential risk (Table 4-2 and Figure 4-6). This result is similar to the long-term patterns (87% of the Reef). Approximately 11% of the Reef was exposed to combined potential risk categories II–IV, which is still a relatively large area at approximately 40,000 km². However, only 1% of the Reef was in the highest exposure category (IV) and only 2% of the Reef was in category III (Table 4-2); the total area of these categories combined was 9,345 km². These patterns were very similar to the long-term patterns (Table 4-2). Patterns were also similar across marine regions, with more than 80% of each region classified as no / very low risk and less than 2% classified as category III or category IV, respectively (Figure 4-7b). It is important to note that while these percentages are relatively small, the total areas are still significant, especially when considering specific habitat areas.

Table 4-2: Areas (km²) and percentages (%) of the Reef lagoon, coral reefs and surveyed seagrass affected by different risk categories of exposure during the 2020–21 wet season and the long-term. The last three rows show the differences between % affected in 2020–21 and the long-term average (■: increase, ■: decrease, and ■: no change, difference <5%). Areas south of the Marine Park (Hervey Bay) are not included.

Reef lagoon		Total		Potential Risk category				Total area exposed II-IV
				No / very low	Lowest		Highest	
					I	II	III	
Surface area	area	348,839	2021	308,729	30,766	5,638	3,707	40,111
			LT	304,664	35,767	4,853	3,555	44,175
	%	100%	2021	88%	9%	2%	1%	11%
			LT	87%	10%	1%	1%	13%
Coral reefs	area	24,914	2021	21,945	2,621	244	104	2,969
			LT	23,147	861	98	43	1,002
	%	100%	2021	88%	11%	1%	<1%	12%
			LT	96%	4%	<1%	<1%	4%
Surveyed seagrass	area	4,660	2021	1,302	2,031	815	512	3,358
			LT	875	2,387	691	687	3,765
	%	100%	2021	28%	44%	17%	11%	72%
			LT	19%	51%	15%	15%	81%
Difference (2021 – Long Term average)	Surface area			1%	-1%	1%	<1%	-2%
	Coral Reef			-8%	7%	<1%	<1%	8%
	Surveyed seagrass			9%	-7%	2%	-4%	-9%

Reef waterbodies: Only the inshore Reef waters, including the enclosed (macro-tidal enclosed coastal and enclosed coastal waterbodies combined) and open coastal (macro-tidal open coastal and open coastal waterbodies combined) were exposed to the highest categories of potential risk (III and IV, Figure 4-7a). Open coastal waters were however largely exposed to the lowest category of potential risk only (II: 58%) and only 9% and 1% of the open coastal waters were exposed to the potential risk category III and IV. The enclosed coastal waters had the largest proportion of waters classified as higher risk, with 44% of the combined inshore waters exposed to risk category IV. Approximately 77% (<3,600 km²) of the Reef seagrass occur in the inshore waters, but only 4% (< 900 km²) of the Reef corals (Appendix C-6). The mid-shelf and offshore waterbodies were largely classified as no / very low potential risk (92% of the mid-shelf and 99% of the offshore waters) (Figure 4-7a).

Similar cross-shore patterns were observed across Reef marine regions (Figure 4-7c) and all regions were largely classified as no or very low potential risk. Mid-shelf waterbodies in the Cape York and Wet Tropics regions had the greatest exposure to potential risk category II (36% and 24% of the Cape York and the Wet Tropics mid-shelf waters). The Burdekin region open coastal waterbody had the greatest exposure to risk categories III (17% of the Burdekin waters), followed by the Wet Tropics (14%) and Cape York (10%). In the other Reef regions, less than 10% of the open coastal waterbodies were exposed to risk categories III. Differences across regions are further described in the Regional Reporting (Section 4.3 to 4.8).

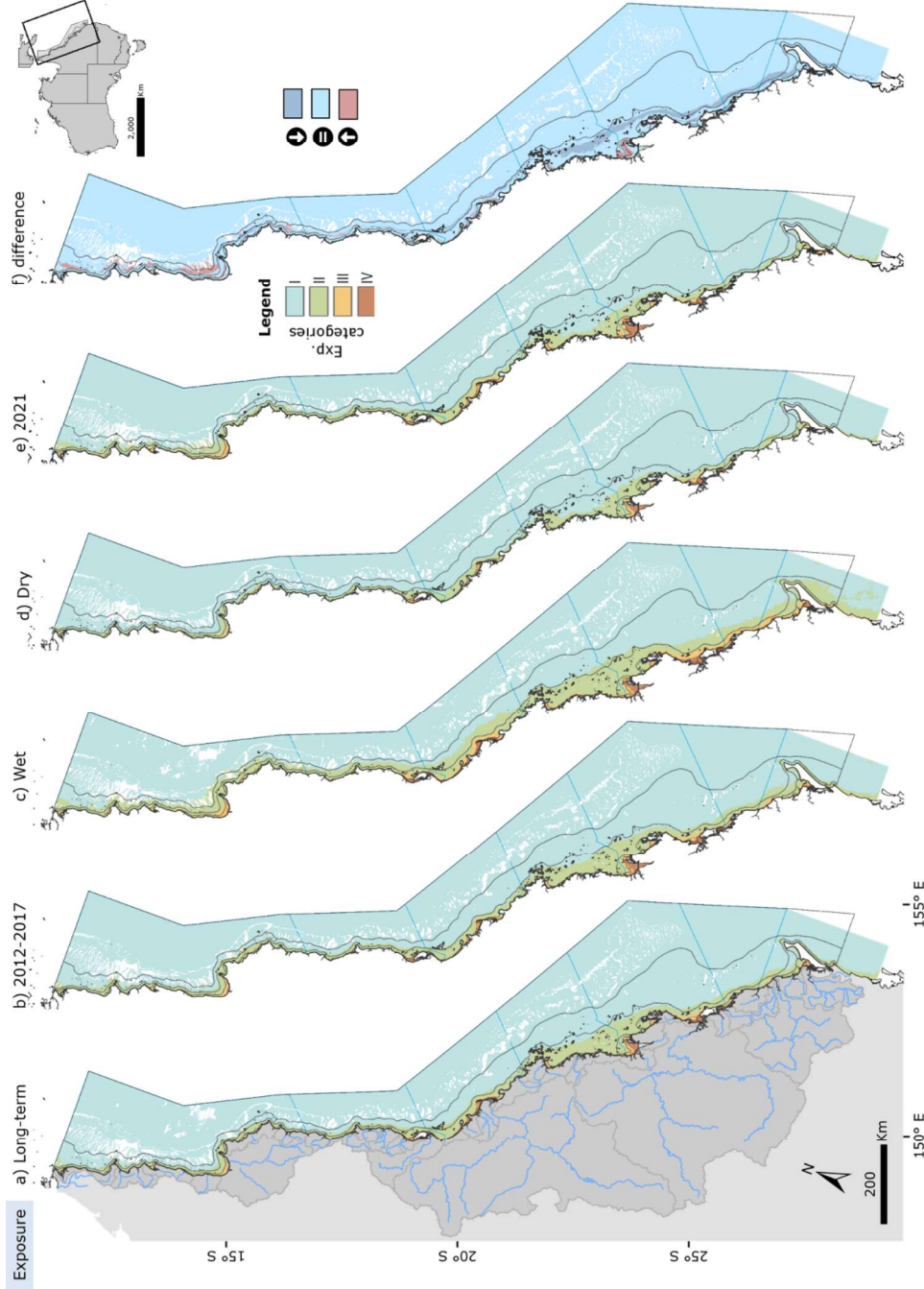


Figure 4-6: Map showing the reclassified surface exposure in the a) long-term, b) representative coral recovery period (2012–2017, 132 weeks), c) typical wet-year and d) typical dry-year wet season composites and e) 2020–21 wet seasons (22 weeks). Except for the coral recovery period, reference maps (long-term, Wet and Dry frequency maps) are updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure they remains valid as a representative period and to improve their accuracy as more satellite data are available. Last update was in 2019 (16 wet seasons). Relative potential risk categories range from I: no to low risk to IV: highest risk. f) Difference map showing areas with an increase (in red, \oplus) and decrease (in purple, \ominus) in risk category in 2019–20 against long-term trends (calculated as (e) 2021 minus (a) long-term).

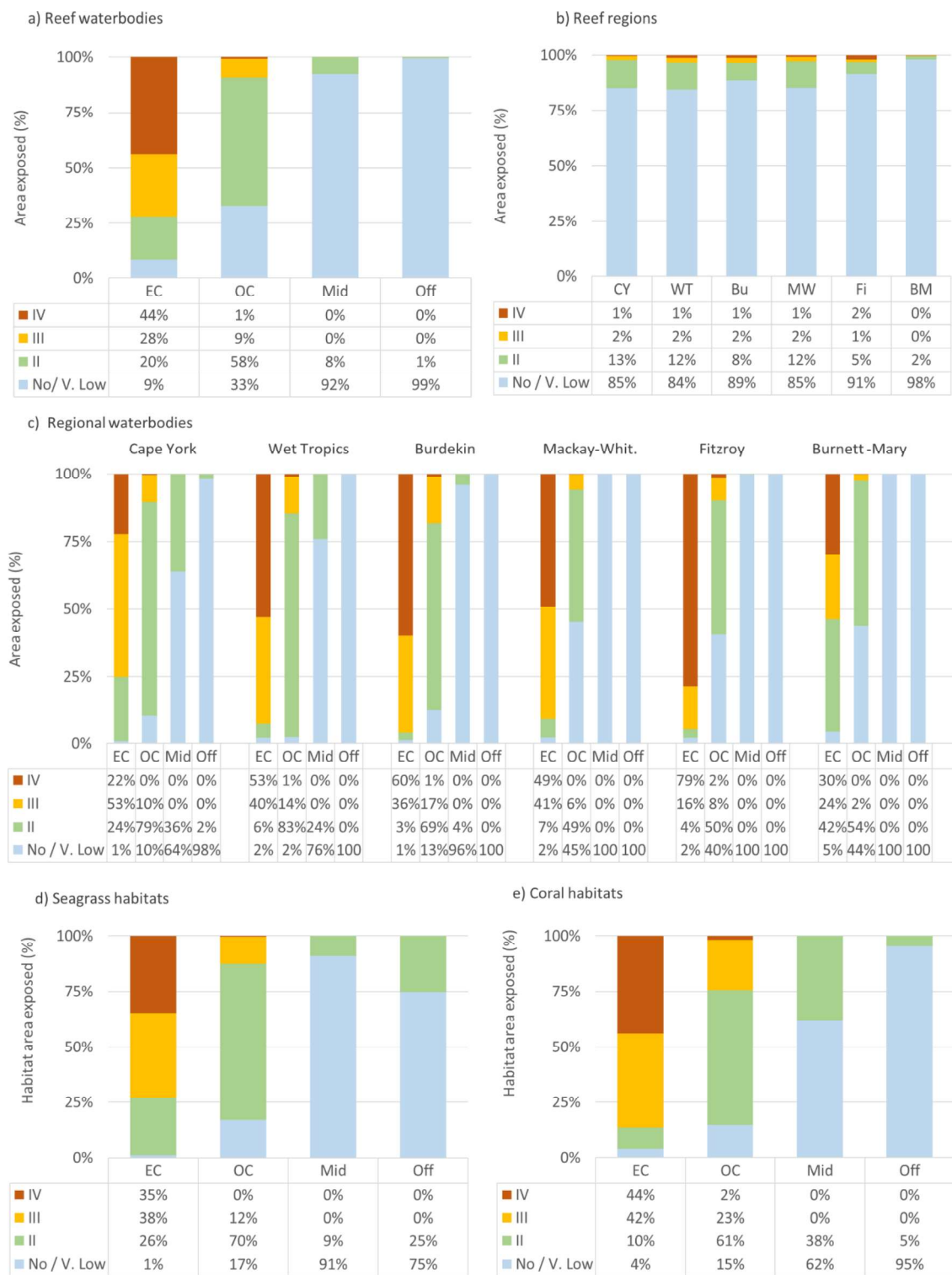


Figure 4-7: Percentage of the a) Reef waterbodies, b) Reef regions, c) regional Reef waterbodies, d) seagrass and e) coral habitats affected by different risk categories of exposure during the 2020–21 wet season.

Reef habitats (coral reefs and seagrasses): In 2020–21, it was estimated that:

- Approximately 12% of coral reefs (or almost 3,000 km²) were exposed to combined potential risk categories II–IV (Table 4-2). However, less than 2% were in the highest exposure categories IV and III and only the enclosed coastal and open coastal coral reef habitats were exposed, equating to 348 km² (Figure 4-6e). The total enclosed coastal coral reef area affected by the highest exposure categories was 86% (44% to cat. IV and 42% to cat. III). Only 2% of the open coastal reefs were exposed to cat. IV and 23% to category III. Midshelf and offshore coral reefs were only exposed to the lowest risk category II or to no potential risk. The coral areas exposed to potential risk categories III and IV were similar to the long-term patterns (< 2% of the coral reefs, Table 4-2). There was however an increase in area exposed to the lowest potential risk category (II: + 7%).
- Approximately 72% of seagrasses (or almost 3,360 km²) were exposed to combined potential risk categories II–IV. Approximately 11% (512 km²) were in the highest exposure category (IV) and 17% were in category III (815 km²) and only the enclosed coastal and open coastal seagrass habitats were exposed (Figure 4-6d). The total enclosed coastal seagrass area affected by the highest exposure categories was 73% (35% to cat. IV and 38% to cat. III). Only 12% of the open coastal seagrasses were exposed to cat. III and none were exposed to the highest category IV. Mid-shelf and offshore seagrasses were only exposed to the lowest risk category II or to no potential risk. The seagrass areas exposed to combined potential risk categories III and IV in 2020–21 were similar to the long-term, and there was a decrease in area exposed to the lowest potential risk category (II: -7%).

4.2 Mapping the dispersal of river-derived DIN, fine sediment and PN

An improved understanding of dispersal of river-derived DIN, fine sediment and PN has been developed using the eReefs marine models. The process involves dispersing modelled end-of-catchment loads in individual river plumes, and then the dispersal from each river plume is summed to represent the total fine sediment, DIN, or PN dispersed in that year. For all pollutants, the ‘anthropogenic’ influence was predicted by calculating the difference between a pre-development load scenario and the 2020–21 loading. A time series from 2003 to 2021 is also presented. In the years marked with asterisks, eReefs simulations were not available, so a multi-annual average tracer was used to disperse loads in these years. While the estimates have lower reliability relative to the years where tracer maps were available, they are still considered more robust than methods used in previous reports.

4.2.1 River-derived DIN dispersal

2021 water year

The estimated wet season river-derived DIN loading in the Reef lagoon for the 2021 water year is shown in Figure 4-8 (left panel), with a relatively low area of influence. Only small differences were shown between the 2020–21, pre-development and anthropogenic loading scenarios, with an area of limited anthropogenic DIN loading in the Wet Tropics region.

There is lower confidence in the pre-development DIN load in the Normanby basin (Cape York region) and, for this model, there is considered to be limited anthropogenic DIN. This is reflected in the difference map where there is very limited DIN influence in this area.

Trends in annual river-derived DIN loading to the Reef 2003–2021

The model-predicted river-derived DIN loading provides an estimate of the dispersion of end-of-catchment DIN loads in Reef waters, and the resulting maps highlight spatial and temporal variation in DIN loading. The time series from 2003 to 2021 (Figure 4-9) showed distinct inter-annual variability, driven by river flow and pollutant loads. The areas of influence in 2020–21 were comparable to other years with river discharge above the long-term median (for example,

2017-18) but considerably smaller than in the more extreme high-flow years, 2018-19 and 2010-11.

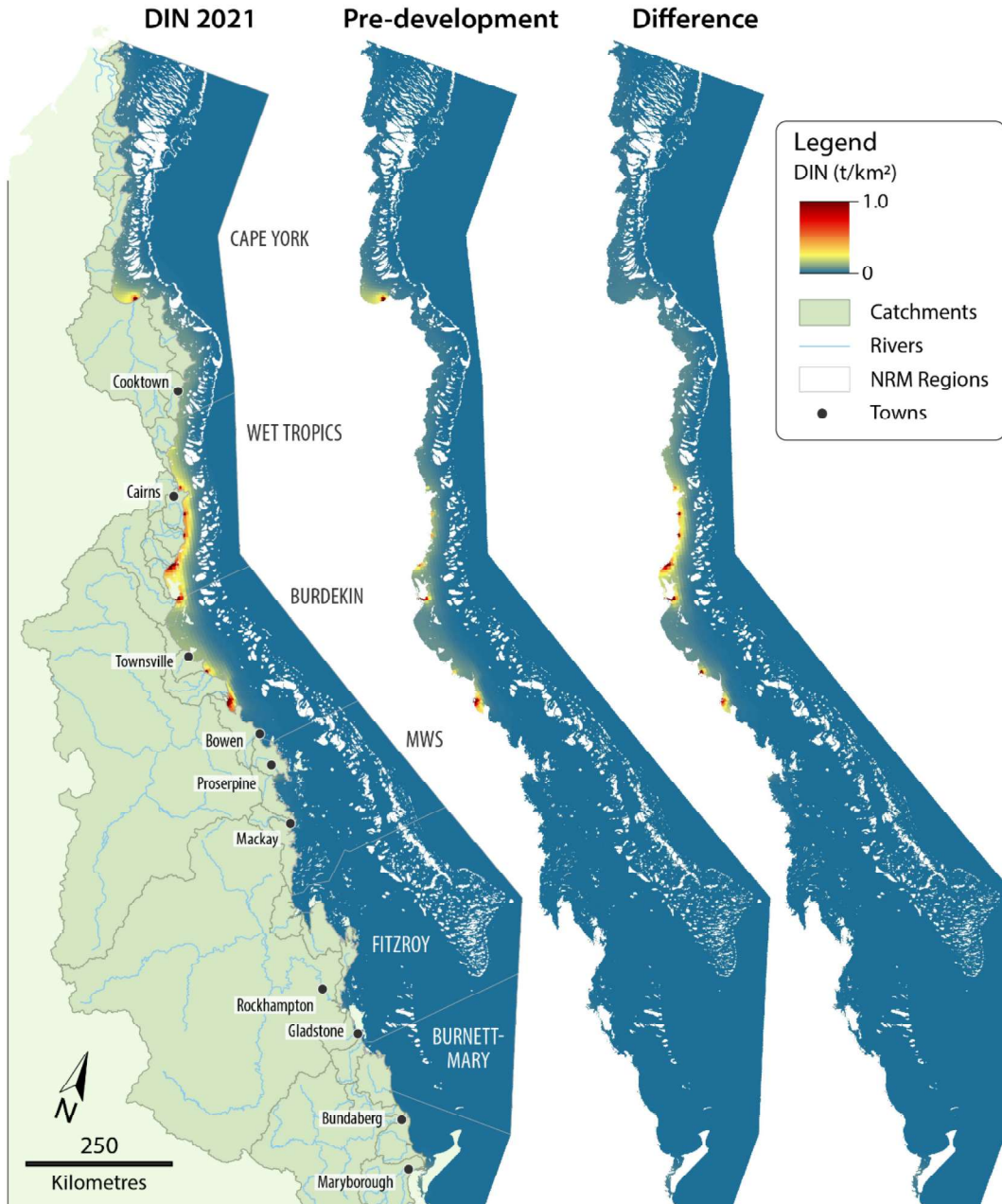


Figure 4-8: River-derived DIN loading (tonnes km⁻², relative scale) in the Reef lagoon, modelled for the (left panel) 2021 water year (1 October to 30 September), (centre panel) pre-development loads, and (right panel) difference between the DIN loading for pre-development and 2021 estimates.

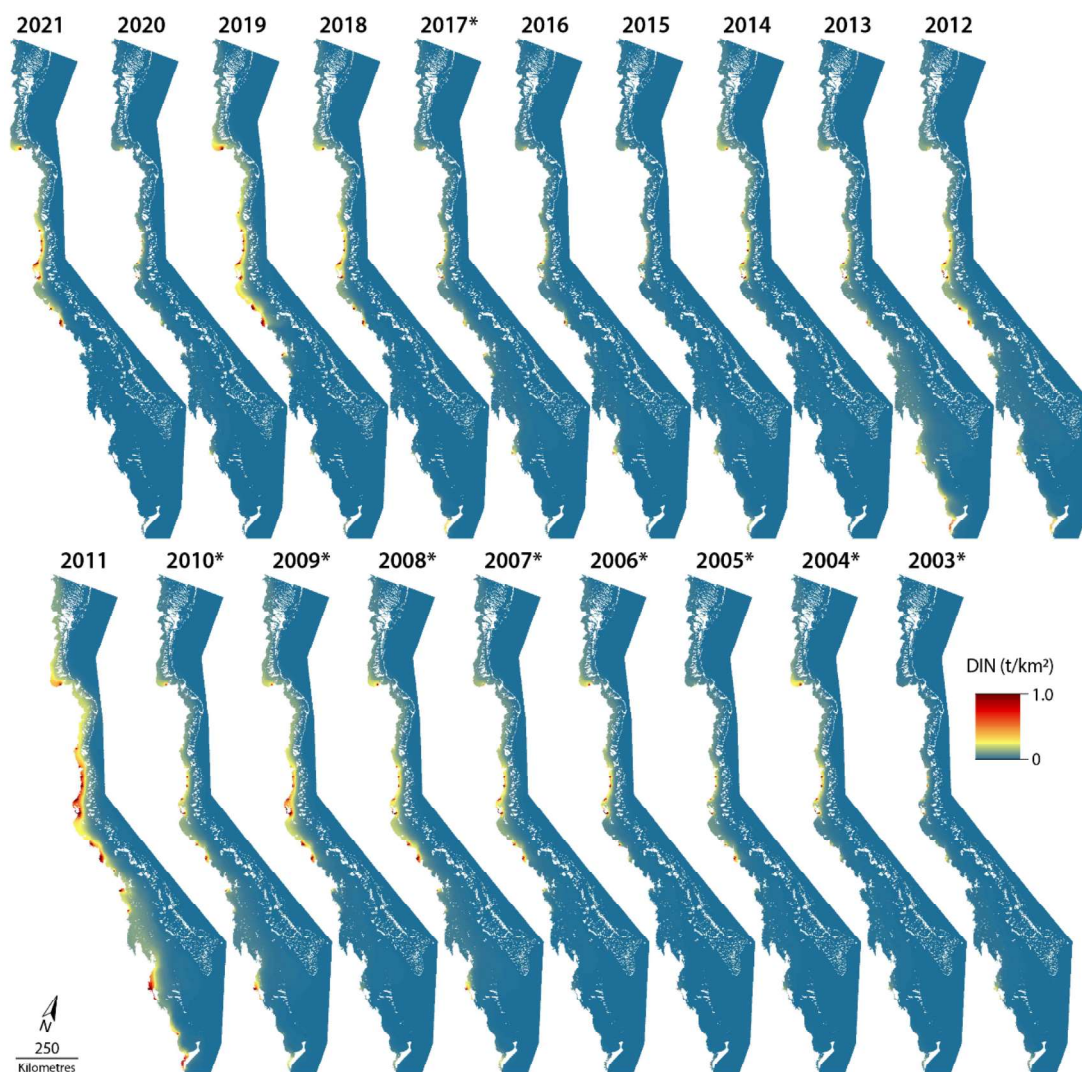


Figure 4-9: River-derived DIN loading (tonnes km^{-2} , relative scale) over the Reef lagoon for the 2003 to 2021 water years (1 October to 30 September). The years marked with asterisks are modelled using a multiannual average tracer.

The greatest extent of model-predicted DIN loading was observed in 2011 (associated with cyclone Yasi), with large areas of dispersed DIN estimated in all regions except for Cape York.

The regions presenting higher DIN loading have remained relatively constant over the years, with higher loading typically observed in the Wet Tropics, Burdekin, and Mackay-Whitsunday NRM regions. The greatest incidence of high DIN loading occurred in the Wet Tropics region in all years (although this is less obvious in 2019–20) and, within the Wet Tropics, the areas of greatest values were correlated with large river discharge events in 2009, 2011, 2018 and 2019. High loading was also observed in each region during different years. For example, high values in the Burdekin region in 2005, each year between 2008 and 2012, 2018 and 2019 (Figure 4-9).

4.2.2 River-derived TSS dispersal

The 2021 water year

The estimated wet season river derived TSS loading for the 2020-21 water year is shown in Figure 4-10 (left panel), with a limited area of influence. Notable differences were shown between the 2020-21 and pre-development loading scenarios, with the area of greatest anthropogenic influence in the Burdekin region.

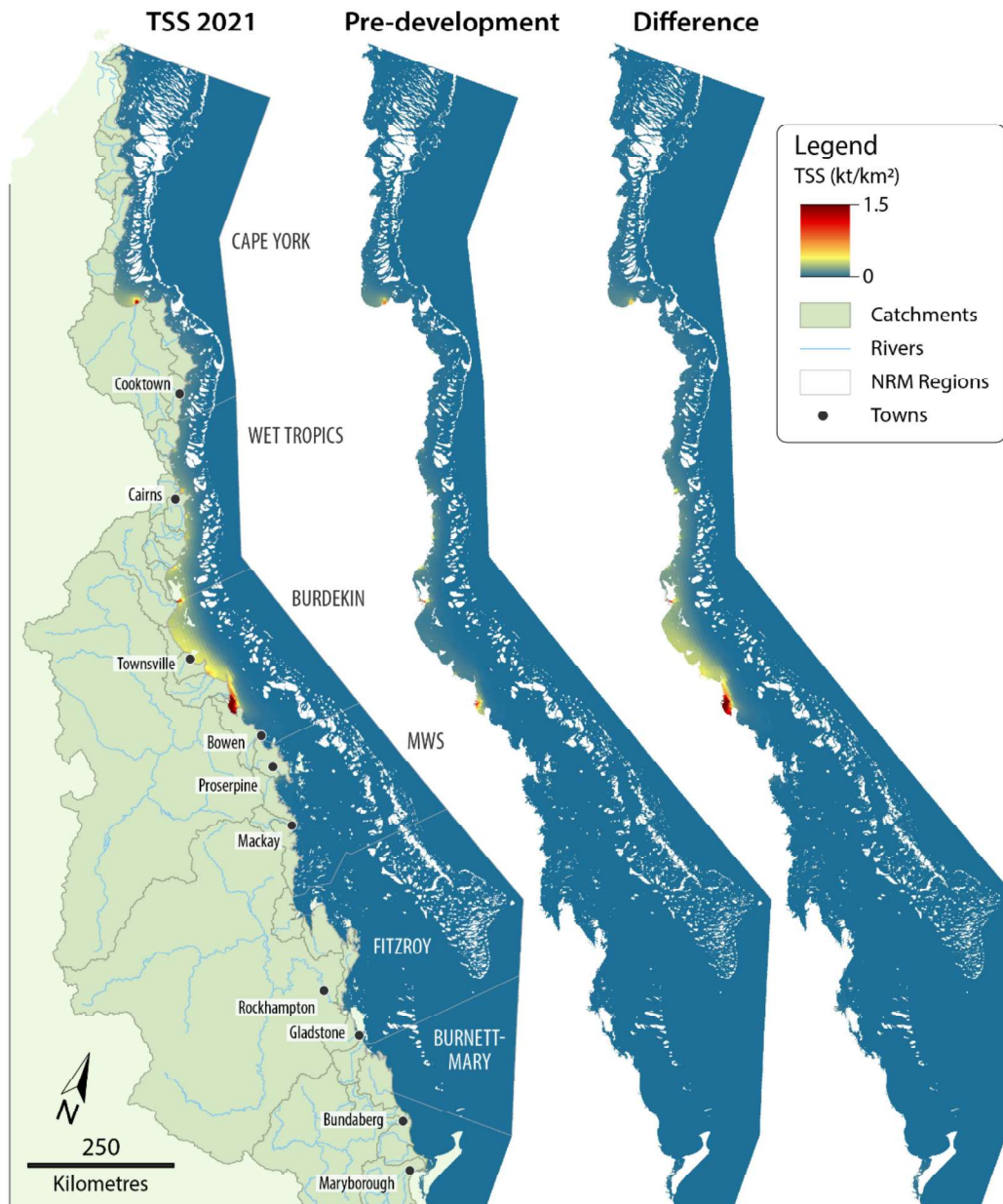


Figure 4-10: TSS (kilotonnes km⁻², relative scale) in the Reef lagoon, modelled for the (left panel) 2020-21 water year (1 October to 30 September), (centre panel) pre-development loads, and (right panel) difference between the TSS loading for pre-development and 2020-21 estimates.

While there has clearly been increased erosion in the Normanby basin since the pre-development scenario, there is still debate on the export/delivery of TSS to the Reef lagoon as sediment is deposited on the floodplain. Hence the model has treated the pre-development and current loads from the Normanby basin the same, as reflected in the difference map. This needs to be updated in future models as improved estimates are now available.

Trends in annual river-derived TSS loading to the Reef 2003–21

The time-series from 2003 to 2020 (Figure 4-11) showed distinct inter-annual differences, driven by river flow and pollutant loads. The areas of influence in 2020–21 were comparable to other years close to or slightly above the long-term median river discharge.

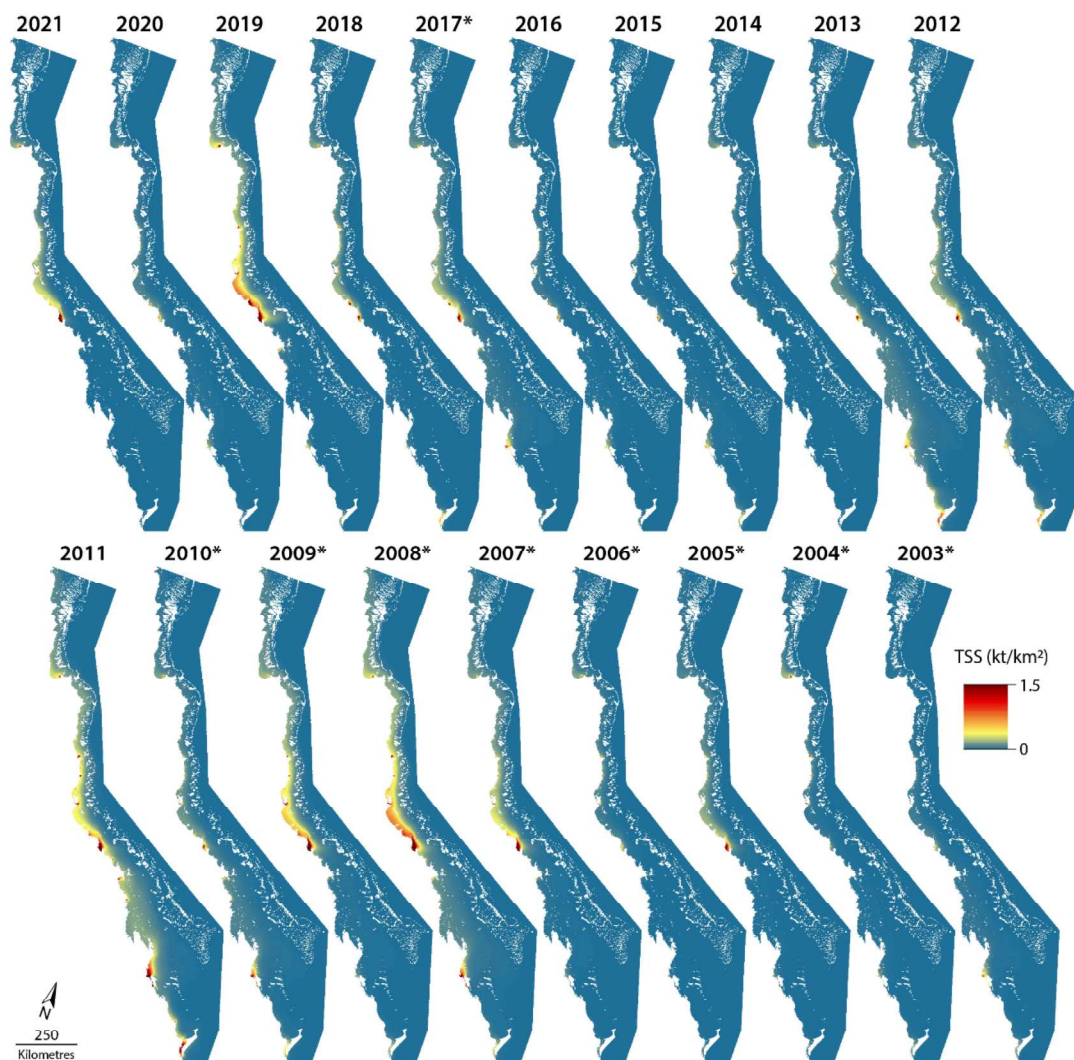


Figure 4-11: TSS loading (kilotonnes per km², relative scale) over the Reef lagoon for the 2003 to 2021 water years (1 October to 30 September). The years marked with asterisks are modelled using a multiannual average tracer.

The greatest extent was observed in 2011 linked to heavy rain associated with cyclone Tasha and the subsequent influence of severe cyclone Yasi. The regions with the highest TSS loading were typically the Burdekin, and to a lesser extent, the Fitzroy. The greatest frequency of the high river-derived TSS loading occurred in the Burdekin region and was correlated with large river discharge events (for example, in 2005, 2007–2009, 2011–2012, 2017 and 2019). High loading was also observed in each region in different years (Figure 4-11).

4.2.3 River-derived PN dispersal

The 2021 water year

The estimated wet season river derived PN loading for the 2020-21 water year is shown in Figure 4-12 (left panel) and showed similar patterns to both the DIN and TSS loading maps, with limited influence of PN loading along most of the Reef coast.

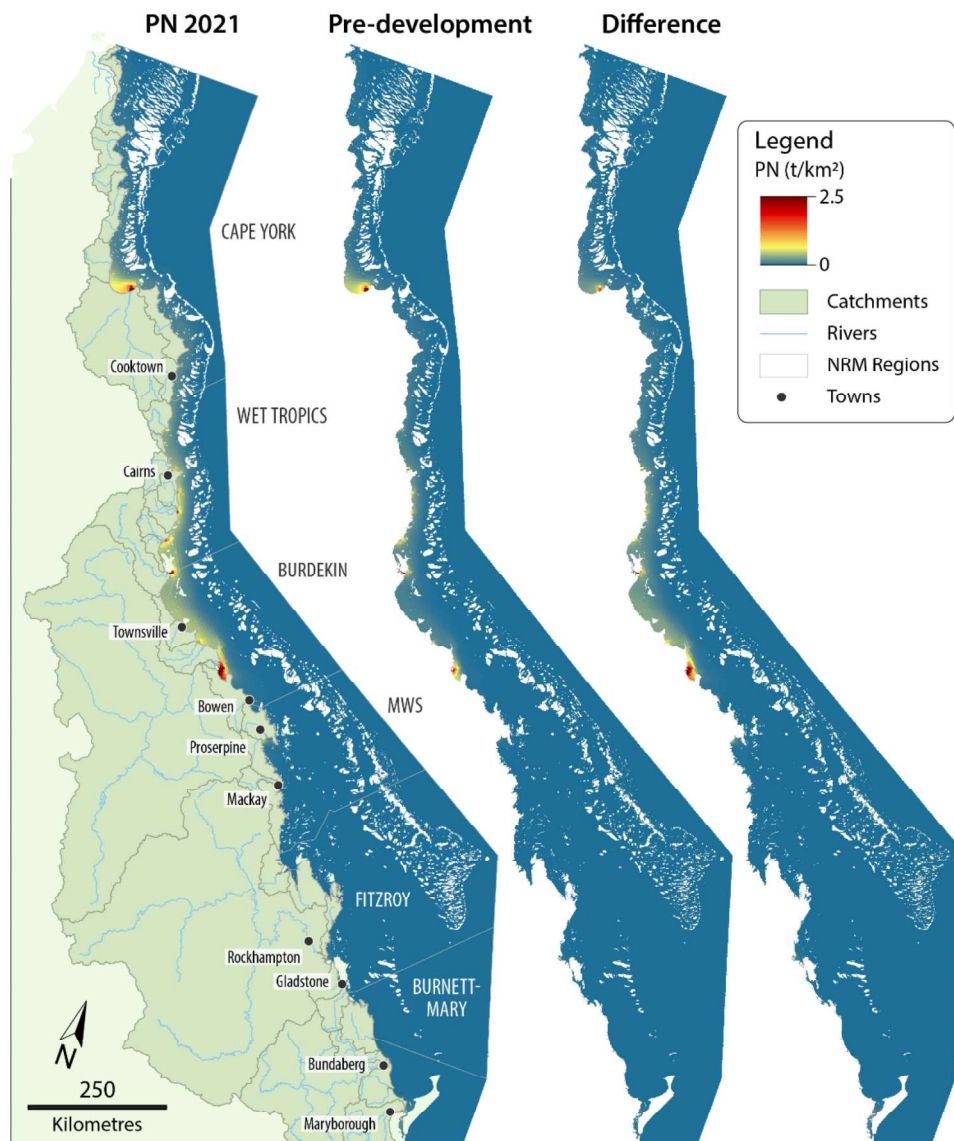


Figure 4-12: River-derived PN loading (tonnes km⁻², relative scale) in the Reef lagoon, modelled for the (left panel) 2021 water year (1 October to 30 September), (centre panel) pre-development loads, and (right panel) difference between the PN loading for pre-development and 2021 estimates.

The ‘anthropogenic’ influence map (Figure 4-12 right panel) was similar to the 2020–21 output, suggesting anthropogenic influence confined to coastal waters. The same issues exist for PN in the Normanby basin as described for DIN and TSS above, giving this result low certainty.

Trends in annual river-derived PN loading to the Reef 2003–2021

The times series from 2003 to 2021 for PN loading (Figure 4-13) also showed distinct inter-annual differences, driven by river flow and pollutant loads. The greatest extent of the higher model predicted PN loading was observed in 2008, 2009, 2011 (covering almost the entire Reef), 2013, 2017 and 2019. The areas with the highest PN loading in these years were typically in the Burdekin region.

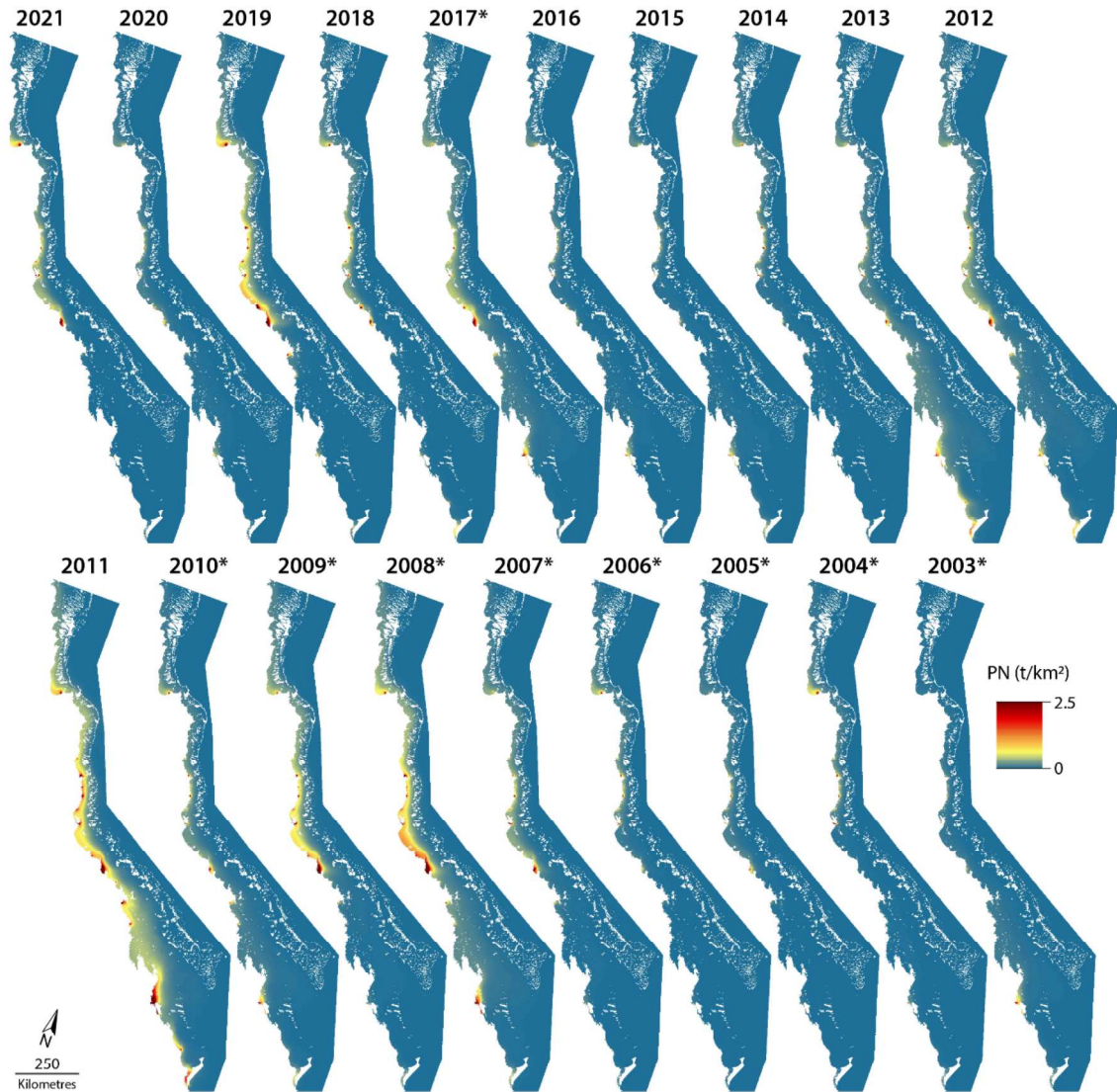


Figure 4-13: River-derived PN loading (tonnes km⁻², relative scale) over the Reef lagoon for the 2003 to 2021 water years (1 October to 30 September). The years marked with asterisks are modelled using a multi-annual average tracer.

4.3 Regional exposure of coastal waters and ecosystems to wet season discharge

The results of the remote sensing analysis for each region are presented below. This provides smaller-scale interpretation of the results, which can be highly variable between locations, thereby enhancing the relevance of the remote sensing products for regional managers.

4.3.1 Cape York region

As described for the Reef, a number of remote sensing products were generated to represent wet season water quality conditions in the Cape York region. These maps are presented in a panel of weekly characteristics throughout the 22-week wet season period (Figure 4-14 and Figure 4-15) and in Figure 4-16, which presents the frequency of the combined primary and secondary water types, the frequency of primary, secondary and tertiary wet season water types individually, the exposure maps in the long-term and 2020–21 wet season, and a difference map showing areas exposed to an increased risk in 2021. Details in the panels include river discharge, wind speed and direction, weekly maps of wet season colour classes, and the location and timing of *in situ* data collection.

The Sentinel monitoring products (when not obstructed by cloud cover) clearly illustrated wet season surface water movements in the Cape York region, as well as the influence of river discharge including changes in water colour from nutrient and sediment inputs and resuspension (Figure 4-14 and Figure 4-15). Discharge in the Cape York region was 1.5–2 times the long-term median (Section 3.2.2). There were two minor flood events around the end of January (weeks 8–9) and the end of April (weeks 21–22) and one larger event around late February-early March (weeks 12–14). The larger flood plumes were captured following this larger event off the Normanby, Stewart, Lockhart and Pascoe Rivers. The quality of the weekly composites around these dates was however degraded due to the frequent cloud cover.

Primary flood waters generally had minimal exposure on mid-shelf reefs in Princess Charlotte Bay and the Northern Cape York (Figure 4-16) but reached the mid-shelf waters of Princess Charlotte Bay in week 12. Secondary waters extended further offshore from early February and occasionally reached the mid-shelf reefs. No large primary plume was captured in the southern region of Cape York, but secondary and tertiary waters extended further offshore from mid-January (week 8) to early March (week 14) and occasionally reached the mid-shelf reefs.

Sampling of the Cape York waters occurred during and between the main flood events. A full description of water quality patterns and flood plumes is available in Section 5.1 of this report.

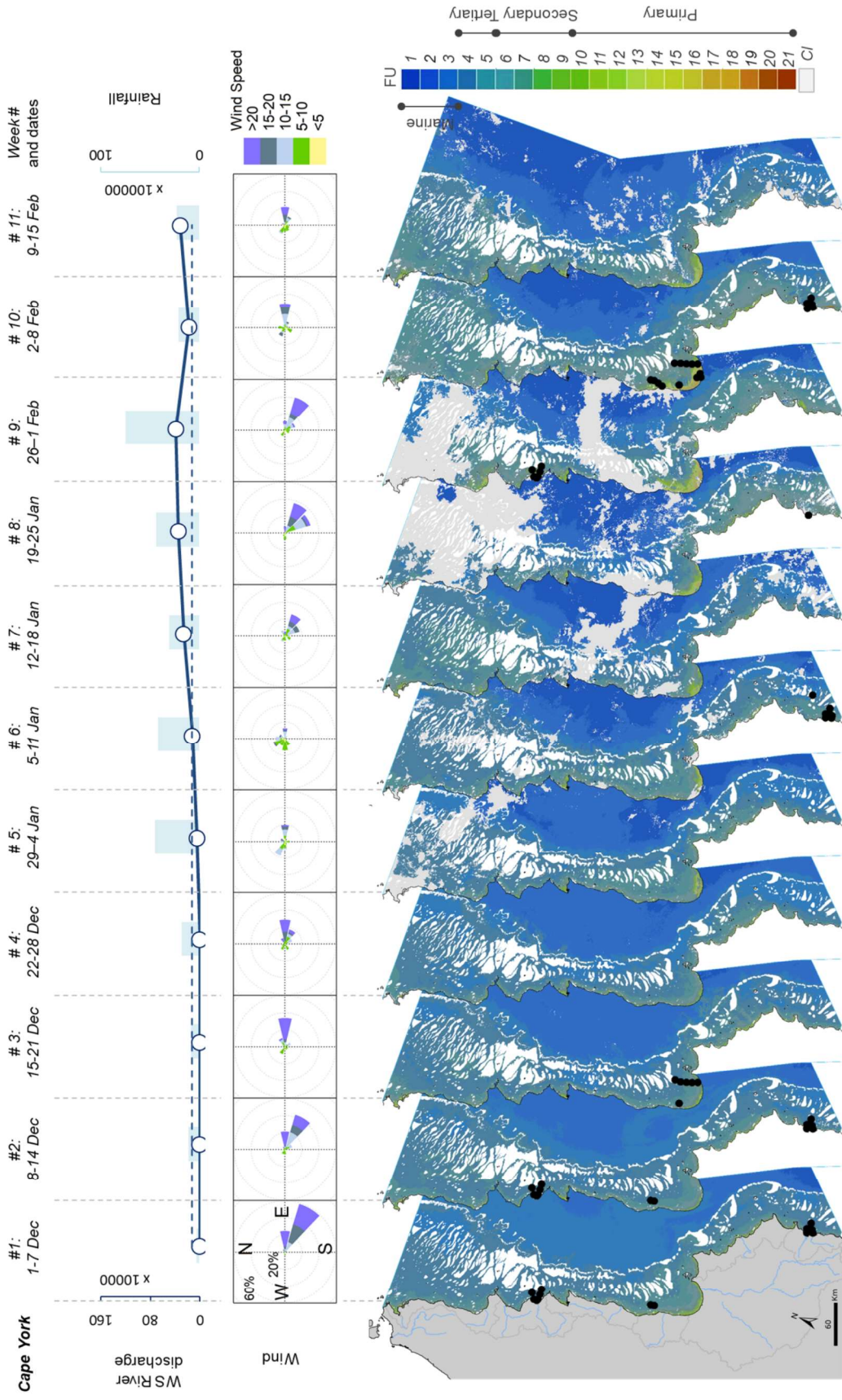


Figure 4-14: Panel of water quality and environmental characteristics in the Cape York region throughout the 2020–21 wet season period: weeks 1 to 11. Includes: 2020–21 weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h^{-1}) for each week; and FU colour class maps showing the location of the *in situ* data collected (black dots). The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the Pascoe, Stewart, Normanby and Endeavour Rivers.

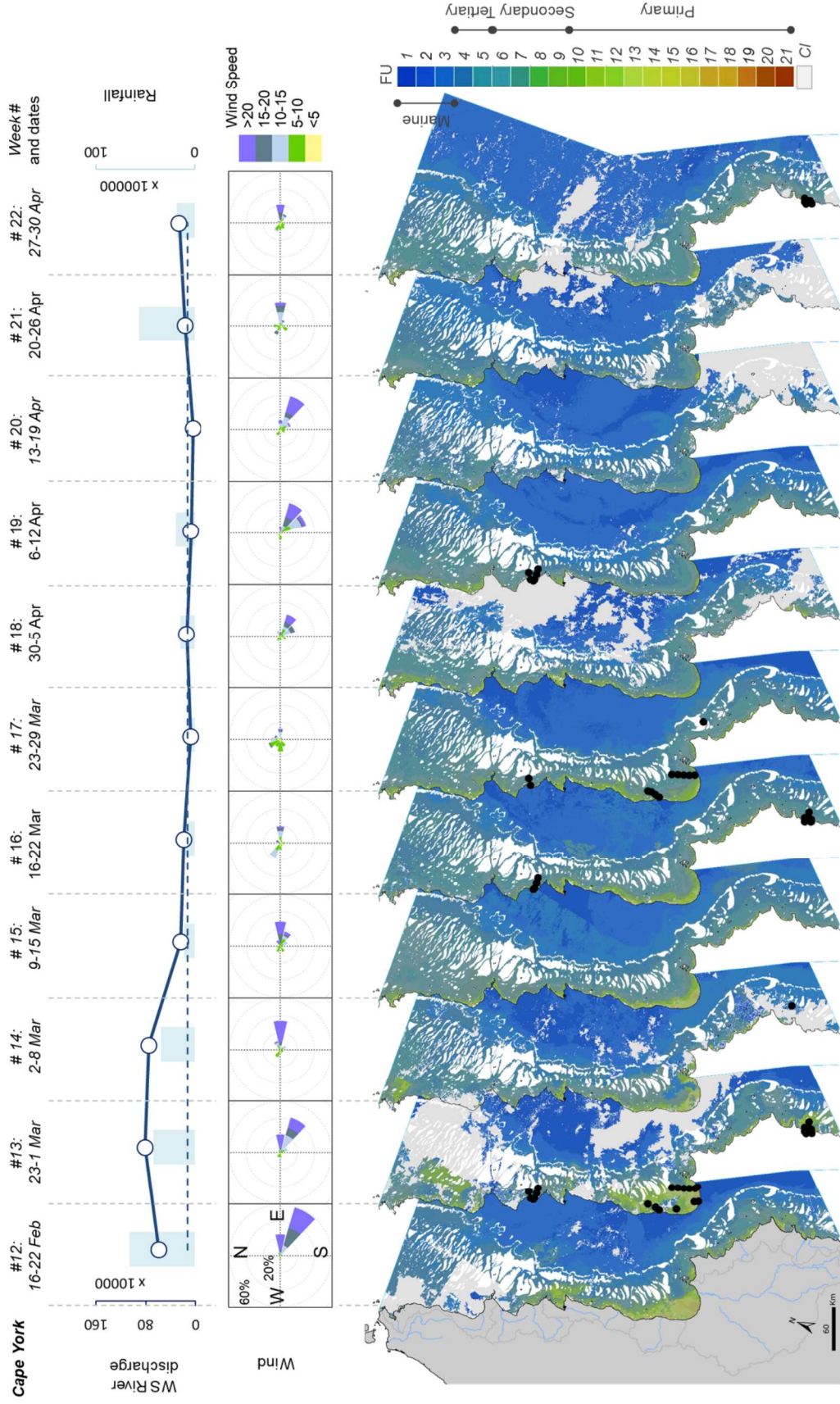


Figure 4-15: Panel of water quality and environmental characteristics in the Cape York region throughout the 2020–21 wet season period: weeks 12 to 22. Includes: 2020–21 weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h⁻¹) for each week; and FU colour class maps showing the location of the *in situ* data collected (black dots). The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the Pascoe, Stewart, Normanby and Endeavour Rivers.

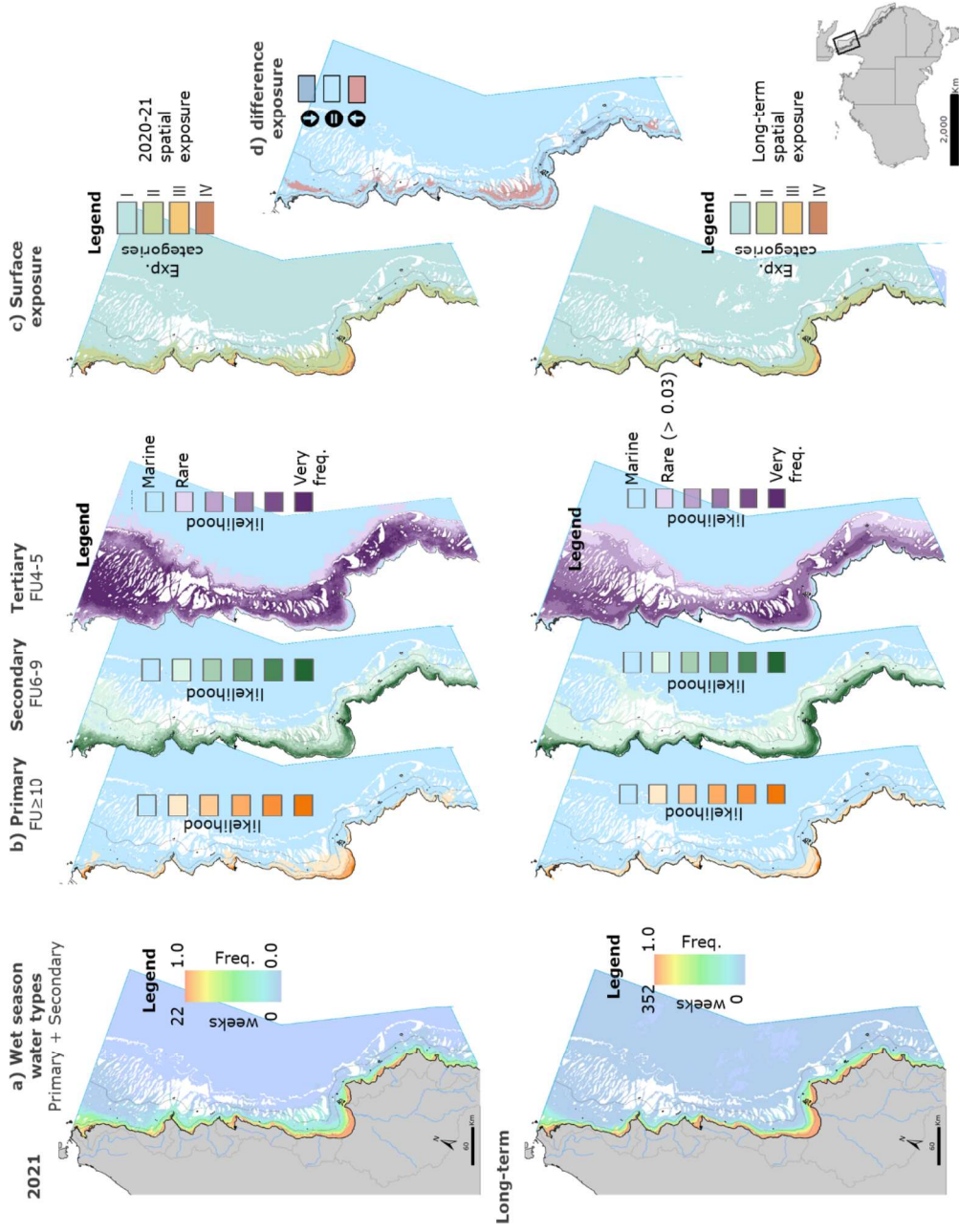


Figure 4-16: Long-term and current year remote sensing results for the Cape York region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), $0.2-0.4$, $0.4-0.6$, $0.6-0.8$ and $0.8-1$ (very frequent)]; c) exposure in the long-term (bottom) and 2020–21 wet season (top); and d) a difference map showing any areas with an increase (in red, \uparrow) or decrease (in purple, \downarrow) in risk category in 2020–21 against long-term trends [calculated as (c, top) exposure in 2021 minus (c, bottom) long-term]. Note that optical water types – especially the tertiary water type – do not always correspond to direct catchment discharge influence and can also be due to coastal and marine processes (see definitions in Table 2-2).

Table 4-3 presents the areas (km²) and percentages (%) of Cape York region, coral reef, and seagrass areas affected by different categories of exposure (or potential risk) based on satellite-derived wet season water types.

The exposure categories are not validated against ecological health data and represent relative potential risk categories for seagrass and coral reef ecosystems. Category I (No or Very low risk) represents waters with ambient or detectable but low water quality concentrations and therefore low risk of any detrimental ecological effect. Areas exposed to category I are presented in Table 4-3, but not described below. The areas and percentages of ecological communities affected by the different categories of exposure were calculated as a relative measure between regions and the long-term average.

In 2020–21, it was estimated that:

- Cape York region: Approximately 85% of Cape York was not exposed to a potential risk, similar to long-term patterns (89%, Table 4-3). Approximately 15% (or 14,277 km²) of the Cape York region was exposed to combined potential risk categories II–IV. However, only 1% (483 km²) of the Cape York region was in the highest exposure category (IV) and 2% (1,704 km²) was in category III.
- Cape York waterbodies: The mid-shelf and offshore Cape York waterbodies were largely exposed to no / very low risk (64% and 98% of the Cape York mid-shelf and offshore waterbodies). Only the enclosed coastal and open coastal Cape York waters were exposed to the highest categories of potential risk (III and IV). The area exposed was however spatially limited and corresponded to 53% (cat. III) and 22% (cat. IV) of the total Cape York enclosed coastal area (Figure 4-7c) and 10% of the open coastal areas (open coastal areas were not exposed to cat. IV).
- Cape York habitats:
 - **Coral reefs:** Approximately 76% of Cape York reefs were not exposed to a potential risk. Less than 1% of corals were in the highest exposure category (IV) and 1% in category III (combined 161 km²) (Table 4-3) and they were all inshore - and more particularly enclosed coastal - reefs (Figure 4-17 a). Approximately 1% and 2% (< 300 km²) of the Cape York corals reefs occur in the enclosed and open coastal waters, respectively (Appendix C-6).

The coral area exposed to higher potential risk corresponded to 51% (cat. III) and 37% (cat. IV) of the total enclosed coastal coral reef area in Cape York, and to 30% (cat. III) and only 3% (cat. IV) of the total open coastal coral reef area. Mid-shelf reefs were exposed to the lower risk category II or to no / very low risk (56% and 44% of the total mid-shelf coral reef area in Cape York). 88% of the Cape York offshore reefs were classified as no / very low risk (Figure 4-17 a).

- **Seagrasses:** Approximately 63% (or 1,670 km²) of seagrasses in the Cape York region were exposed to combined potential risk categories II–IV (Table 4-3), 5% (131 km²) of seagrasses were in the highest exposure category (IV) and 14% were in category III (379 km²), and they were all inshore- and more particularly enclosed coastal - seagrasses (Figure 4-17 b). A total of 27% and 40% (~ 1800 km²) of the Cape York seagrass occur in the enclosed and inshore waters respectively (Appendix C-6).

The seagrass area exposed to higher potential risk corresponded to 40% (cat. III) and 18% (cat. IV) of the total enclosed coastal seagrass area in Cape York and to only 9% (cat. III) of the total open coastal seagrass area. Mid-shelf and Offshore seagrasses were largely classified as no / very low risk (89% and 75% of the Cape York mid-shelf and offshore seagrasses).

- **Comparison to long-term trends:** The coral areas exposed to highest potential risk categories III and IV were similar to the long-term patterns (<2% of the coral reefs). There was however an increase in the coral area exposed to the lowest potential risk category (II: +17%). The seagrass areas exposed to highest potential risk categories III and IV were similar to the long-term patterns. There was however a decrease in the seagrass area exposed to the lowest potential risk category (II: -8%).

Table 4-3: Areas (km²) and percentages (%) of the Cape York region, coral reefs, and surveyed seagrass affected by different categories of exposure during the 2020–21 wet season and the long-term. The last three rows show the differences between % affected in 2020–21 and the long-term average (■: increase, ■: decrease, ■: no change, difference <5%). Areas south of the Marine Park (Hervey Bay) are not included.

Cape York		Total		Potential Risk category				Total area exposed II-IV	
				No / Very low	Lowest		Highest		
					I	II	III		IV
Surface area	area	96,316	2021	82,039	12,091	1,704	483	14,277	
			LT	86,044	8,649	1,125	498	10,272	
	%	100%	2021	85%	13%	2%	1%	15%	
			LT	89%	9%	1%	1%	11%	
Coral reefs	area	10,375	2021	7,932	2,282	113	48	2,443	
			LT	9,837	496	34	8	538	
	%	100%	2021	76%	22%	1%	<1%	24%	
			LT	95%	5%	<1%	<1%	5%	
Surveyed seagrass	area	2,655	2021	986	1,160	379	131	1,670	
			LT	777	1,371	319	189	1,878	
	%	100%	2021	37%	44%	14%	5%	63%	
			LT	29%	52%	12%	7%	71%	
<i>Difference (2021 – Long Term average)</i>		<i>Surface area</i>		-4%	4%	1%	<1%	4%	
		<i>Coral Reef</i>		-19%	17%	<1%	<1%	19%	
		<i>Surveyed seagrass</i>		8%	-8%	2%	-2%	-8%	

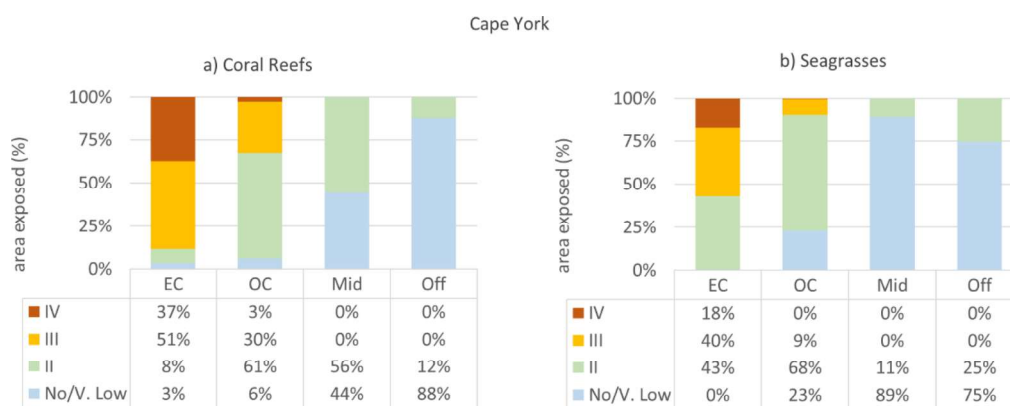


Figure 4-17: Percentage of the Cape York region a) coral reef and b) seagrass habitats affected by different risk categories of exposure during the 2020–21 wet season.

4.3.2 Wet Tropics region

As described for the Reef, a number of remote sensing products were generated to represent wet season water quality conditions in the Wet Tropics region. These maps are presented in a panel of weekly characteristics throughout the 22-week wet season period (Figure 4-18 and Figure 4-19) and in Figure 4-20, which presents the frequency of the combined primary and secondary water types; the frequency of primary, secondary and tertiary wet season water types individually; the exposure maps in the long-term and 2020–21 wet season; and a difference map showing areas exposed to an increased risk in 2021. Details in the panels include river discharge, wind speed and direction, weekly maps of wet season colour classes, and the location and timing of *in situ* data collection.

The Sentinel monitoring products (when not obstructed by cloud cover as around weeks 5, 7, 13 and 21) clearly illustrated wet season surface water movements in the Wet Tropics region, as well as the influence of river discharge including changes in water colour from nutrient and sediment inputs and resuspension (Figure 4-18 and Figure 4-19). Discharge in the Wet Tropics region was over but less than 1.5 times the long-term median (Section 3.2.2). There were three flood events influencing the Wet Tropics during the 2020–21 wet season: around mid-January (weeks 5 and 6), the end of February to early March (weeks 12–14) and the end of April (week 21).

Weekly composites of the Wet Tropics region and the primary likelihood map (Figure 4-20b) showed that primary waters were confined to the Wet Tropics river mouths and in the enclosed coastal waters most of the wet season. Tully primary waters ($FU \geq 10$) reached the open coastal waters (including Dunk Island) and the mid-shelf waters off the Tully and Johnstone Rivers in week 12 (16 to 22 February), most probably linked to greater rainfall in week 12. However, generally, primary flood waters had minimal impact on the open coastal and mid-shelf regions and ecosystems of the Wet Tropics in 2020–21. Secondary waters extended further offshore from end of January to early March and reached the mid-shelf region. This was also the period of greatest discharge in the region. Off the Barron River, a large primary plume was observed on week 6 (5 to 11 January) reaching the mid-shelf region and Green Island reefs were occasionally exposed to secondary waters in January (weeks 6, 8, 10 and 22). A larger band of primary water was also observed all along the wet tropic coast and reaching the open coastal waters in early April (week 18). This was not linked to any rainfall even but rather potentially linked to strong south-easterly winds measured during this week.

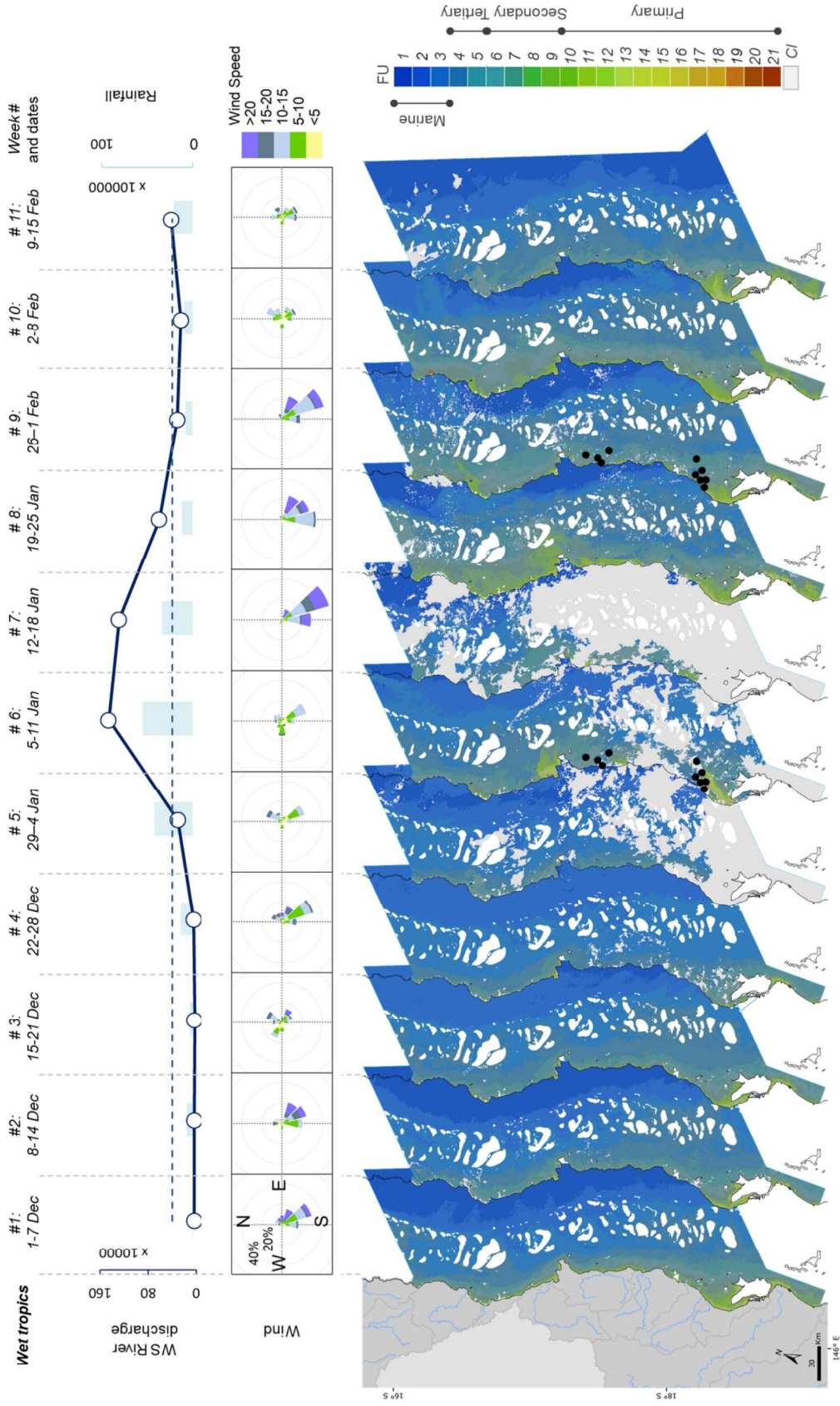


Figure 4-18: Panel of water quality and environmental characteristics in the Wet Tropics region throughout the 2020–21 wet season period: weeks 1 to 11. Includes: 2020–21 weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h⁻¹) for each week; and FU colour class maps showing the location of the *in situ* data collected (black dots). The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the Barron, Daintree, Herbert, Mossman, Mulgrave, Murray, North Johnstone, Russell, South Johnstone and Tully Rivers.

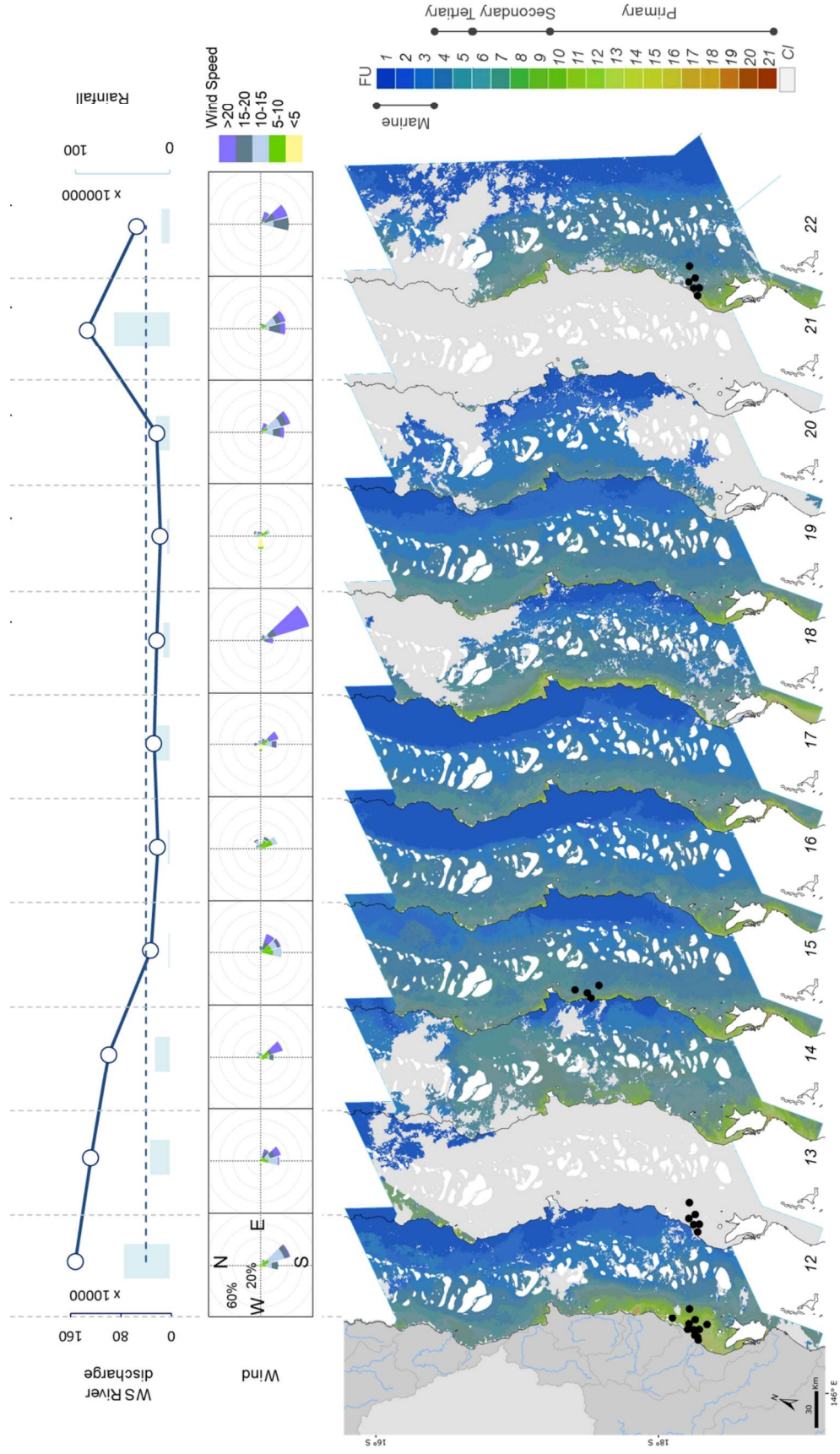


Figure 4-19: Panel of water quality and environmental characteristics in the Wet Tropics region throughout the 2020–21 wet season period: weeks 12 to 22. Includes: 2020–21 weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h⁻¹) for each week; and FU colour class maps showing the location of the *in situ* data collected (black dots). The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the Barron, Daintree, Herbert, Mossman, Mulgrave, Murray, North Johnstone, Russell, South Johnstone and Tully Rivers.

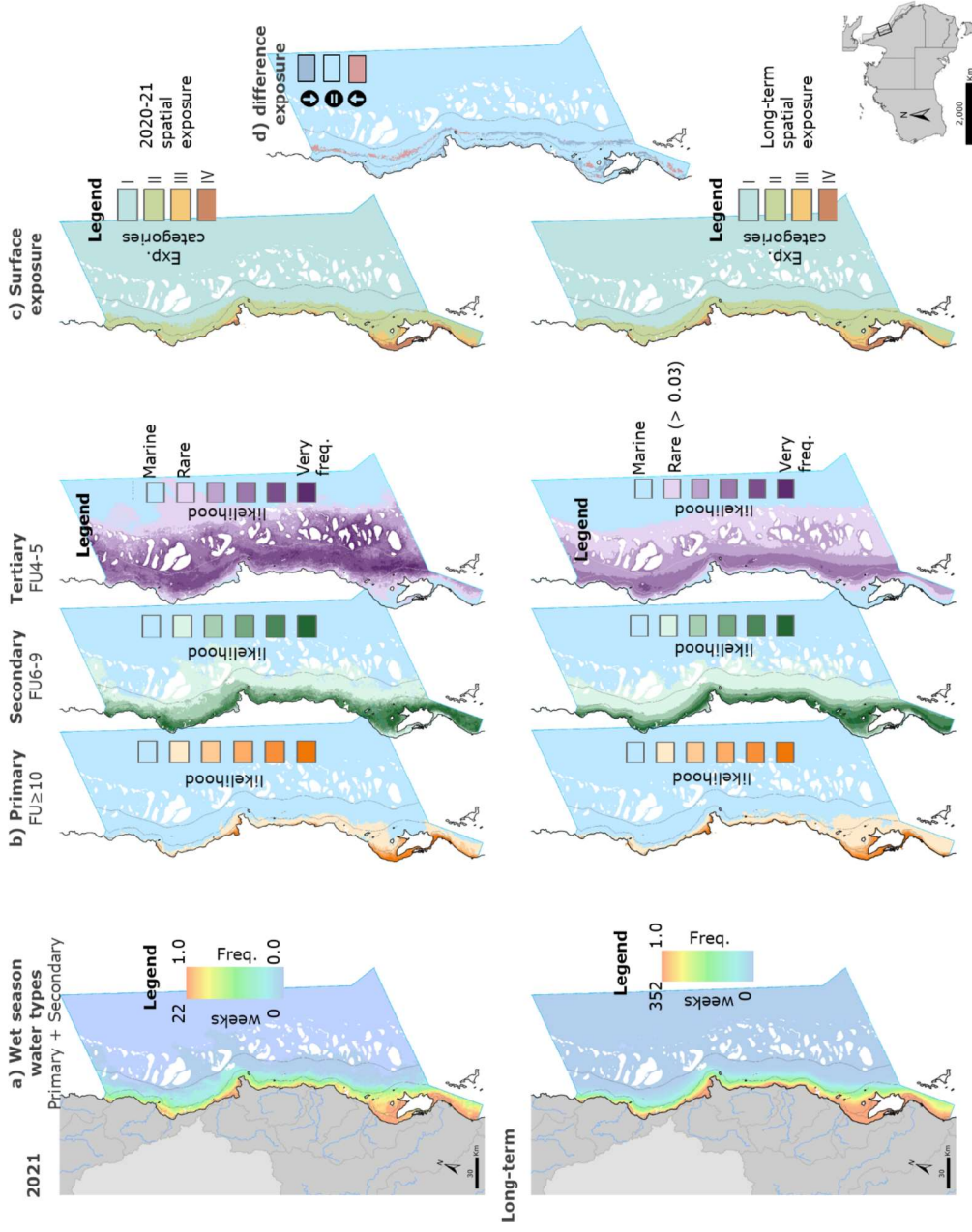


Figure 4-20: Long-term and current year remote sensing results for the Wet Tropics region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), $0.2-0.4$, $0.4-0.6$, $0.6-0.8$ and $0.8-1$ (very frequent)]; c) exposure in the long-term (bottom) and 2020–21 wet season (top); and d) a difference map showing any areas with an increase (in red, \oplus) or decrease (in purple, \ominus) in risk category in 2020–21 against long-term trends [calculated as (c, top) exposure in 2021 minus (c, bottom) long-term]. Note that optical water types – especially the tertiary water type – do not always correspond to direct catchment discharge influence, and can also be due to coastal and marine processes (see definitions in Table 2-2).

Table 4-4 presents the areas (km²) and percentage (%) of Wet Tropics region, coral reef, and seagrass areas affected by different categories of exposure (or potential risk) based on satellite-derived wet season water maps.

The exposure categories are not validated against ecological health data and represent relative potential risk categories for seagrass and coral reef ecosystems. Category I (No or Very low risk) represents waters with ambient or detectable but low water quality concentrations and therefore low risk of any detrimental ecological effect. Areas exposed to category I are presented in Table 4-4, but not described below. The areas and percentages of ecological communities affected by the different categories of exposure were calculated as a relative measure between regions and the long-term average.

In 2020–21, it was estimated that:

- Wet-Tropics wide: 84% of the Wet Tropics region was not exposed to a potential risk, similar to long-term patterns (84%, Table 4-4). 16% (or about 5000 km²) of the Wet Tropics region was exposed to combined potential risk categories II–IV. However, only 1% (399 km²) of the region was in the highest exposure category (IV) and only 2% was in category III (707 km²).
- Wet Tropics waterbodies: only the enclosed coastal and open coastal Wet Tropics waters were exposed to the highest categories of potential risk (III and IV). The open coastal area exposed was however spatially limited and corresponded to 14% (cat. III) and 1% (cat. IV) of the total Wet Tropics inshore area (Figure 4-7c). A total of 40% and 53% of the enclosed coastal areas were exposed to categories III and IV respectively. The mid-shelf and offshore Wet Tropics waterbodies were largely exposed to no/very low risk (76% and 100% of the Wet Tropics mid-shelf and offshore waterbodies).
- Wet Tropics habitats:
 - **Coral reefs:** 4% of coral reefs in the Wet Tropics region were exposed to a potential risk (combined potential risk categories II–IV) (Table 4-4). However, less than 1% of coral were in the highest exposure category (IV), 1% were in the category III (combined 41 km²) and they were all enclosed coastal or open coastal reefs (Figure 4-21a). Only 3% (~ 80 km²) of the Wet Tropics corals occur in the inshore waters (Appendix C-6).

The open coastal coral area exposed to higher potential risk was limited and corresponded to 38% (cat. III) and 5% (cat. IV) of the total open coastal reef area in the Wet Tropics. A total of 51% and 43% of the enclosed coastal areas were exposed to categories III and IV respectively. Mid-shelf reefs were largely exposed to no potential risk (>90% of the total mid-shelf and offshore reef areas in the Wet Tropics).

- **Seagrasses:** A total of 99% (or 229 km²) of seagrasses in the Wet Tropics region were exposed to a potential risk (combined potential risk categories II–IV) (Table 4-4). A total of 28% (65 km²) of seagrasses were in the highest exposure category (IV) and 37% (85 km²) were in category III, and they were all inshore seagrasses (Figure 4-21b). 98% (~230 km²) of the Wet Tropics seagrass occur in the inshore waters (Appendix C-6).

The open coastal seagrass area exposed to higher potential risk was limited. It corresponded to 24% (cat. III) and 1% of the total inshore coastal seagrass in the Wet Tropics. A total of 46% and 48% of the total enclosed coastal seagrass were exposed to categories III and IV, respectively. Mid-shelf seagrasses were largely classified as no / very low risk (62% of the Wet Tropics mid-shelf seagrasses) or the lowest category of potential risk (II: 38% of the Wet Tropics mid-shelf seagrasses).

- **Comparison to long-term trends:** The coral and seagrass areas in the Wet Tropics region exposed to combined potential risk categories II–IV in 2019–20 were similar to the average long-term areas (changes ≤ 5%).

Table 4-4: Areas (km²) and percentages (%) of the Wet Tropics region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2020–21 wet season and the long-term. The last three rows show the differences between % affected in 2020–21 and the long-term average (red: increase, blue: decrease, green: no change, difference <5%). Areas south of the Marine Park (Hervey Bay) are not included.

Wet Tropics		Total		Potential Risk category				Total area exposed II-IV
				No / Very low	Lowest Highest			
					I	II	III	
Surface area	area	31,976	2021	26,890	3,979	707	399	5,086
			LT	26,928	3,919	710	419	5,048
	%	100%	2021	84%	12%	2%	1%	16%
			LT	84%	12%	2%	1%	16%
Coral reefs	area	2,425	2021	2,339	45	32	9	86
			LT	2,380	34	10	2	46
	%	100%	2021	96%	2%	1%	<1%	4%
			LT	98%	1%	<1%	<1%	2%
Surveyed seagrass	area	232	2021	3	79	85	65	229
			LT	14	40	79	99	219
	%	100%	2021	1%	34%	37%	28%	99%
			LT	6%	17%	34%	43%	94%
<i>Difference (2021 – Long-term average)</i>		<i>Surface area</i>		<1%	<1%	<1%	<1%	0%
		<i>Coral Reef</i>		-2%	1%	<1%	<1%	2%
		<i>Surveyed seagrass</i>		-5%	17%	3%	15%	5%

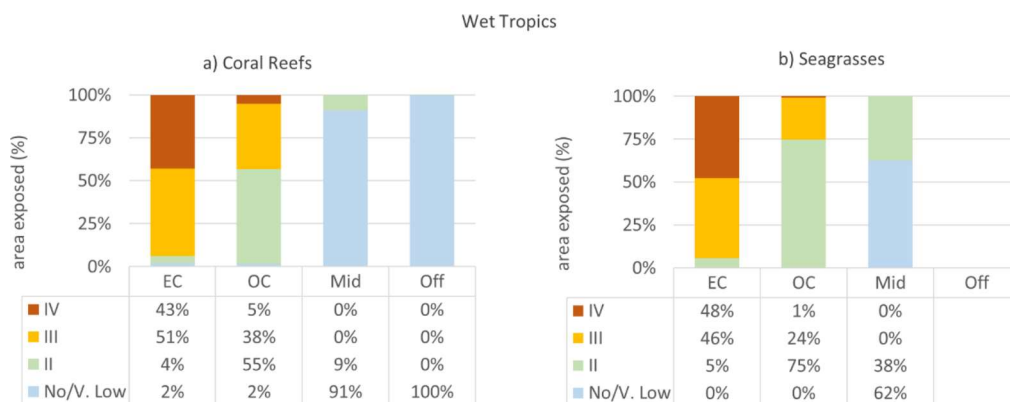


Figure 4-21: Percentage of the Wet Tropics region a) coral reef and b) seagrass habitats affected by different risk categories of exposure during the 2020–21 wet season.

4.3.3 Burdekin region

As described for the Reef, a number of remote sensing products were generated to represent wet season water quality conditions in the Burdekin region. These maps are presented in a panel of weekly characteristics throughout the 22-week wet season period (Figure 4-22 and Figure 4-23) and in Figure 4-24, which presents the frequency of the combined primary and secondary water types; the frequency of primary, secondary and tertiary wet season water types individually; the exposure maps in the long-term and 2020–21 wet season; and a difference map showing areas exposed to an increased risk in 2021. Details in the panels include river discharge, wind speed and direction, weekly maps of wet season colour classes, and the location and timing of *in situ* data collection.

The Sentinel monitoring products (when not obstructed by cloud cover as in weeks 5–7) clearly illustrated wet season surface water movements in the Burdekin region, as well as the influence of river discharge including changes in water colour from nutrient and sediment inputs and resuspension (Figure 4-22 and Figure 4-23). Discharge in the Burdekin region was less than 1.5 to 2 times the long-term median during the 2020–21 wet season (Section 3.2.2). One major flood event influenced the Burdekin region around mid-January (weeks 5–7) and one smaller around end of February (week 13).

Weekly composites and the primary likelihood map (Figure 4-24) of the Burdekin region showed that primary waters were confined next to the Burdekin River mouth and in the enclosed coastal waters most of the wet season. Burdekin primary waters ($FU \geq 10$) reached the open coastal waters in weeks 6 to 10 and in week 14 following both the major and smaller discharge events (weeks 5 to 7 and week 13). Ross primary waters also reached the open coastal waters, including magnetic island in weeks 14. Generally, however, primary waters had minimal impact on the open coastal and mid-shelf regions and ecosystems of the Burdekin region in 2020–21. Secondary waters extended further offshore from week 8 (19 to 25 January) and in week 14 reached the boundary between the open coastal and mid-shelf region, which could also be linked to the elevated discharge in the previous week. As in the Wet Tropics, a larger band of primary water was also observed all along the coast and reaching the open coastal waters in early April (week 18), which could potentially be linked to strong south-easterly winds measured during this week.

Table 4-5 presents the areas (km^2) and percentage (%) of Burdekin region, coral reef, and seagrass areas affected by different categories of exposure (or potential risk) based on satellite-derived wet season water types.

The exposure categories are not validated against ecological health data and represent relative potential risk categories for seagrass and coral reef ecosystems. Category I (No or Very low risk) represents waters with ambient or detectable but low water quality concentrations and therefore low risk of any detrimental ecological effect. Areas exposed to category I are presented in Table 4-5, but not described below. The areas and percentages of ecological communities affected by the different categories of exposure were calculated as a relative measure between regions and the long-term average.

In 2020–21, it was estimated that:

- Burdekin-wide: 89% of Burdekin region was not exposed to a potential risk, similar to long-term patterns (86%, Table 4-5). 11% (or about 5,300 km^2) of the Burdekin region was exposed to combined potential risk categories II–IV. However, only 1% (584 km^2) of the region was in the highest exposure category (IV) and 2% (1,084 km^2) was in category III.
- Burdekin waterbodies: only the enclosed coastal and open coastal Burdekin waters were exposed to the highest categories of potential risk (III and IV). The open coastal area exposed was however spatially limited and corresponded to 17% (cat. III) and 1% (cat. IV) of the total Burdekin open coastal area (Figure 4-7c), 36% and 60% of the enclosed coastal areas were exposed to categories III and IV respectively. The mid-shelf and

offshore Burdekin waterbodies were largely exposed to no / very low risk (96% and 100% of the Burdekin mid-shelf and offshore waterbodies).

- Burdekin habitats:

- **Coral reefs:** Approximately 2% of coral reefs in the Burdekin region were exposed to combined potential risk categories II–IV. However, less than 1% of corals were in the highest exposure categories IV and III (combined 19 km²) (Table 4-5). Only 1% (< 40 km²) of the Burdekin corals occur in the inshore waters (Appendix C-6).

The open coastal coral area exposed to higher potential risk was limited and corresponded to 48% (cat. III) of the total inshore coral reef area in the Burdekin region (no open coastal reefs were exposed to the higher risk category IV) (Figure 4-25a). A total of 63% and 36% of the enclosed coastal areas were exposed to categories III and IV respectively. Mid-shelf and offshore coral reefs were largely exposed to no / very low risk (91% and 100% of the total mid-shelf reef area in the Burdekin region).

- **Seagrasses:** Approximately 92% (or 649 km²) of seagrasses in the Burdekin region were exposed to combined potential risk categories II–IV (Table 4-5). Only 17% (124 km²) of seagrasses were in the highest exposure category (IV) and 29% (208 km²) were in category III, and they were all inshore seagrasses (Figure 4-25b). A total of 99% (~700 km²) of the Burdekin seagrasses occur in the inshore waters (Appendix C-6).

The open coastal seagrass area exposed to higher potential risk was limited and corresponded to 26% (cat. III) of the total inshore seagrass area in the Burdekin region (no open coastal reefs were exposed to the higher risk category IV). A total of 38% and 60% of the enclosed coastal areas were exposed to categories III and IV respectively. Mid-shelf seagrasses were largely exposed to the lower category of risk (II, 69% of the Burdekin mid-shelf seagrasses) or to no / very low risk (31% of the Burdekin mid-shelf seagrasses).

- **Comparison to long-term trends:** The coral and seagrass areas in the Burdekin region exposed to combined potential risk categories II–IV in 2020–21 were both similar to the average long-term areas (changes <5%).

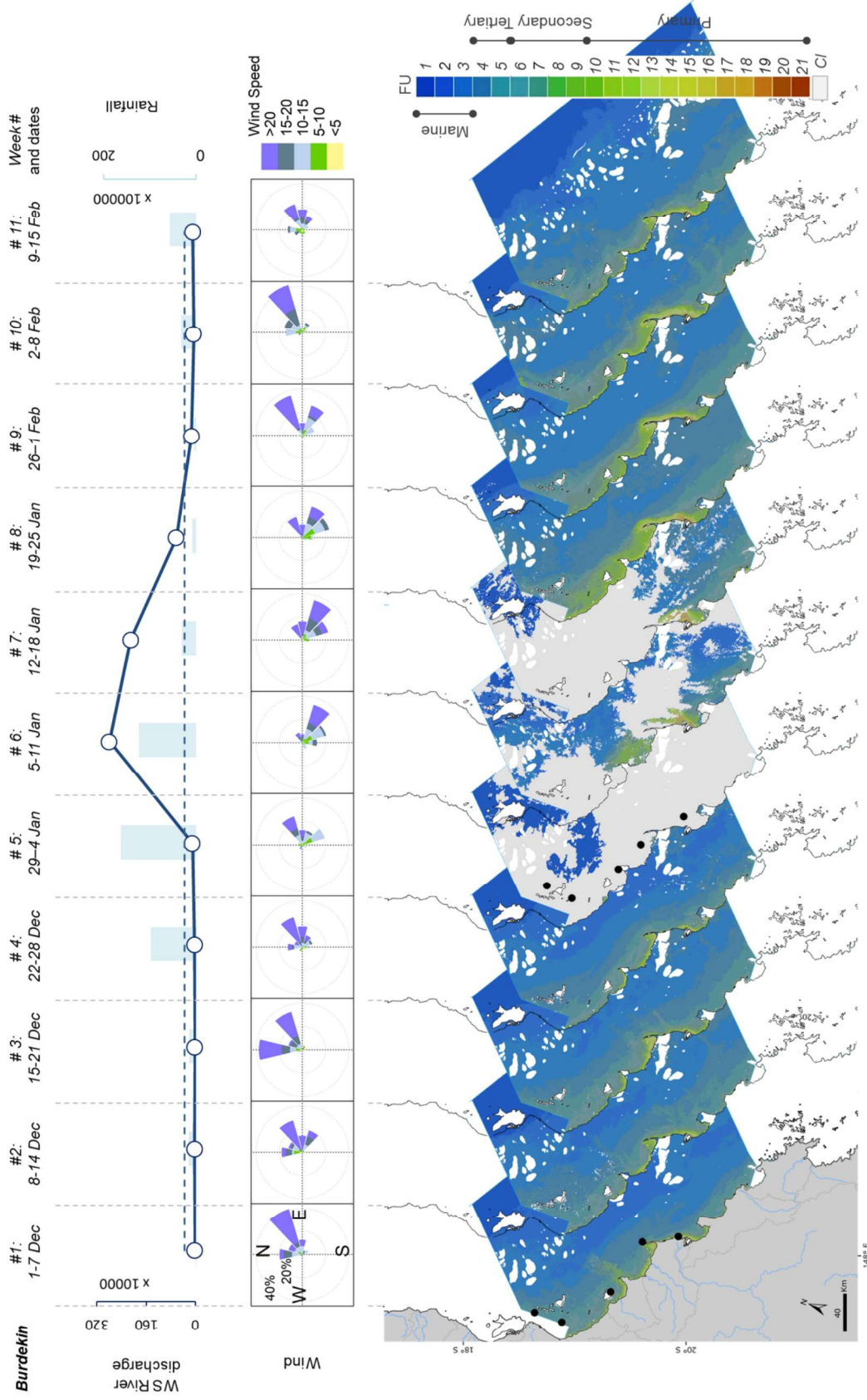


Figure 4-22: Panel of water quality and environmental characteristics in the Burdekin region throughout the 2020–21 wet season period: weeks 1 to 11. Includes: 2020–21 weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h⁻¹) for each week; and FU colour class maps showing the location of the *in situ* data collected (black dots). The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the Black, Ross, Haughton, Burdekin and Don rivers.

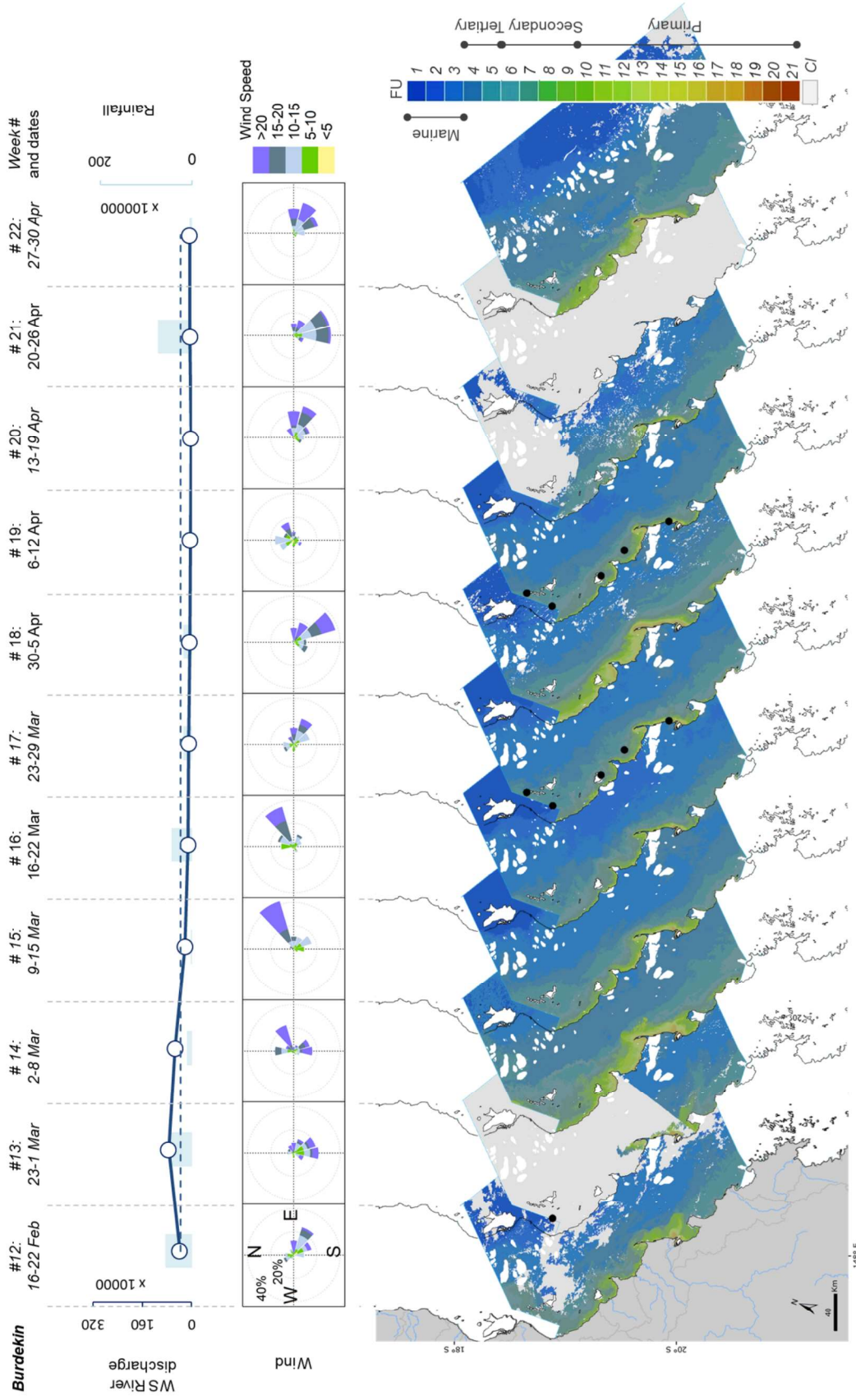


Figure 4-23: Panel of water quality and environmental characteristics in the Burdekin region throughout the 2020–21 wet season period: weeks 12 to 22. Includes: 2020–21 weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h⁻¹) for each week; and FU colour class maps showing the location of the *in situ* data collected (black dots). The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the Black, Ross, Haughton, Burdekin and Don rivers.

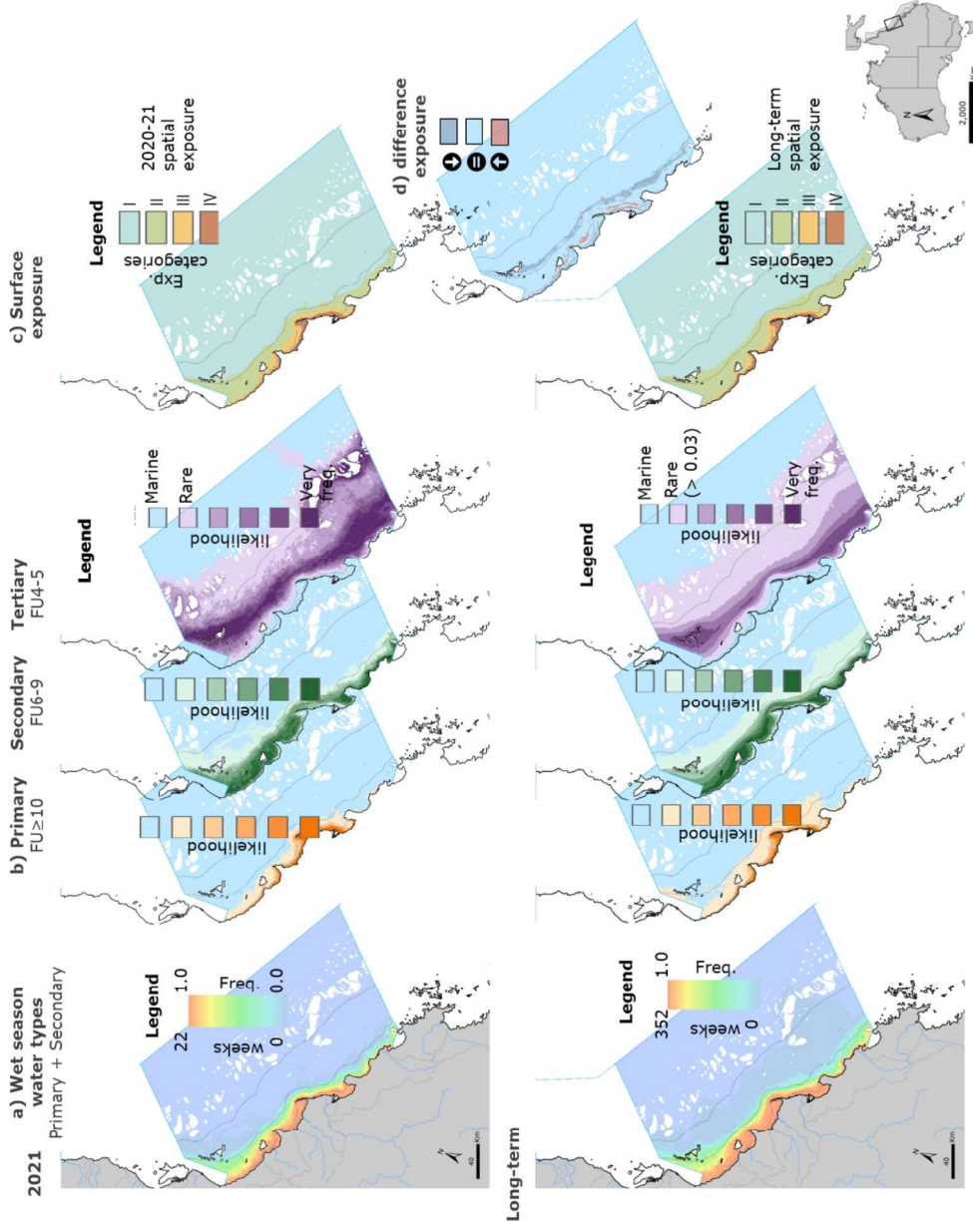


Figure 4-24: Long-term and current year remote sensing results for the Burdekin region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), $0.2-0.4$, $0.4-0.6$, $0.6-0.8$ and $0.8-1$ (very frequent)]; c) exposure in the long-term (bottom) and 2020–21 wet season (top); and d) a difference map showing any areas with an increase (in red, \oplus) or decrease (in purple, \ominus) in risk category in 2020–21 against long-term trends [calculated as (c, top) exposure in 2021 minus (c, bottom) long-term]. Note that optical water type – especially the tertiary water type – do not always correspond to direct catchment discharge influence, and can also be due to coastal and marine processes (see definitions in Table 2-2).

Table 4-5: Areas (km²) and percentages (%) of the Burdekin region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2020–21 wet season and the long-term (2003–2018). The last three rows show the differences between % affected in 2021 and the long-term average (■: increase, ■: decrease, ■: no change, difference <5%). Areas south of the Marine Park (Hervey Bay) are not included.

Burdekin		Total		Potential Risk category				Total area exposed II-IV
				No / very low	Lowest		Highest	
					I	II	III	
Surface area	area	47,009	2021	41,685	3,656	1,084	584	5,324
			LT	40,627	4,867	914	602	6,382
	%	100%	2021	89%	8%	2%	1%	11%
			LT	86%	10%	2%	1%	14%
Coral reefs	area	2,966	2021	2,914	33	17	2	53
			LT	2,916	36	13	1	50
	%	100%	2021	98%	1%	1%	<1%	2%
			LT	98%	1%	<1%	<1%	2%
Surveyed seagrass	area	708	2021	59	318	208	124	649
			LT	32	346	184	146	676
	%	100%	2021	8%	45%	29%	17%	92%
			LT	5%	49%	26%	21%	95%
<i>Difference (2021 – Long Term average)</i>		<i>Surface area</i>		3%	-2%	<1%	<1%	-3%
		<i>Coral Reef</i>		<1%	<1%	<1%	<1%	0%
		<i>Surveyed seagrass</i>		3%	-4%	3%	-4%	-3%

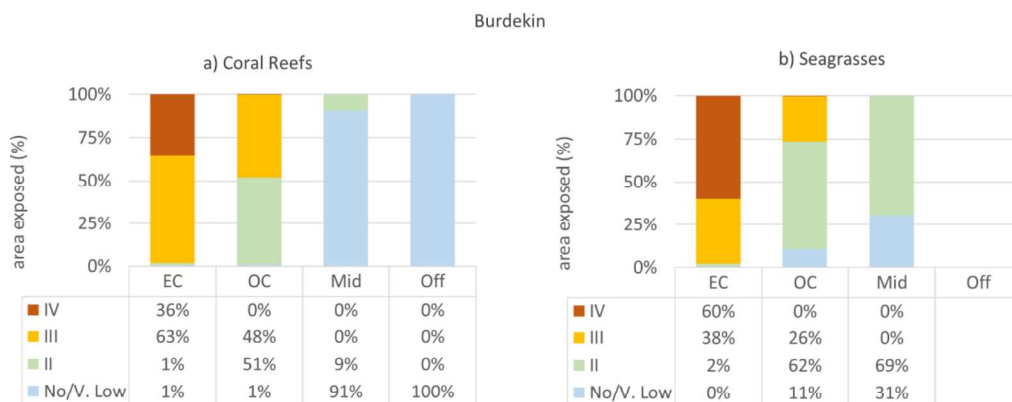


Figure 4-25: Percentage of the Burdekin region a) coral reef and b) seagrass habitats affected by different risk categories of exposure during the 2020–21 wet season.

4.3.4 Mackay-Whitsunday region

As described for the Reef, a number of remote sensing products were generated to represent wet season water quality conditions in the Mackay-Whitsunday region. These maps are presented in a panel of weekly characteristics throughout the 22-week wet season period (Figure 4-26 and Figure 4-27) and in Figure 4-28, which presents the frequency of the

combined primary and secondary water types; the frequency of primary, secondary and tertiary wet season water types individually; the exposure maps in the long-term and 2020–21 wet season; and a difference map showing areas exposed to an increased risk in 2021. Details in the panels include river discharge, wind speed and direction, weekly maps of wet season colour classes, and the location and timing of *in situ* data collection.

The Sentinel-3 monitoring products (when not obstructed by cloud cover as in weeks 5-6) clearly illustrated wet season surface water movements in the Mackay-Whitsunday region, as well as the influence of river discharge including changes in water colour from nutrient and sediment inputs and resuspension (Figure 4-26 and Figure 4-27). Discharge in the Mackay-Whitsunday region was under the long-term median (Section 3.2.2) and no major flood events influenced the region during the 2020–21 wet season.

Weekly composites and the primary likelihood map (Figure 4-28) of the Mackay-Whitsunday region showed that primary waters were confined to the river mouths and in the enclosed coastal waters most of the wet season. Primary waters (CC4) reached the open coastal waters in week 7, following a small rainfall event in week 6 (5 to 11 January), but, generally, primary flood waters had minimal impact on the open coastal and mid-shelf regions and ecosystems of the Mackay-Whitsunday region in 2020–21. Secondary waters extended largely into the open coastal region from mid-January and reached the mid-shelf region in week 11 (9 to 15 February). There were also relatively larger primary and secondary areas in weeks 14 and 18. This does not appear to be linked to any discharge events and could rather be linked to wind-driven resuspension. Similarly, tertiary water also frequently affected the mid-shelf and offshore reefs of the Mackay-Whitsunday region in 2020–21, which did not seem to be linked to the riverine discharge in the region. Possible explanations include upwelling productivity or temperature related influences (see also Section 4.1).

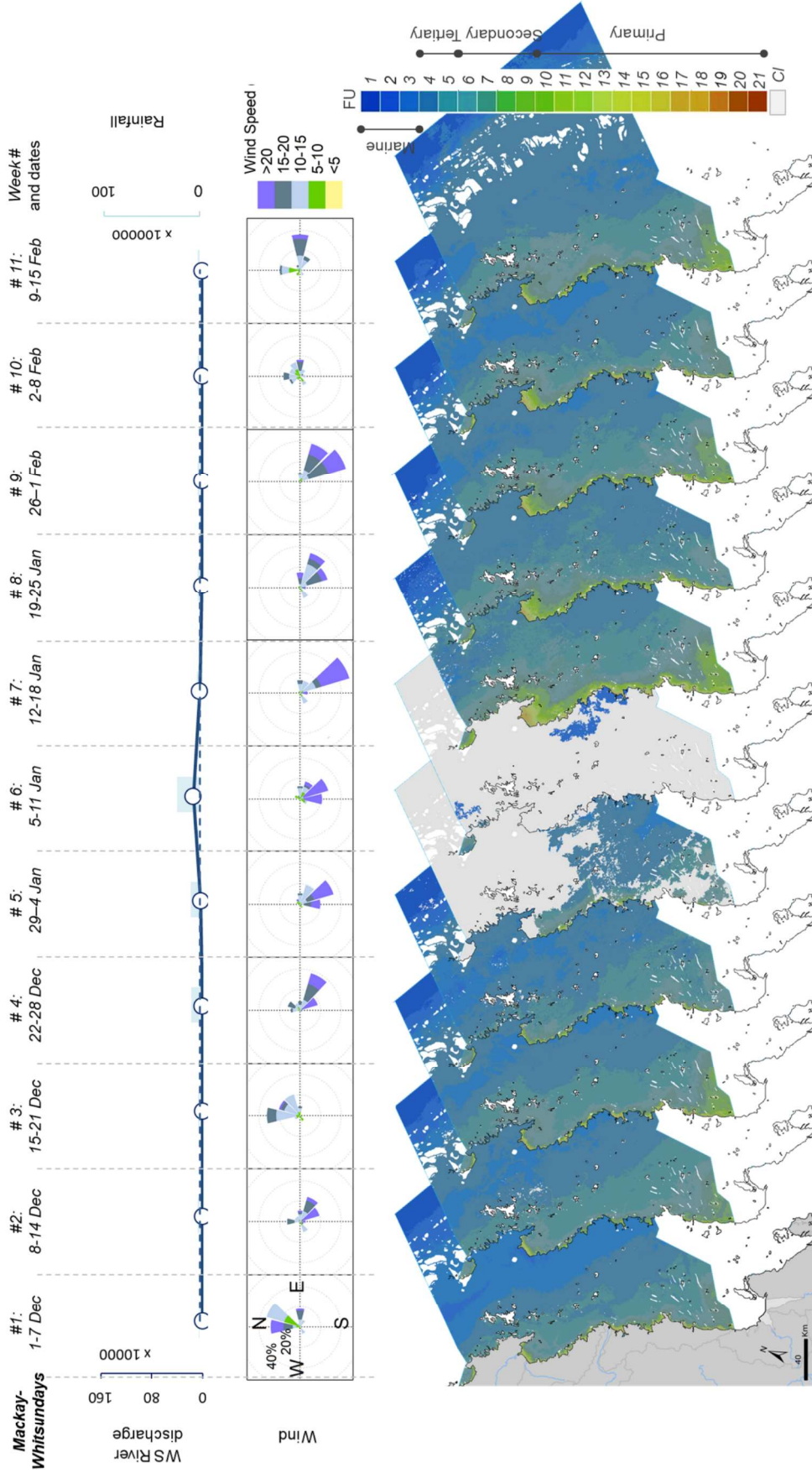


Figure 4-26: Panel of water quality and environmental characteristics in the Mackay-Whitsunday region throughout the 2020–21 wet season period: weeks 1 to 11. Includes: 2020–21 weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h-1) for each week; and FU colour class maps showing the location of the *in situ* data. The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the O’Connell and Pioneer Rivers and Sandy Creek.

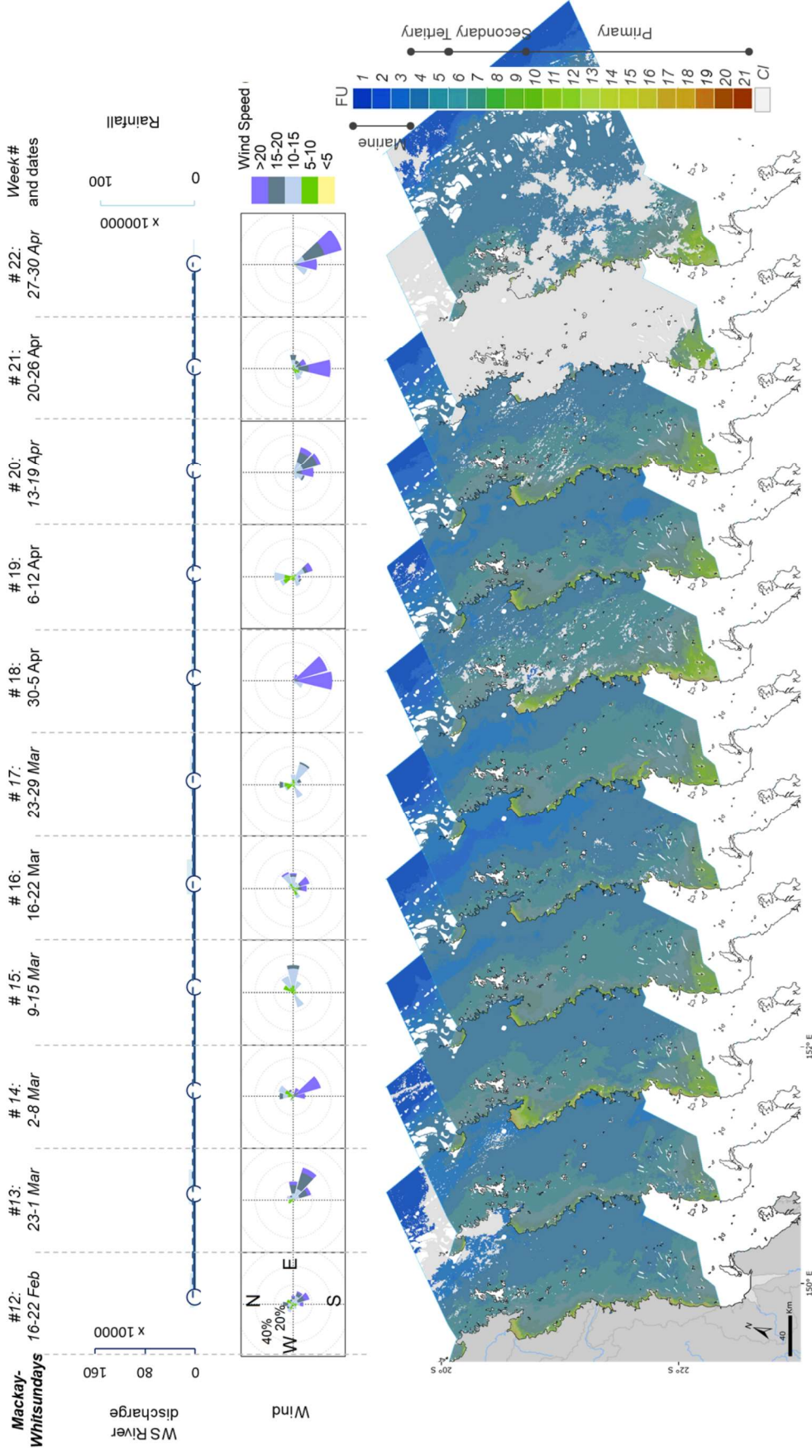


Figure 4-27: Panel of water quality and environmental characteristics in the Mackay-Whitsunday region throughout the 2020-21 wet season period: weeks 12 to 22. Includes: weekly river discharge (ML) and rainfall (ML); wind roses showing the wind direction and speed (km h^{-1}) for each week; and FU colour class maps showing the location of the *in situ* data. The mean long-term weekly river discharge is indicated by a dotted blue line. Weekly river discharges are the sum of discharge (ML) from the O'Connell and Pioneer Rivers and Sandy Creek.

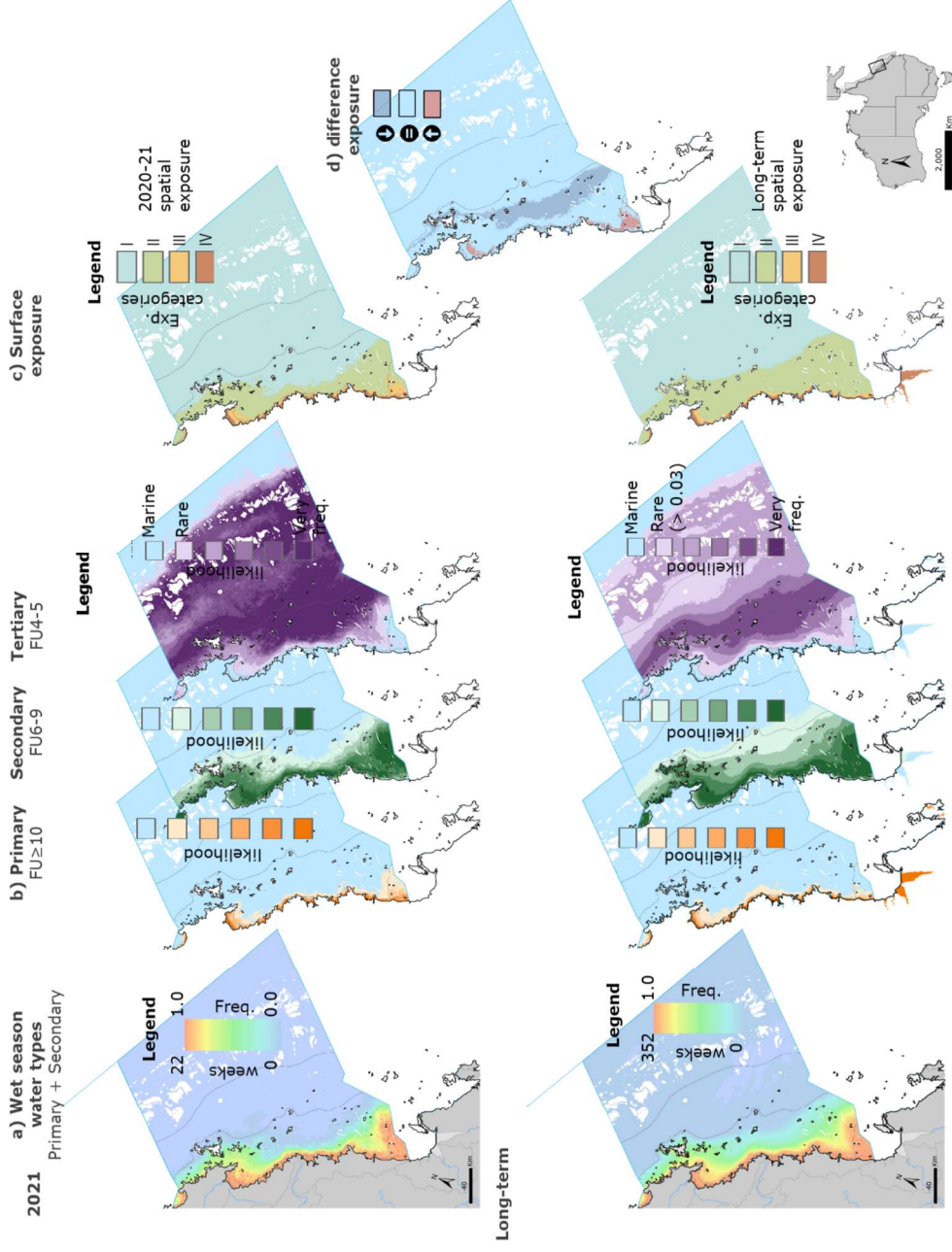


Figure 4-28: Long-term and current year remote sensing results for the Mackay-Whitsunday region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), $0.2-0.4$, $0.4-0.6$, $0.6-0.8$ and $0.8-1$ (very frequent)]; c) exposure in the long-term (bottom) and 2020–21 wet season (top); and d) a difference map showing areas with an increase (in red, \oplus) or decrease (in purple, \ominus) in risk category in 2020–21 against long-term trends [calculated as (c, top) exposure in 2020 minus (c, bottom) long-term]. Note that optical water types – especially the tertiary water type – do not always correspond to direct catchment discharge influence, and can also be due to coastal and marine processes (see definitions in Table 2-2)..

Table 4-6 presents the areas (km²) and percentage (%) of Mackay-Whitsunday region, coral reef, and seagrass areas affected by different categories of exposure (or potential risk) based on satellite-derived wet season water types.

The exposure categories are not validated against ecological health data and represent relative potential risk categories for seagrass and coral reef ecosystems. Category I (No or Very low risk) represents waters with ambient or detectable but low water quality concentrations and therefore low risk of any detrimental ecological effect. Areas exposed to category I are presented in Table 4-6, but not described below. The areas and percentages of ecological communities affected by the different categories of exposure were calculated as a relative measure between regions and the long-term average.

Table 4-6: Areas (km²) and percentages (%) of the Mackay-Whitsunday region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2020–21 wet season and the long-term. The last three rows show the differences between % affected in 2021 and the long-term average (red: increase, blue: decrease, green: no change, difference ≤5%). Areas south of the Marine Park (Hervey Bay) are not included.

Mackay-Whitsunday		Total		Potential Risk category				Total area exposed II-IV
				No / very low	Lowest Highest			
					I	II	III	
Surface area	area	48,957	2021	41,737	5,797	997	426	7,220
			LT	38,701	9,320	515	419	10,255
	%	100%	2021	85%	12%	2%	1%	15%
			LT	79%	19%	1%	1%	21%
Coral reefs	area	3,216	2021	3,010	157	39	9	206
			LT	3,004	194	16	2	212
	%	100%	2021	94%	5%	1%	<1%	6%
			LT	93%	6%	<1%	<1%	7%
Surveyed seagrass	area	307	2021	25	171	46	65	282
			LT	19	169	42	77	288
	%	100%	2021	8%	56%	15%	21%	92%
			LT	6%	55%	14%	25%	94%
<i>Difference (2021 – Long-term average)</i>	<i>Surface area</i>			6%	-7%	1%	<1%	-6%
	<i>Coral Reef</i>			1%	-1%	<1%	<1%	-1%
	<i>Surveyed seagrass</i>			2%	1%	1%	-4%	-2%

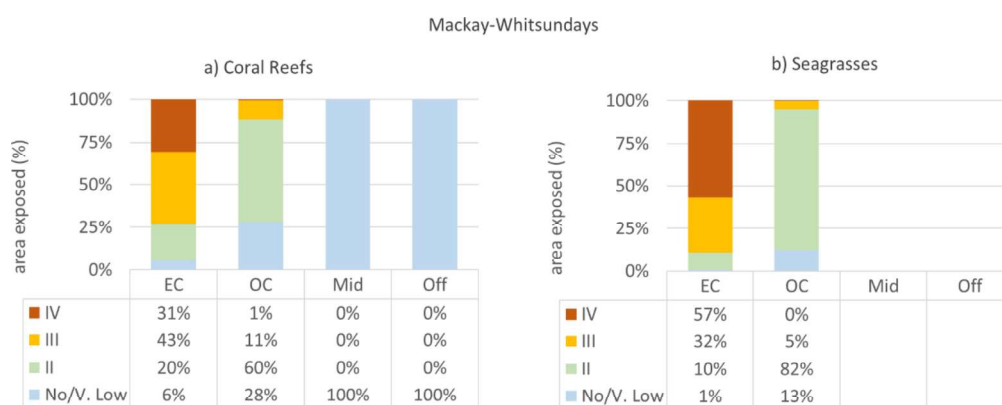


Figure 4-29: Percentage of the Mackay-Whitsunday region a) coral reef and b) seagrass habitats affected by different risk categories of exposure during the 2020–21 wet season.

In 2020–21, it was estimated that:

- **Mackay-Whitsunday wide:** 85% of the Mackay-Whitsunday region was not exposed to a potential risk, over to long-term patterns (79%, Table 4-6). A total of 15% of the Mackay-Whitsunday region was exposed to combined potential risk categories II–IV (or about 7,200 km²). However, only 1% (426 km²) of the region was in the highest exposure category (IV) and 2% (997 km²) in category III.
- **Mackay-Whitsunday waterbodies:** only the enclosed coastal and open coastal Mackay-Whitsunday waters were exposed to the highest categories of potential risk (III and IV). The open coastal area exposed was however spatially limited and corresponded to 6% (cat. III) of the total Mackay-Whitsunday inshore area (Figure 4-7c, the open coastal Mackay-Whitsunday area was not exposed to the higher risk category IV). A total of 41% and 49% of the enclosed coastal areas were exposed to categories III and IV respectively. The mid-shelf and offshore Mackay-Whitsunday waterbodies were not exposed to potential risk.
- **Mackay-Whitsunday habitats:**

- **Coral reefs:** Approximately 6% (or 206 km²) of coral reefs in the Mackay-Whitsunday region were exposed to combined potential risk categories II–IV (Table 4-6). However, less than 1% of coral were in the highest exposure category (IV) and 1% in category III (combined 48 km²), and they were all enclosed coastal or open coastal reefs (Figure 4-29a). A total of 9% (< 300 km²) of the Mackay-Whitsunday corals occur in the inshore waters (Appendix C-6).

The open coastal coral area exposed to higher potential risk was spatially limited and corresponded to 11% (cat. III) and 1% (cat. IV) of the total open coastal reef area in the Mackay-Whitsunday region. A total of 43% and 31% of the enclosed coastal areas were exposed to categories III and IV respectively. Mid-shelf and offshore reefs were not exposed to a potential risk.

- **Seagrasses:** All of the surveyed seagrass in the Mackay-Whitsunday region are located in the inshore area (Appendix C-6). Approximately 92% of seagrasses in the Mackay-Whitsunday region were exposed to combined potential risk categories II–IV (282 km²). A total of 21% (65 km²) of seagrasses were in the highest exposure category (IV) and 15% (46 km²) were in category III (Table 4-6).

The open coastal seagrass area exposed to higher potential risk was spatially limited and corresponded to 5% (cat. III) of the total open coastal seagrass area in the Mackay-Whitsunday region (the open coastal Mackay-Whitsunday area was not exposed to the higher risk category IV) (Figure 4-29b). Approximately 32% and

- 57% of the enclosed coastal areas were exposed to categories III and IV respectively.
- **Comparison to long-term trends:** The coral and seagrass areas in the Mackay-Whitsunday region exposed to combined potential risk categories II–IV in 2020–21 were very similar to the long-term areas ($\leq 2\%$ change).

4.3.5 Fitzroy and Burnett-Mary regions

As no water quality monitoring is currently conducted under the MMP in the Fitzroy and Burnett-Mary regions, the remote sensing results for these regions are typically not reported. However, the results of the assessment of potential risk are presented below as they are relevant context for the coral reef and seagrass data in these regions. This year, water quality monitoring in the Fitzroy region has been recommenced via a separately funded project, and the results of this are included as Appendix D. It should be noted that exposure maps have a higher degree of uncertainty in the Fitzroy and Burnett-Mary regions than in those described above, due to limited validation of water quality conditions from *in situ* monitoring.

As with all regions, the exposure categories are not validated against ecological health data and represent relative potential risk categories for seagrass and coral reef ecosystems. Category I (No or Very low risk) represents waters with ambient or detectable but low water quality concentrations and therefore low risk of any detrimental ecological effect. Area exposed to category I are presented in Table 4-7 but not described. The areas and percentages of ecological communities affected by the different categories of exposure were calculated as a relative measure between regions and the long-term average.

Fitzroy

The river discharge from the Fitzroy region in 2020–21 was under the long-term median, and there were no large flood plumes captured in satellite imagery in the Fitzroy region during the wet season. Weekly composites of the Fitzroy region showed that primary waters were confined in the enclosed coastal waters next to the Fitzroy and Calliope River mouths. Primary waters reached the open coastal waters north of Curtis Island regularly from mid-January (week 7, 12 to 18 Jan) but generally, primary flood waters had limited impact on the open coastal and mid-shelf regions and ecosystems of the Fitzroy region in 2020–21. Secondary waters extended largely into the open coastal region from mid-January (week 7, 12 to 18 Jan.) and reached the mid-shelf region in weeks 7–9 (12 Jan to 1 Feb).

Table 4-7 presents the areas (km²) and percentage (%) of Fitzroy region, coral reef, and seagrass areas affected by different categories of exposure (or potential risk) based on satellite-derived wet season water maps. In 2020–21, it was estimated that:

- Fitzroy-wide: 91% of the Fitzroy region was not exposed to a potential risk, over the long-term patterns (88%, Table 4-7). 9% (or about 7,400 km²) of the Fitzroy region was exposed to combined potential risk categories II–IV. However, only 2% (1,723 km²) of the region was in the highest exposure category (IV) and 1% (1,053 km²) in category III.
- Fitzroy waterbodies: only the enclosed coastal and open coastal Fitzroy waters were exposed to the highest categories of potential risk (III and IV). The open coastal area exposed was however spatially limited and corresponded to 8% (cat. III) and 2% (cat. IV) of the total Fitzroy inshore area (Figure 4-7c). 16% and 79% of the enclosed coastal areas were exposed to categories III and IV respectively. The mid-shelf and offshore Fitzroy waterbodies were not exposed to a potential risk.

- Fitzroy habitats:
 - **Coral reefs:** Approximately 3% of coral reefs in the Fitzroy region were exposed to combined potential risk categories II–IV (Table 4-7). However, only 2% of coral were in both the highest exposure category (IV) and category III (combined 65 km²), and they were all enclosed coastal or midshelf reefs (Figure 4-30a). Only 4% (< 200 km²) of the Fitzroy corals occur in the inshore waters (Appendix C-6).
The open coastal coral area exposed to higher potential risk was limited and corresponded to 22% (cat. III) and 1% (cat. IV) of the total open coastal coral reef area in the Fitzroy. Approximately 11% and 86% of the enclosed coastal areas were exposed to categories III and IV respectively. All of the mid-shelf and offshore reefs were classified as no / very low risk.
 - **Seagrasses:** Approximately 75% (or 356 km²) of seagrasses in the Fitzroy region were exposed to combined potential risk categories II–IV (Table 4-7). 18% (87%) of seagrasses were in the highest exposure category (IV) and 15% (72 km²) were in category III, and they were all inshore seagrasses (Figure 4-30b). Approximately 81% (< 400 km²) of the Fitzroy seagrasses occur in the inshore waters (Appendix C-6).
The open coastal seagrass area exposed to higher potential risk was limited and corresponded to 3% (cat. III) of the total open coastal seagrass area in the Fitzroy region (no open coastal seagrasses were exposed to the higher risk category IV). 39% and 52% of the enclosed coastal areas were exposed to categories III and IV respectively. 100% of the mid-shelf seagrasses were exposed to the lower category of risk (II).
 - **Comparison to long-term trends:** The coral areas exposed to highest potential risk categories III and IV were similar to the long-term patterns (<1% of the coral reefs) The seagrass areas in the Fitzroy region exposed to combined potential risk categories II–IV in 2020–21 were below (-21%) the average long-term areas.

Table 4-7: Areas (km²) and percentages (%) of the Fitzroy region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2020–21 wet season and the long-term. The last three rows show the differences between % affected in 2020–21 and the long-term average (red: increase, blue: decrease, green: no change, difference ≤5%). Areas south of the Marine Park (Hervey Bay) are not included.

Fitzroy		Total		Potential Risk category				Total area exposed II-IV
				No / Very low	Lowest		Highest	
					I	II	III	
Surface area	area	86,869	2021	79,440	4,653	1,053	1,723	7,429
			LT	76,616	7,457	1,322	1,475	10,253
	%	100%	2021	91%	5%	1%	2%	9%
			LT	88%	9%	2%	2%	12%
Coral reefs	area	4,881	2021	4,721	94	35	30	159
			LT	4,729	100	22	30	152
	%	100%	2021	97%	2%	1%	1%	3%
			LT	97%	2%	<1%	<1%	3%
Surveyed seagrass	area	478	2021	122	197	72	87	356

			LT	20	286	34	137	457
	%	100%	2021	25%	41%	15%	18%	75%
			LT	4%	60%	7%	29%	96%
Difference (2021 – Long-term average)	Surface area			3%	-4%	-1%	<1%	-3%
	Coral Reef			0%	<1%	<1%	<1%	0%
	Surveyed seagrass			21%	-19%	8%	-11%	-21%

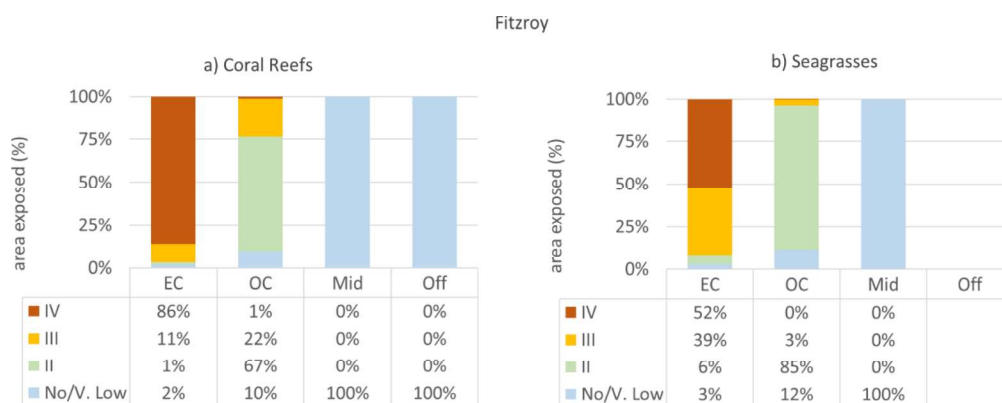


Figure 4-30: Percentage of the Fitzroy region a) coral reef and b) seagrass habitats affected by different risk categories of exposure during the 2020–21 wet season.

Burnett-Mary

The river discharge from the Burnett-Mary region in 2020–21 was below the long-term median, and there were no large flood plumes captured in satellite imagery in the Burnett-Mary region during the wet season. Primary waters were largely confined in enclosed coastal waters off Hummock Hill Island but this may also be linked to resuspension of sediments in the shallow waters and had limited impact on the open coastal and mid-shelf regions of the Burnett-Mary region in 2020–21. Secondary waters were largely confined to the open coastal waters.

Table 4-8 presents the areas (km²) and percentage (%) of Burnett-Mary region, coral reef, and seagrass areas affected by different categories of exposure (or potential risk) based on satellite-derived wet season water maps.

In 2020–21, it was estimated that:

- Burnett-Mary wide: Approximately 98% of the Burnett-Mary region was not exposed to a potential risk, which was similar long-term patterns (95%, Table 4-8). 2% of the Burnett-Mary region (or about 775 km²) was exposed to combined potential risk categories II–IV, with less than 1% in both the highest exposure category (IV) and category III (combined 185 km²).
- Burnett-Mary waterbodies: only the enclosed coastal and open coastal Burnett-Mary waters were exposed to the highest categories of potential risk (III and IV). The open coastal area exposed was however spatially limited and corresponded to 2% (cat. III) of the total Burnett-Mary inshore area (Figure 4-7c, the open coastal Burnett-Mary waters were not exposed to the highest category of potential risk IV). A total of 24% and 30% of the enclosed coastal areas were exposed to categories III and IV respectively. A total of 100% of the mid-shelf and offshore Burnett-Mary waterbodies were exposed to no / very low risk.

- Burnett-Mary habitats:

- **Coral reefs:** Approximately 2% of coral reefs in the Burnett-Mary region were exposed to combined potential risk categories II–IV (Table 4-8). Less than 1% of coral were exposed to the highest risk categories III and IV (about 1 km²) and there were all enclosed coastal or open coastal reefs (Figure 4-31a). Only 2% (< 10 km²) of the Mackay-Whitsunday corals occur in the inshore waters (Appendix C-6).

The open and enclosed coastal coral area exposed to potential risk category III were limited and corresponded to 9% and 17% of the total enclosed coastal and open coastal coral reef area in the Burnett-Mary region. A negligible proportion of reefs (<1%) were exposed to the higher potential risk category IV in both regions). All of the mid-shelf coral reefs were exposed to no / very low risk. There are no offshore reefs in the Burnett-Mary region.

- **Seagrasses:** Approximately 60% (or 156 km²) of seagrasses in the Burnett-Mary region were exposed to combined potential risk categories II–IV (Table 4-8). However, 12% (32 km²) of seagrasses were in the highest exposure category (IV) and 7% (18 km²) were in category III and they were all enclosed coastal or open coastal seagrasses (Figure 4-31b). A total of 71% (< 200 km²) of the Mackay-Whitsunday corals occur in the inshore waters (Appendix C-6).

The open coastal seagrass area exposed to higher potential risk were highly limited and corresponded to only 1% (cat. III) of the total inshore seagrass area in the Burnett-Mary region (none were exposed to the highest category IV). A total of 20% and 35% of the enclosed coastal seagrass areas were exposed to categories III and IV respectively 100% of the Mid-shelf seagrasses in the Burnett-Mary region were exposed to no / very low risk.

- **Comparison to long-term trends:** The coral areas in the Burnett-Mary region exposed to combined potential risk categories II–IV in 2020–21 were similar to long-term areas. The seagrass area in the Burnett-Mary region is slightly over the average long-term areas (+7%), but this is related to an increase in seagrass area exposed to the lowest potential risk category II.

Table 4-8: Areas (km²) and percentages (%) of the Burnett-Mary region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2020–21 wet season and the long-term. The last three rows show the differences between % affected in 2020–21 and the long-term average (red: increase, blue: decrease, green: no change, difference ≤5%). Areas south of the Marine Park (Hervey Bay) are not included.

Burnett-Mary		Total		Potential Risk category				Total area exposed II-IV
				No / Very low	Lowest		Highest	
					I	II	III	
Surface area	area	37,713	2021	36,938	590	93	92	775
			LT	35,748	1,556	267	142	1,965
	%	100%	2021	98%	2%	<1%	<1%	2%
			LT	95%	4%	<1%	<1%	5%
Coral reefs	area	285	2021	279	5	1	0	6
			LT	281	0	3	0	4
	%	100%	2021	98%	2%	<1%	<1%	2%
			LT	99%	0%	<1%	<1%	<1%

Surveyed seagrass	area	259	2021	103	107	18	32	156
		LT	9	170	39	42	251	
	%	100%	2021	40%	41%	7%	12%	60%
			LT	3%	36%	8%	9%	53%
Difference (2021 – Long term average)			Surface area	3%	-2%	<1%	<1%	-3%
			Coral Reef	-1%	2%	<1%	<1%	2%
			Surveyed seagrass	37%	5%	-1%	3%	7%

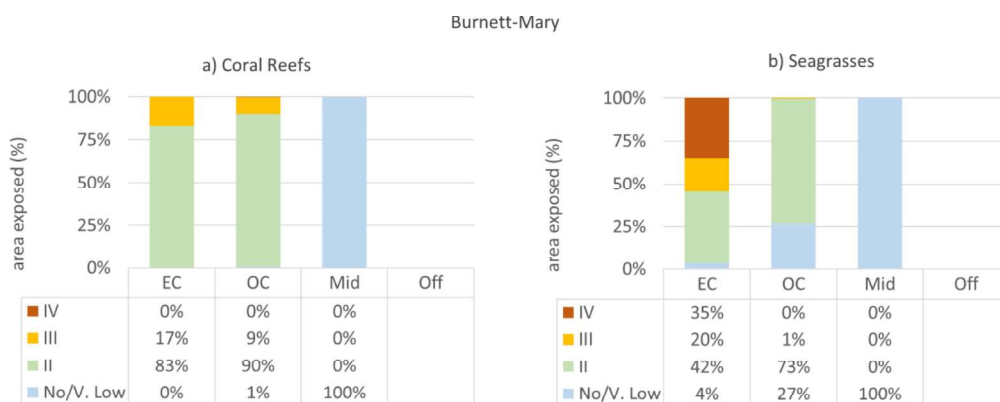


Figure 4-31: Percentage of the Burnett-Mary region a) coral reef and b) seagrass habitats affected by different risk categories of exposure during the 2020–21 wet season.

4.4 Modelling and mapping summary and discussion

Water type frequency maps (Sentinel-3 data)

For this report, Sentinel-3 satellite images of the reef and the Forel-Ule colour scale (FU, 21 colour classes) were used to produce map Reef water types instead of the MODIS imagery and the wet season colour scale (wet season, 6 colour classes). FU equivalent water types were defined by grouping the FU colour classes 1–3 (equivalent to marine waters in the WS scale), FU colour classes 4–5 (equivalent to WS Tertiary water type), FU colour classes 6–9 (equivalent to wet season secondary water type) and FU ≥ 10 (equivalent to wet season primary water type), as defined in Petus *et al.* (2019 and Table 2-2). This change was made in response to concerns that quality of the MODIS satellite images was declining and that MODIS sensors could be decommissioned in the near future due to their increasing age (MODIS-Aqua was launched in 1999 and MODIS-Terra sensor in 2002) (Petus *et al.*, 2019).

Results are very encouraging and confirmed that Sentinel-3 satellite data and the FU scale are useful for mapping Reef optical water types. Sentinel maps showed an inshore-to-offshore spatial pattern similar to the well-documented MODIS patterns (for example, Waterhouse *et al.*, 2021), with the highest frequency of the primary water type (typically enriched in sediment and dissolved organic matter, brownish turbid waters) in the inshore waterbody. Mid-shelf waterbodies were most frequently exposed to the secondary and tertiary water types and offshore waterbodies were most frequently exposed to the tertiary water type (typically with low land-sourced contaminant concentrations, a low risk of any detrimental ecological effect and often mixed with the influence of marine processes, concentrations but with a low risk of any detrimental ecological effect). Furthermore, a pilot study (Appendix E) showed that Sentinel FU monitoring products can be adjusted to report on water colour trends in the dry

season. This is an important step toward characterising conditions that promote reef habitat recovery through dry season.

Only 3% of the Reef (inshore waters only) was exposed to primary waters during the 2020–21 wet season, and 16% of the Reef to secondary waters, which was similar to the patterns for the long-term and representative coral recovery period. However, for the third year in a row, the Reef area exposed to tertiary waters was unexpectedly large (57% of the Reef) and covered a larger area than all reference periods, including the 'wet' years (56% of the Reef). This result is related to anomalously large tertiary areas measured in the mid-shelf and offshore region of the Reef, which is almost certainly due to oceanic processes such as upwelling rather than direct catchment discharge influence.

Exposure maps (Sentinel-3 and field water quality data)

Tertiary waters are associated with low land-sourced contaminant concentrations) and a low magnitude score in the Reef exposure assessment. While tertiary areas in 2020–21 were much larger than usual, this did not result in increasing the Reef-wide potential risk. The total Reef area exposed to a potential risk in 2020–21 was spatially limited and similar to the long-term patterns. Eighty eight percent of the Reef was exposed to no or very low potential risk and only 3% (but almost 10,000 km²) of the Reef was in the highest exposure categories III and IV.

Cross-shore, the offshore and mid-shelf and waterbodies were largely classified as no or very low potential risk (92% and 99% respectively). Open coastal waters were largely exposed to the lowest category of risk (II, 58% of the open coastal waterbody) and only 9% and 1% of the open coastal waters were exposed to the highest potential risk categories III and IV. The Reef enclosed coastal waters had the highest relative potential risk, with 28% and 44% of the enclosed coastal waters exposed to categories III and IV, respectively. This, however, represent a very small proportion of the total size of the Reef (less than 2% of the Reef).

As a result, mid-shelf and offshore Reefs habitats (seagrass and coral reefs) were either exposed to the lowest risk category II or to no potential risk and were not exposed to the highest exposure categories III and IV. Open coastal seagrasses and coral reefs were largely exposed to the lowest category of risk (II, 70% and 61% of the total Reef seagrass and coral areas, respectively). Enclosed coastal habitats were the most at risk, with 73% (less than 1% of the total coral reef area of the Reef) and 86% (~ 6% of the total seagrass area in the Reef) of the total enclosed coastal seagrasses and corals in the Reef classified as category III or IV. Enclosed coastal areas are shallow regions of the Reef. It is likely that wind-driven sediment resuspension (some of which may have been originally derived from the Reef river discharge) or bottom influence may influence the TSS concentrations and resulting exposure results in this very coastal region.

Habitat areas exposed to a potential risk (combined risk categories II, III and IV) were largely similar to the long-term patterns in all regions ($\leq 5\%$ change). There was, however, an increase in coral areas exposed to the lowest risk category (II) in the Cape York region, which was logical with the relatively high discharge measured in Cape York in 2020–21. Inversely, the Mackay-Whitsunday, and Fitzroy regions had low river discharge rates, and a decrease in total surface or seagrass areas exposed to the lowest risk category (II).

It should be noted there are several caveats to the exposure maps:

- This assessment does not take into account the current condition of Reef ecosystems and long-term impacts on these communities. For example, it is recognised that inshore communities may be adapted to wet season water types and exposure history. Therefore, the highest risk of an ecological response could be during large events when primary/secondary water types extend into otherwise low exposure (more offshore) areas.

- Reporting the areas of coral reefs and seagrass in the highest potential exposure categories cannot be assessed in terms of ecological relevance at this stage and is included as a comparative measure between regions and between years.
- One-week exposures are reported for which the ecological consequence is not presently known.
- The degree of validation against *in situ* data varies between regions, with limited current water quality data in the Fitzroy and Burnett-Mary regions.
- It is impossible to fully separate the direct influence of riverine plume from wind- and wave-driven sediment resuspension in optical satellite images, and this may particularly influence exposure results in the shallow enclosed coastal Reef waters.

Satellite methods and tools developed through the MMP to map water types have now proved to be efficient for the mapping of water quality trends in the Reef. However, there is a need to keep integrating spatial and temporal information obtained from the water type maps and *in situ* water quality measurements with environmental data to better understand physical influences that can lead to light reduction and water colour changes across Reef waterbodies, in both wet and dry seasons. The panels showing the environmental pressures combined with the wet season water types (weekly panels) and with dry season water types in the pilot study (Appendix E) provide first answers to these questions, but multi-variate statistical analyses would also be useful to gain further understanding of these processes.

Furthermore, there might also be a need to separate or discard water quality samples collected in the enclosed coastal waters in the characterisation of the water type composition (Section 2.6.2) and the calculations of the exposure scores (Figure 4-5), as GVs for enclosed coastal waters are different from other areas of the Reef. This will be progressed for the next report.

River-derived DIN, TSS and PN loading maps

The estimated wet season river-derived DIN, TSS and PN loading in the Reef lagoon for the 2020 water year showed a relatively low area of influence for all parameters. Only small differences were shown between the 2019–20, pre-development and anthropogenic loading scenarios, with an area of limited anthropogenic DIN loading in the Wet Tropics region and anthropogenic TSS loading in the Burdekin region. For all parameters, the areas of influence in 2019–20 were comparable to other years with river discharge below the long-term median.

Over the extended dataset the NRM regions typically presenting higher loading are:

- DIN: Wet Tropics, Burdekin, and Mackay-Whitsunday
- TSS: Burdekin, and to a lesser extent, Fitzroy
- PN: Burdekin, and to a lesser extent, Princess Charlotte Bay in Cape York, Wet Tropics and Fitzroy.

Note that the limitations of the previous model was driven by average wind conditions that are typically represented in a south-easterly direction was addressed in Gruber *et al.* (2020) by using the eReefs hydrodynamic model and adopting the tracer outputs to represent dispersal. The model is only available from 2010, so results prior to that are assumed using the multiannual average tracer output but using the annually-specific end-of-catchment loads. Further investigation of the results in the context of *in situ* water quality concentrations over time is the next step. However, it is unlikely at this stage that there is sufficient *in situ* data across the Reef to fully validate these results, particularly in the offshore and southern areas of the Reef.

Next steps for refinement remain the same as those identified in the 2018–19 report (Gruber *et al.*, 2020). In particular, it was highlighted that a decay function for modelled material should be incorporated to account for removal from the system. For TSS, removal is predominantly due to settling of suspended sediment, while for DIN, a measure of the influence of river DIN

rather than actual DIN concentrations is required. If phytoplankton take up DIN but it is still in the system, it should still be counted, so rather than an uptake rate, a removal rate is necessary (incorporating losses due to burial, denitrification and perhaps uptake by benthic biota).

5 Focus region water quality and Water Quality Index

The following sections provide detailed analysis of key water quality variables in focus regions in the context of local environmental drivers, specifically focused on identification and interpretation of year-to-year trends. Monitoring results from the duration of the MMP (since 2005) are used to provide context for interpreting recent monitoring. For each of the four focus regions, the following information is included and discussed (with the exception of Cape York, where data are presented differently as some aspects of monitoring in this region differ from other regions):

- a map of monitoring locations
- time-series of the combined discharge from local rivers that influence the focus area
- regional trends in key water quality parameters from 2005 to 2021
- presentation of the long-term trend and annual condition of ambient water quality relative to GVs using the WQ Index.

Site-specific data and additional information tables are presented in Appendix C and include:

- Appendix C-1 Figure C-1: Time-series of chlorophyll and turbidity measured by moored FLNTUSB instruments
- Appendix C-2 Figure C-2: Time-series of temperature and salinity measured by moored Sea-Bird Electronics instruments
- Appendix C-3 Table C-1: Cape York, Wet Tropics, Burdekin and Mackay-Whitsunday: Summary statistics for each water quality variable from each monitoring location, Sept 2020 to Oct 2021
- Appendix C-3 Table C-2: Annual summaries of moored FLNTUSB turbidity measurements for each monitoring location, including percentage exceedances of GVs
- Table C-3 to Table C-7: Summary of water quality data (collected as part of the JCU event-based sampling) across the wet season colour classes and water types.

5.1 Cape York region

The Cape York region is divided into four focus regions: Pascoe River, Stewart River, Normanby Basin and Endeavour Basin. The monitoring results are presented separately for each.

Water quality monitoring commenced in the Cape York region as part of the MMP in January 2017. Twenty-one sites in four focus regions (Figure 5-1) are sampled four to six times per year during ambient conditions. Additional event samples are collected depending on the location and accessibility of flood plumes at these and additional sites. Ambient sampling primarily occurs between October to April (wet season) due to strong trade winds (>25 km h⁻¹) preventing access during the winter months.

The 2020–21 water year is only the fifth year of sampling for the Cape York region. In consultation between CYWMP, AIMS and the Authority, both the analytical laboratory and the number of sites sampled in Cape York changed in 2020 (see Appendix A). Due to changes in number of sites, long-term trends are difficult to assess.

Water quality results within each focus region have been assessed relative to distance from river mouths and compared against the Eastern Cape York Water Quality Guidelines for the enclosed coastal, open coastal, mid-shelf and offshore water bodies (State of Queensland, 2020). For comparison with the guidelines, water quality results have been categorised as ambient wet season, ambient dry season, or event based on an evaluation of the river hydrograph at the time of sampling, antecedent rainfall, salinity measurements, and field

observations. The annual water quality index has also been calculated for each sub-region. This index is based on the current year only and not a comparison against previous data. As this is the first year that the annual index score has been generated for Cape York, a “coaster” format has been used to present the scores, rather than the timeseries format used in other regions.

The Cape York region as a whole received a moderate annual water quality index score for the 2020-21 monitoring year (Figure 5-2). The sub-region scores are also presented in the following sections along with more detailed information on the sub-indicators that are used to calculate the WQ Index and the drivers and pressures seen within each sub-region in 2020-21.

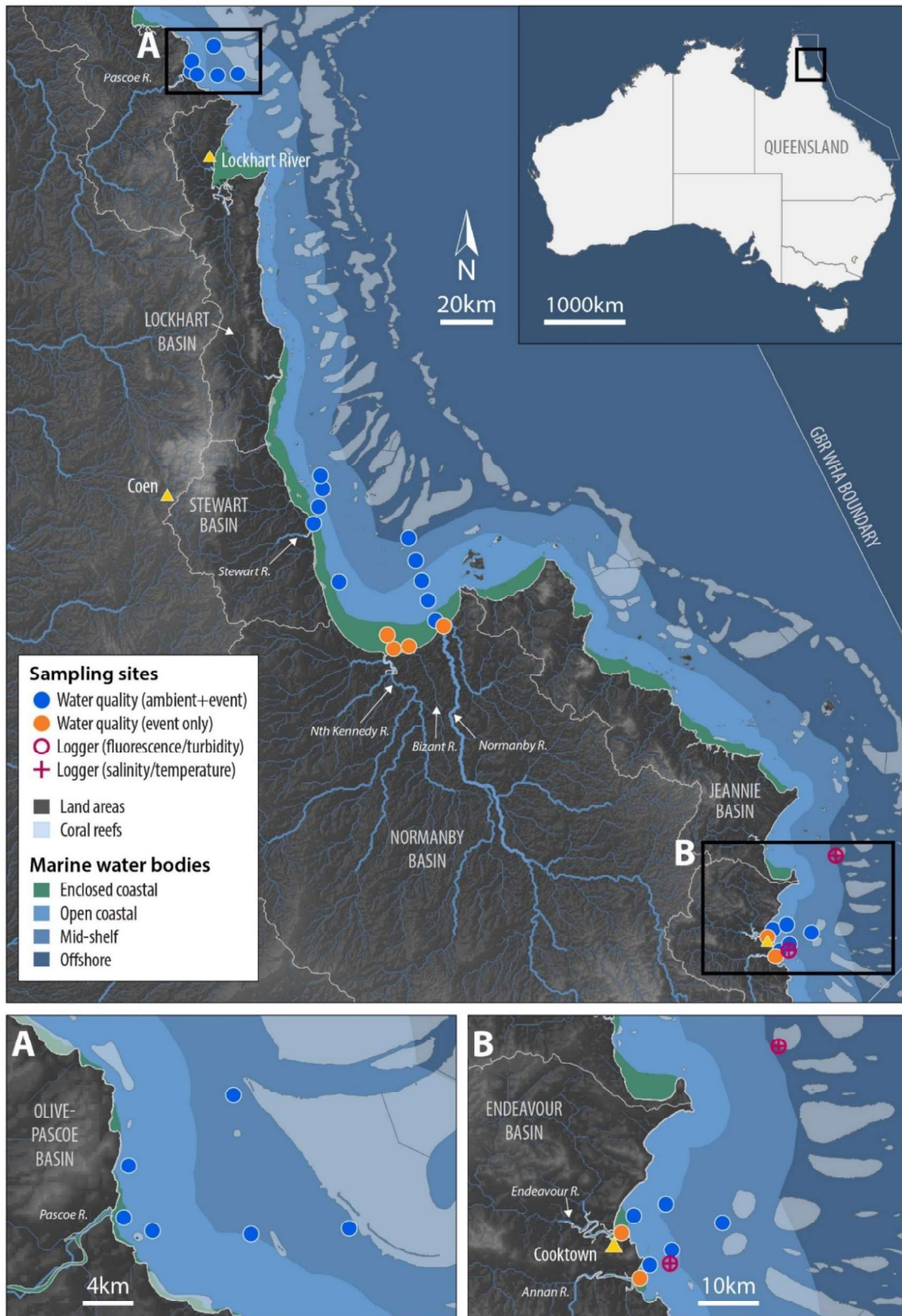


Figure 5-1: Water quality sampling sites in the Cape York region shown with water body boundaries. River datasets for map courtesy Grill *et al.* (2019).

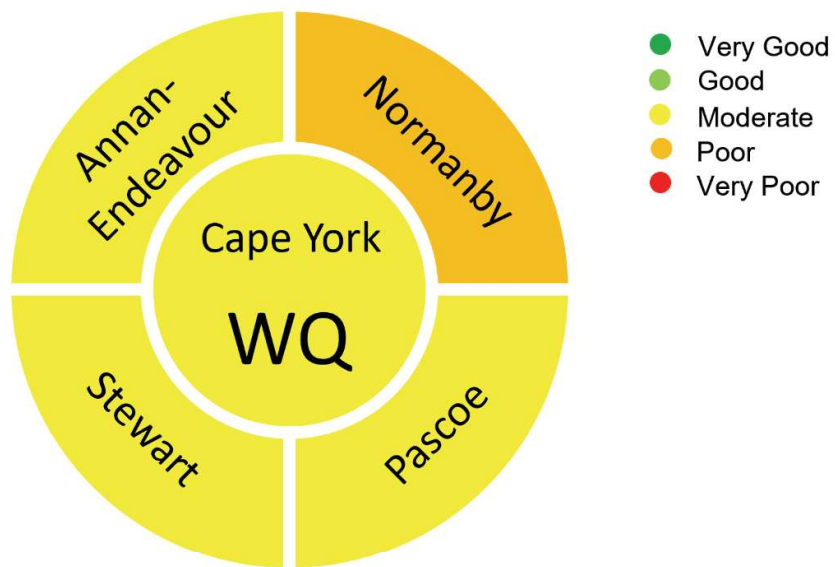


Figure 5-2: Cape York Annual WQ Index “coaster”. Calculations for index formulations are described in Appendix B.

5.1.1 Pascoe

The Pascoe focus region is influenced primarily by discharge from the Pascoe and Olive Rivers. Six sampling sites (Figure 5-3) are located along two transects to the northeast and southeast from the Pascoe River mouth out to Eel Reef and past Middle Reef (locally known as Blue Bells). Floodwaters have been observed flowing in both directions depending on wind and other local conditions during flood events. Enclosed coastal waters near the mouth of the Pascoe and site PRS01 are highly turbid due to tidal flushing and/or wind resuspension of shallow sediments.

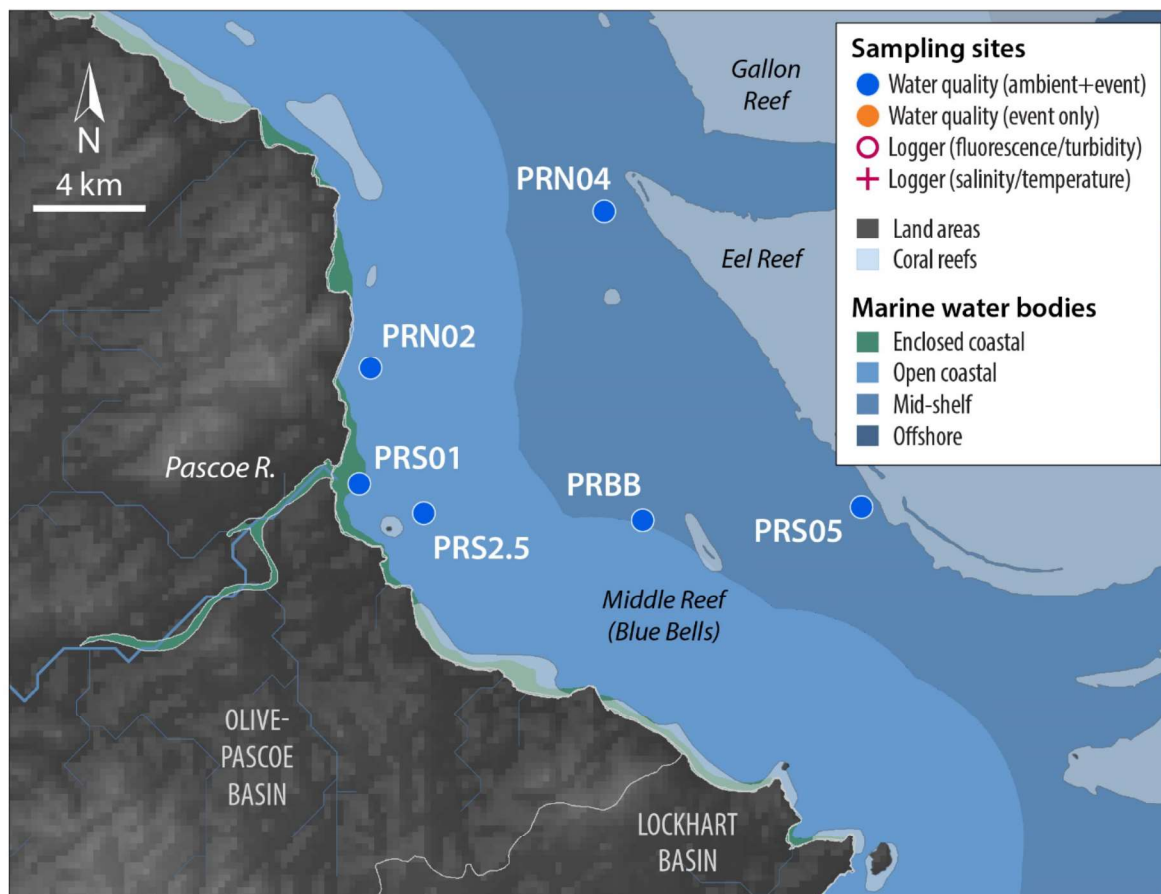


Figure 5-3: Water quality sampling sites in the Pascoe River transect with water body boundaries.

The Pascoe River transect was sampled five times (over 9 days) under ambient wet season conditions from December 2020–April 2021 (Figure 5-4) with a total of 50 surface and subsurface samples collected. Although total discharge for the year was above the annual median discharge, rainfall was consistent over the wet season and there were no major flood events (Figure 5-5). No targeted flood monitoring was conducted, however there was significant freshwater influence in the enclosed coastal and open coastal water bodies during regular sampling conducted in late January/early February and late March 2021 (refer also Figure 4-15).

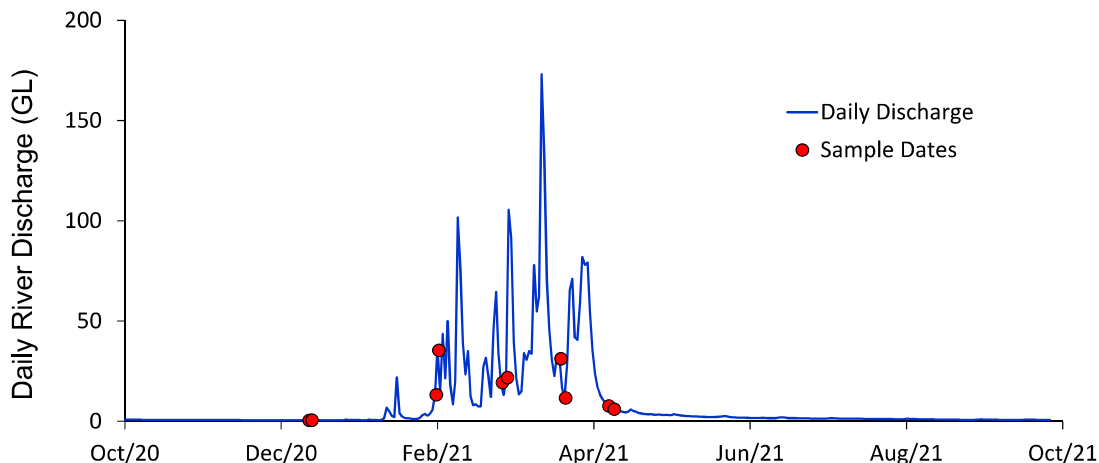


Figure 5-4: Daily discharge for the Pascoe River (gauge 102102A) for the 2020–21 water year. Red dots represent sampling dates.

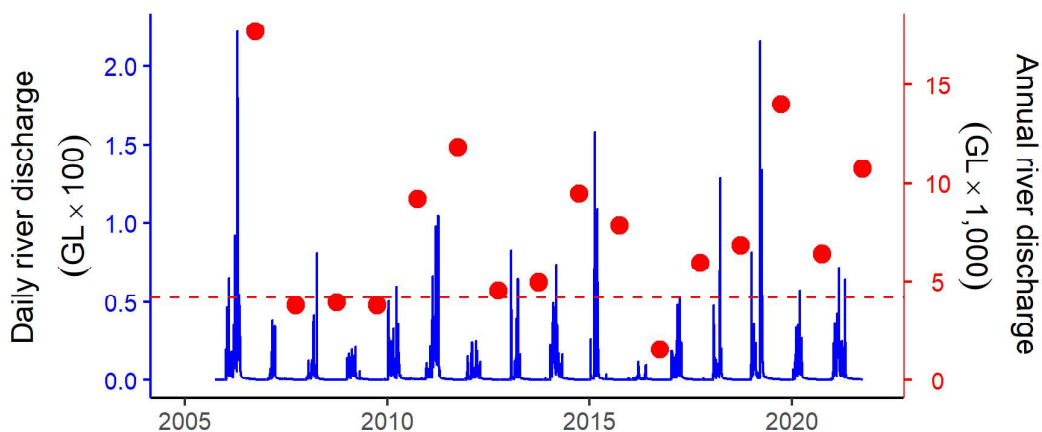


Figure 5-5: Long-term discharge for the Pascoe River (gauge 102102A). Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge.

Estimated annual discharge for the Olive-Pascoe basin was 5356 GL for the 2020–21 water year (Figure 5-5). The discharge and loads calculated for the 2020–21 water year from the Pascoe catchment (not including the Olive catchment) were more than 2-fold above the long-term median. The total discharge and modelled loads estimated for the 2020–21 water year from the Pascoe catchment (upscaled from the Garraway gauge) are shown in Figure 5-6. Over the 15-year period from 2006 to 2007:

- discharge has varied from 425 GL (2015–16) to 3,770 GL (2018–19)
- modelled TSS loads ranged from 20 kt (2015–16) to 194 kt (2018–19)
- modelled DIN loads ranged from 28 t (2015–16) to 275 t (2018–19)
- modelled PN loads ranged from 59 t (2015–16) to 1,068 t (2018–19).

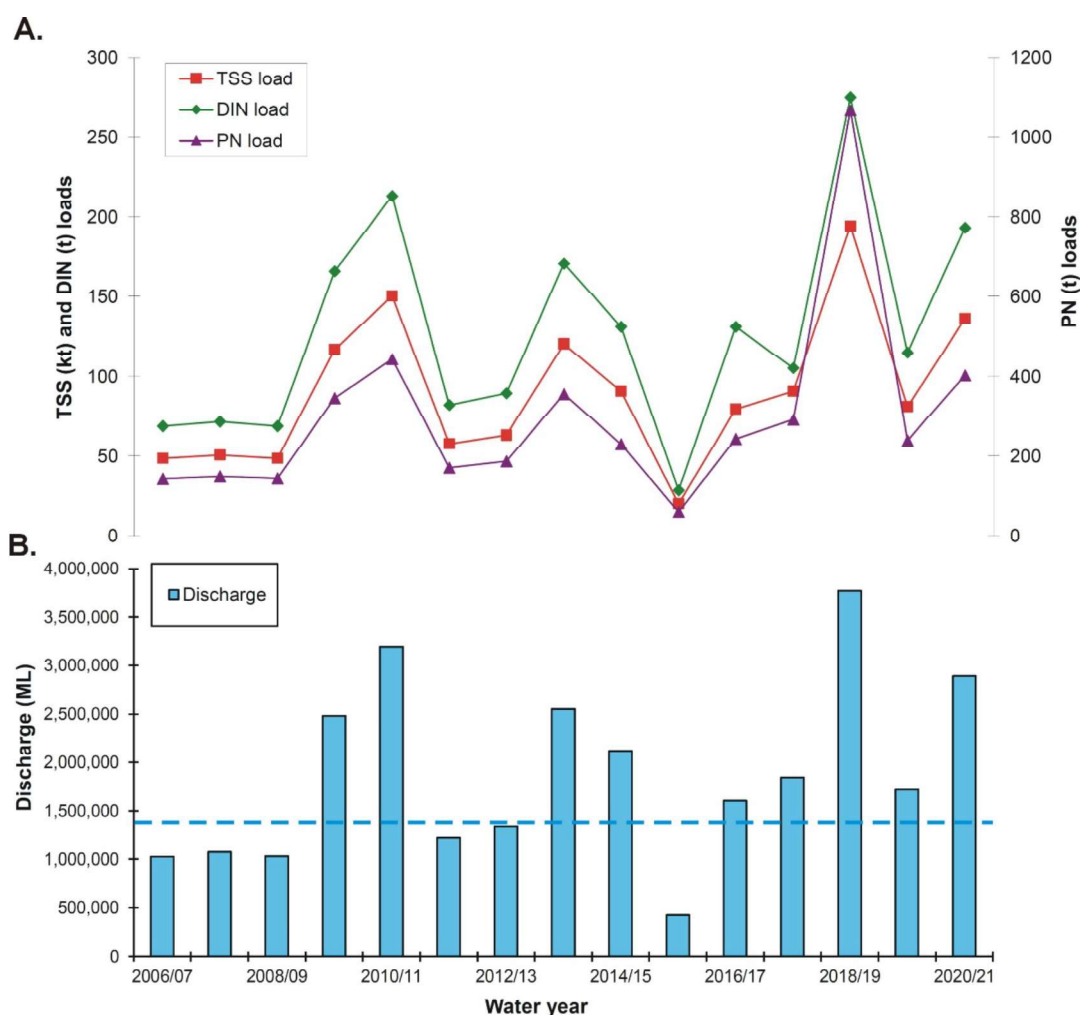


Figure 5-6: Modelled loads of (A) TSS, DIN and PN and (B) discharge for the Pascoe catchment (note Pascoe catchment only, does not include the Olive catchment) from 2006 to 2021. The loads reported here are a combination of ‘best estimates’ based on ‘up-scaled’ discharge data from gauging stations and monitoring data for 2014–15, 2016–17, 2017–18 and 2018–19 and an average of the annual mean concentrations for these four water years applied to the remaining dataset. Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality

There was some freshwater influence in the enclosed coastal water body (salinity ranging from 0 to 15) during the 1 February, 21 March and 11 April 2021 sampling events, resulting in elevated TSS (mean 11.6 mg L^{-1}) and nutrient concentrations (particularly NO_x , $18.9 \text{ } \mu\text{g L}^{-1}$). Low salinity and higher concentrations close to the river mouth are common along the Pascoe transect in the wet season and therefore these data remain characterised as “ambient” for statistical analysis.

Peak daily discharge for the wet season (58 GL) occurred at the Garraway gauge (located 42 km upstream from the mouth) on 14 March 2020 prior to transect sampling on 21 and 23 March 2021. Maximum particulate nutrient and TSS concentrations (31 mg L^{-1}) were measured in the enclosed coastal zone during regular sampling on these days. TSS was relatively low near mid-shelf reefs, however the maximum Chl-a concentration for the wet season ($0.84 \text{ } \mu\text{g L}^{-1}$) was measured at Eel Reef site PRN04 on 23 March 2021, indicating that nutrients delivered by floodwaters had supported increased algal growth over the following weeks.

All sample results are plotted against distance from the river mouth in Figure 5-7.

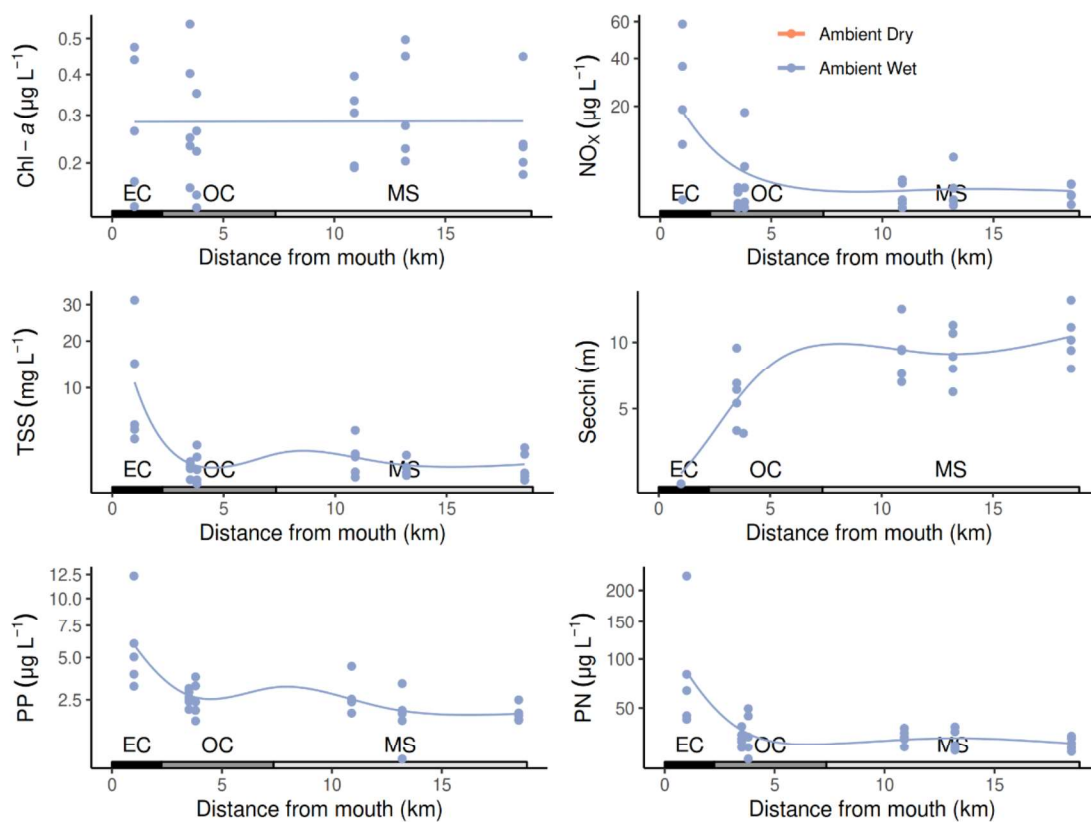


Figure 5-7: Water quality concentrations (surface and subsurface samples) and Secchi depth over distance (km) from river mouth for the Pascoe River focus region (all 2020–21 samples).

Comparison of the 2020–21 ambient results with previous years and the GVs (Table C-1) highlights that:

- Overall, the Pascoe water quality index score was “moderate” (Figure 5-8).
- Ambient TSS concentrations met the annual wet season GVs at most sites (with the exception of PR-BB and PR-S01). This is reflected in the “good” water quality index score shown for clarity.
- Mean Secchi depths were less than the annual GV (≥ 10 m), with the exception of site PRS05 (mid-shelf water body). However, the majority of samples were collected during the wet season, therefore are not representative of annual means.
- NO_x concentrations exceeded the GVs at all Pascoe transect sites and across water bodies. The median NO_x concentration in the enclosed coastal water body (PRS01) was almost 10x higher than the wet season GV. The highest DIN concentrations occurred during periods of freshwater discharge, but exceedances were not limited to periods of low salinity.
- Chl-a at mid-shelf reef sites PR-BB and PR-N04 slightly exceeded the annual GV, however samples collected primarily during the wet season may not be representative of annual median concentrations.
- Median PN concentrations near Eel Reef and Middle Reef in the mid-shelf water body (sites PR-BB, PRN04 and PRS05) also exceeded the annual GVs.

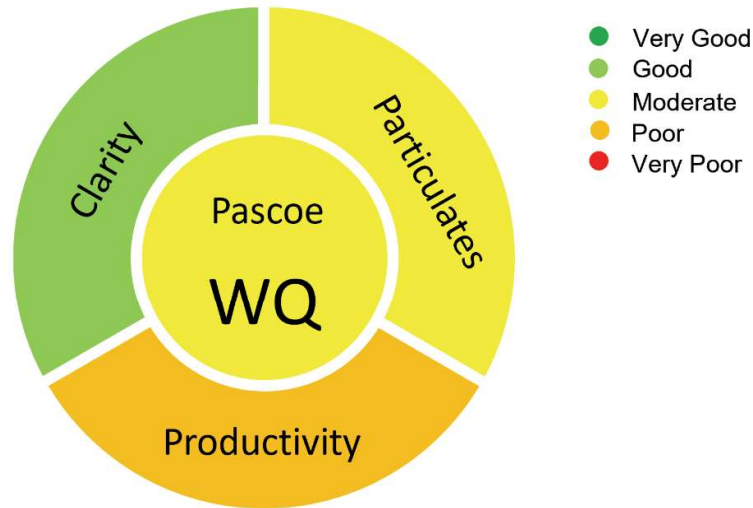


Figure 5-8: Pascoe Annual WQ Index “coaster”. Calculations for index formulations are described in Appendix B.

5.1.2 Stewart

The Stewart focus region is influenced primarily by discharge from the Stewart River, however during flood conditions it can also be influenced by floodwater from the Normanby and Kennedy Rivers and potentially by run-off from coastal creeks and mudflats.

Four sampling sites for the Stewart River are located in a transect from the river mouth to mid-shelf reefs, representing a gradient in water quality (Figure 5-9). The transect (surface and subsurface) was sampled four times (over 6 days) between December 2020 and March 2021 (Figure 5-10). Scheduled sampling in April 2021 did not occur due to road closures resulting from heavy rains. Although there were no major flood events in the Stewart River over the 2020–21 wet season, there was some freshwater influence on coastal waters during the regular sampling events.

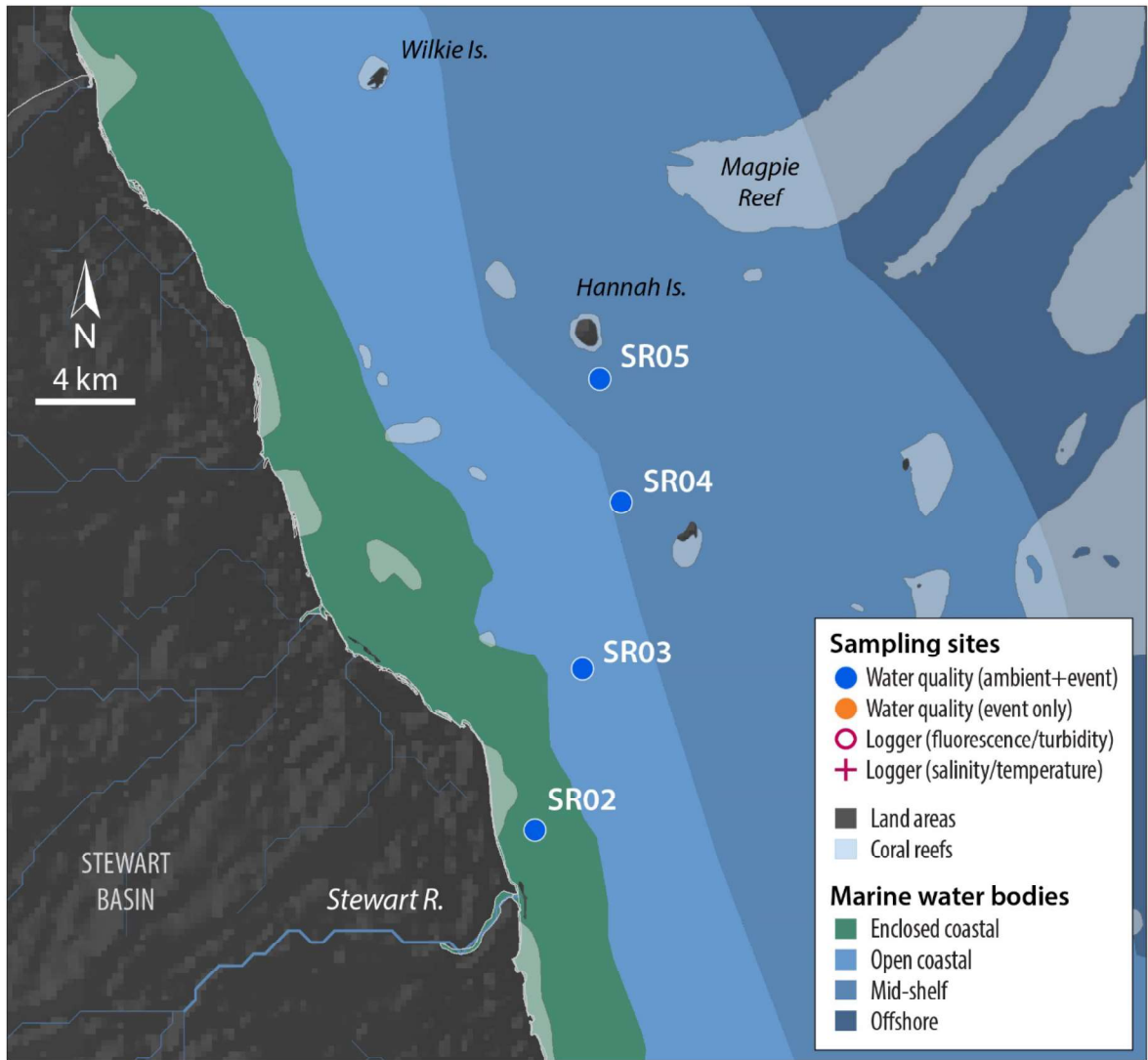


Figure 5-9: Water quality sampling sites in the Stewart River transect with water body boundaries.

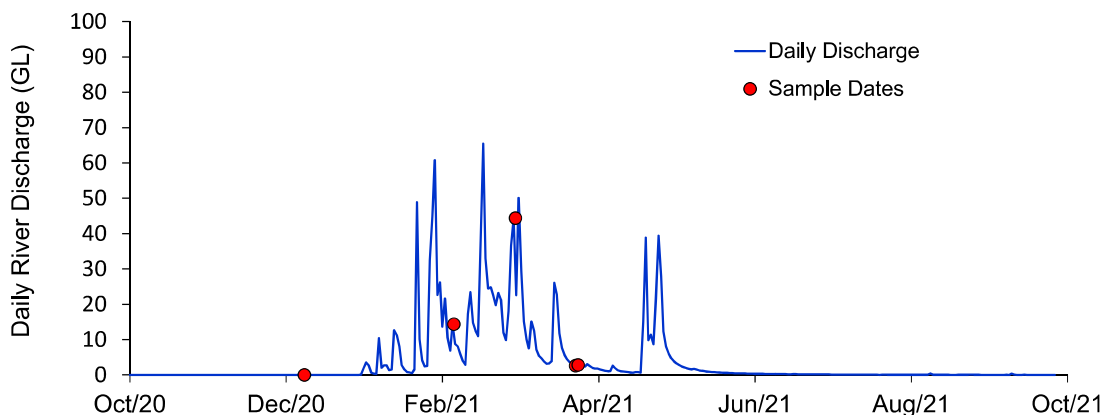


Figure 5-10: Daily discharge and sampling dates for the Stewart River (gauge 104001A) for the 2020–21 wet season.

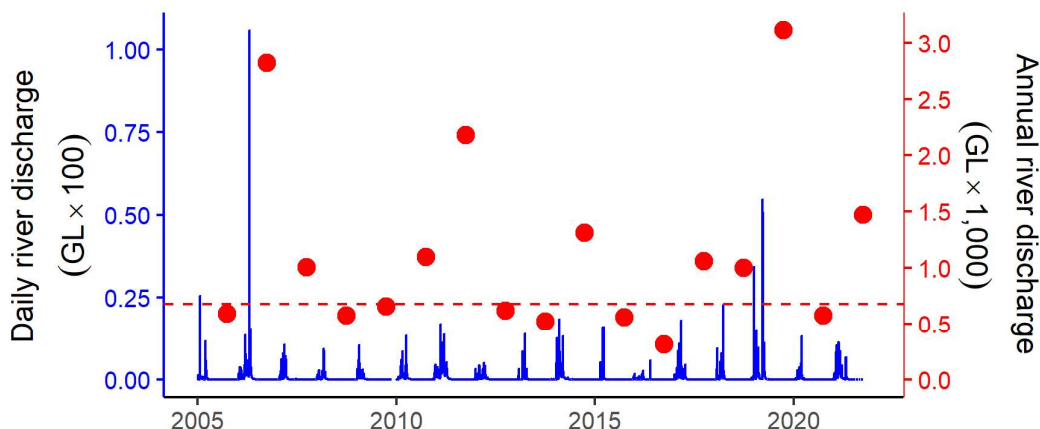


Figure 5-11: Long-term discharge for the Stewart River (gauge 104001A). Daily (blue) and water year (October to September, red circles) discharge volumes shown. Red dashed line represents long-term median annual discharge.

The total annual discharge for 2020–21 water year is estimated at 1470 GL based on the measurements from the Upper Stewart River gauge 104001A (Figure 5-11) corrected for catchment area. The combined discharge and modelled loads estimated for the 2020–21 water year from the Stewart Basin are shown in Figure 5-12. The discharge and loads calculated for the 2020–21 water year from the Stewart Basin were more than twice the long-term median. Over the 15-year period from 2006–07:

- discharge has varied from 299 GL (2014–15) to 3,109 GL (2018–19)
- TSS loads ranged from 9 kt (2014–15) to 93 kt (2018–19)
- DIN loads ranged from 13 t (2014–15) to 140 t (2018–19)
- PN loads ranged from 42 t (2014–15) to 435 t (2018–19).

The estimated area of influence for the Stewart River has not been mapped as it is not included in the currently available version of the eReefs hydrodynamic model.

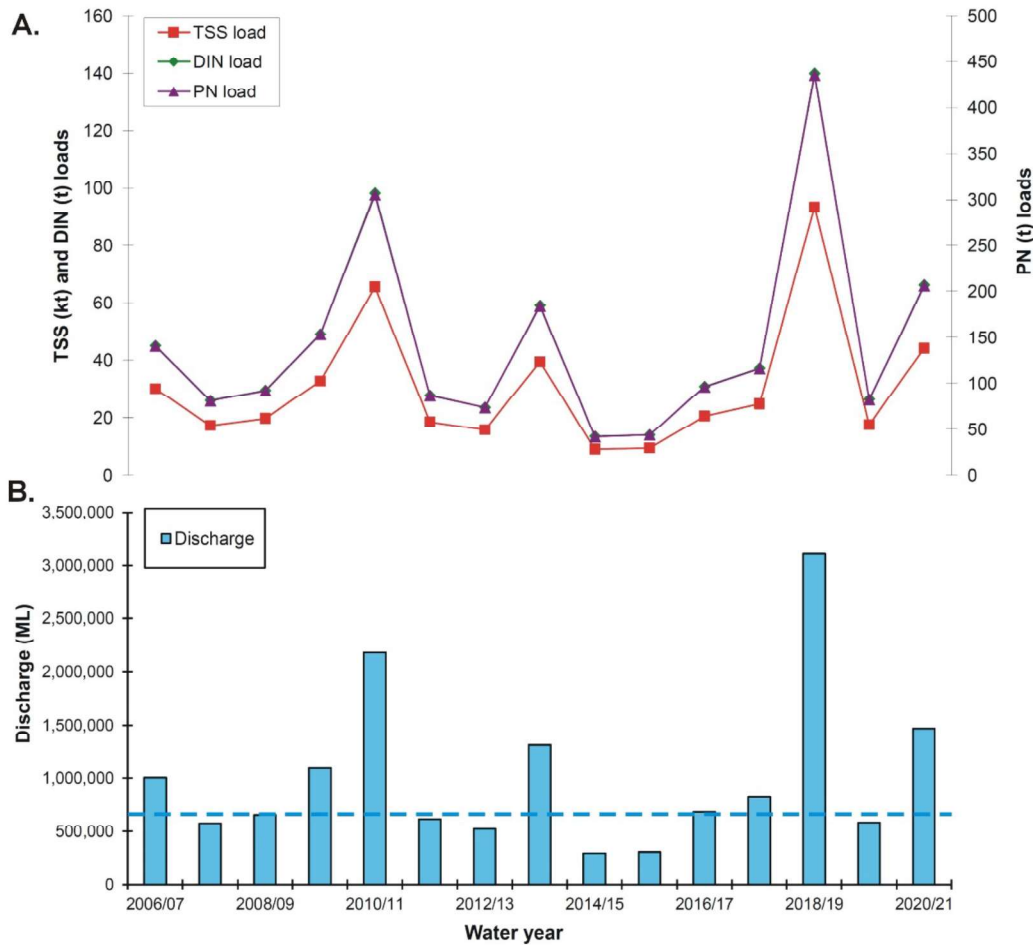


Figure 5-12. Loads of (A) TSS, DIN and PN, and (B) discharge for the Stewart Basin from 2006 to 2021. The loads reported here are based on the best estimates of annual mean concentration informed by nearest neighbour monitoring and by the Source Catchments modelling data and applied to each water year. Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality

The Stewart River transect results include four sampling events during the wet season. The sampling results are plotted against the distance from the river mouth in Figure 5-13 and are compared against the GV for each water body in Table C-1.

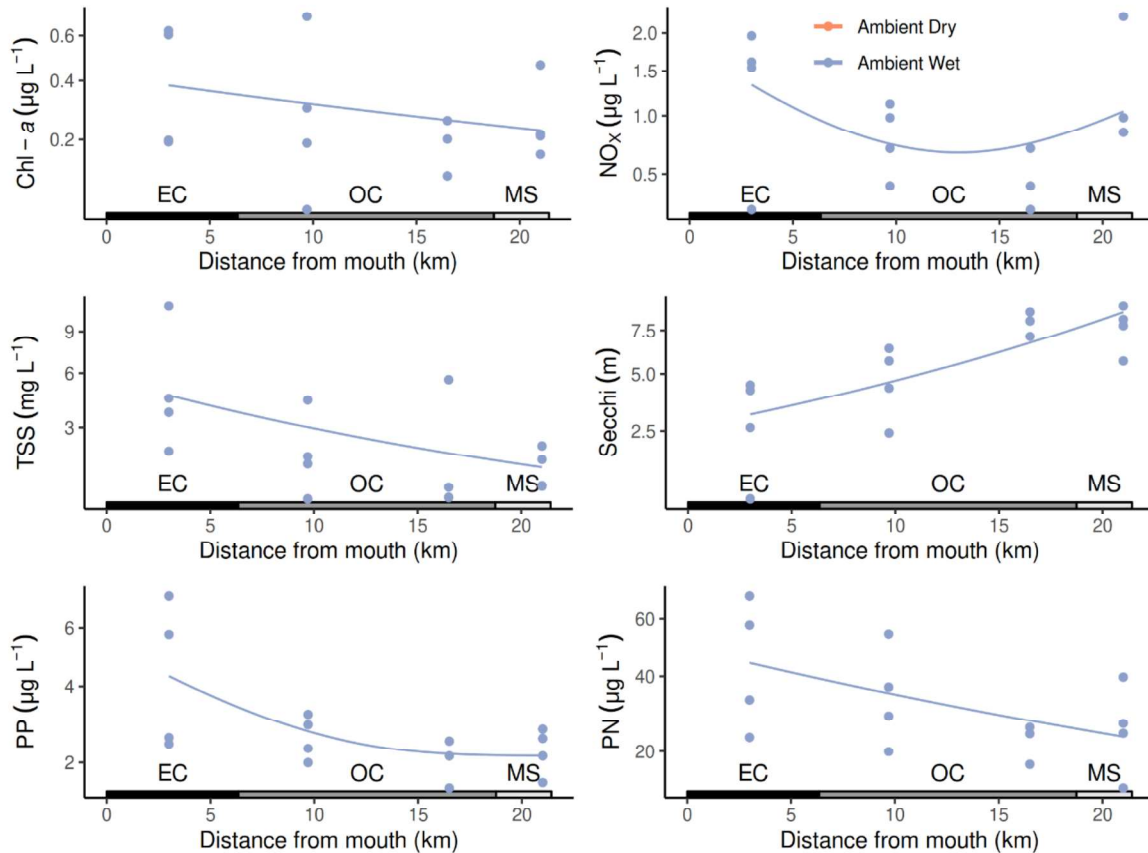


Figure 5-13 Water quality concentrations (surface and subsurface samples) and Secchi depth over distance (km) from river mouth for the Stewart River focus region, during ambient (blue circles) conditions.

Comparison of the 2020–21 ambient results with previous years and the water quality GVs (noting that the 4 sampling trips may not be representative of annual conditions) (Table C-1) highlights that:

- The water quality index for the Stewart region scored “moderate” for clarity, productivity and particulates (Figure 5-14).
- At Hannah Reef (SR05) in the mid-shelf water body, median NO_x , PO_4 , PN and PP all exceeded annual GVs.
- Mean Secchi depth (7.7m) did not meet the annual GV (>10m) at any open coastal or mid-shelf sites.
- Median PN concentrations did not meet the annual GVs at sites in the open coastal zone.
- Water quality at SR02 in the enclosed coastal water body met all wet season GVs with the exception of NO_x .
- Median Chl-a and TSS concentrations met both the annual and wet season GVs at all sites and water bodies.
- Mean TSS concentrations increased in all waterbodies compared to 2019–20 means, but remained below the mean concentrations measured during the high discharge 2018–19 water year.
- Secchi depth in the enclosed coastal water body decreased slightly compared to the previous wet season and increased slightly in the mid-shelf water body.

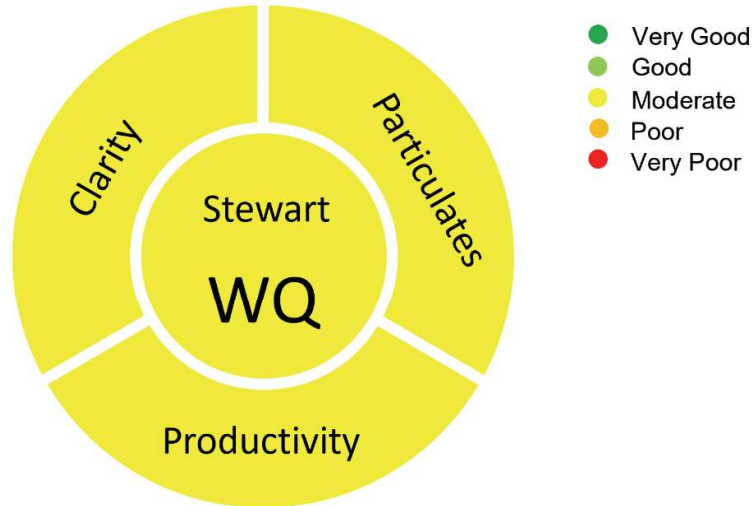


Figure 5-14: Stewart Annual WQ Index “coaster”. Calculations for index formulations are described in Appendix B.

Event water quality

The 2020–21 wet season was relatively wet compared to the previous year, comprising consistent rain but no major flood events. There was some freshwater influence in the enclosed coastal zone (salinity 23 to 30) during the wet season sampling periods. The highest TSS concentration was measured in the enclosed coastal zone on 1 March 2021, which coincided with the peak of a minor flood event. Based on satellite images and the relatively small magnitude of the event (estimated event discharge 300 GL), flood water from this event is likely to have had minimal influence on reefs beyond the open coastal water body.

5.1.3 Normanby

The Normanby focus region is influenced by discharge from the Normanby, Laura, Kennedy, Hann, Mossman, Morehead and Annie Rivers, via three distributaries—the North Kennedy, Normanby and Bizant. Five sampling sites are located along a transect from the Normanby River mouth to open coastal waters and Corbett Reef (Figure 5-15). Site CI01 is located near the Cliff Isles ('Marpa' in traditional Lama Lama language). Four additional event-only sites are NR01 at the Normanby River mouth, two sample sites located near the Kennedy River and one near the Bizant River mouth in the enclosed coastal water body.

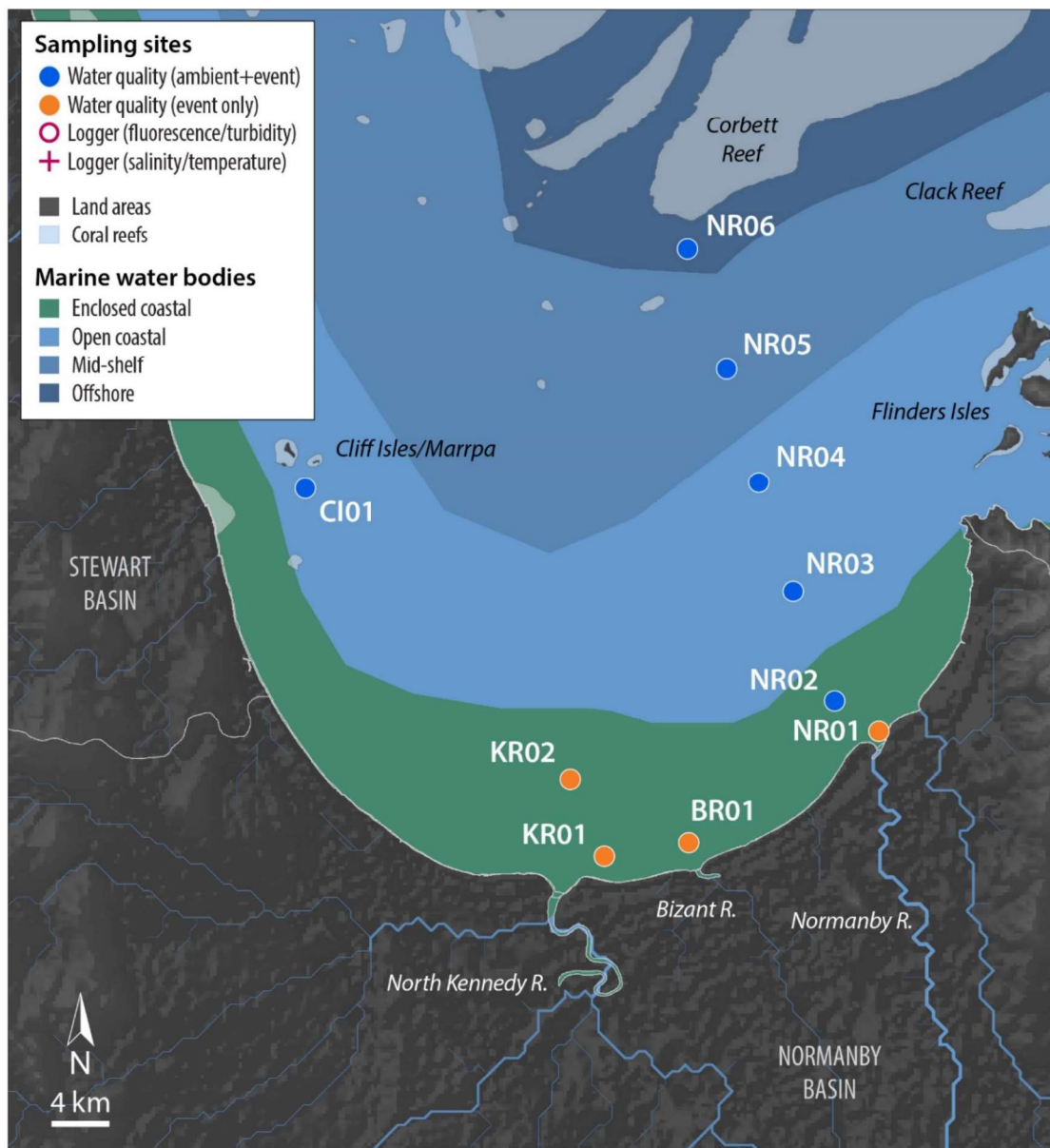


Figure 5-15: Water quality sampling sites in the Normanby Basin focus area with water body boundaries.

A total of 56 surface and sub-surface samples were collected over four sampling periods from December 2020 to March 2021 (Figure 5-16). Intensive sampling was conducted in partnership with Rinyirru Aboriginal Corporation and CSIRO over a three-day period (between 26 February to 1 March 2021) during the largest flood event of the year. Additional event

samples were also collected from floodwaters encountered near the river mouths during regular scheduled sampling on 4 February 2021. Long-term discharge is shown in Figure 5-17.

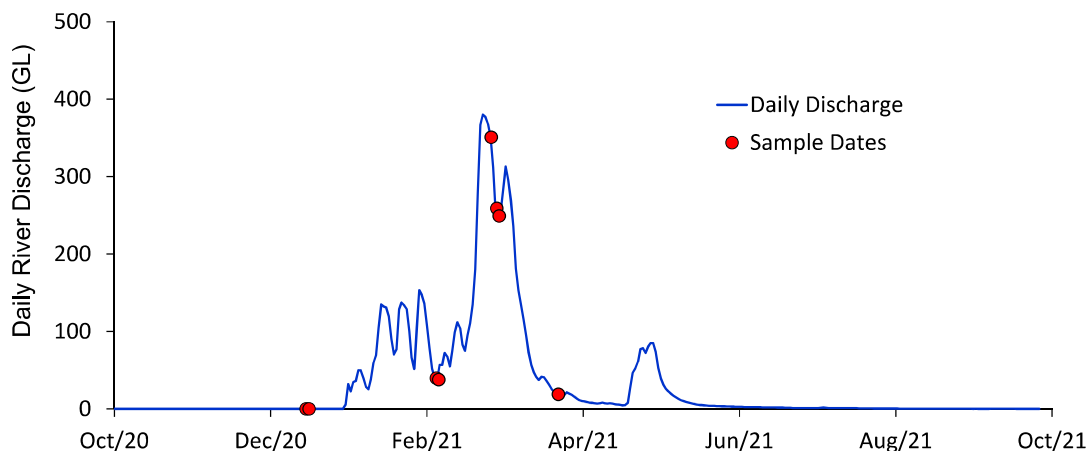


Figure 5-16: Daily discharge and sampling dates for the Normanby River (gauge 105107A) for the 2020–21 wet season. Note there is a 2 to 3-day travel time between the gauge and coastal waters, therefore February event samples were collected earlier in the rising flood stage than shown on the hydrograph.

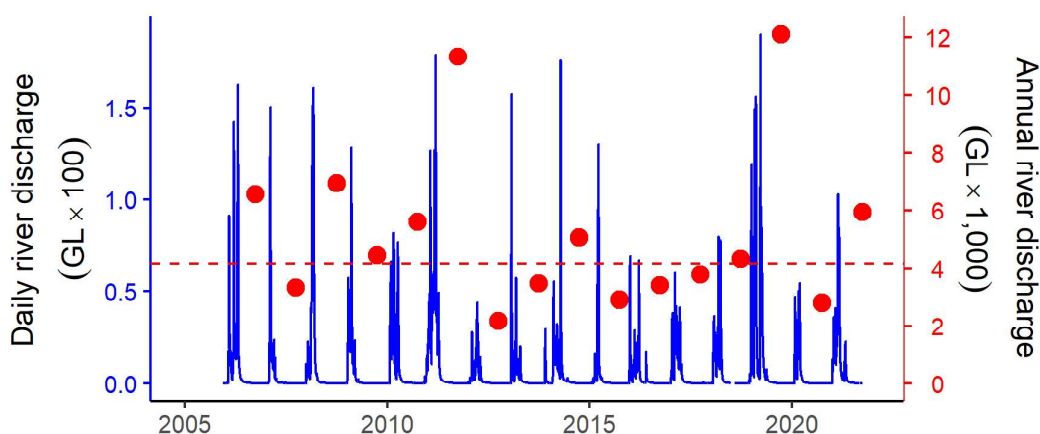


Figure 5-17: Long-term discharge for the Normanby River at gauge 105107A (Kalpowar Crossing). Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Method for estimation is described in Table 2-3.

The estimated discharge (5929 GL) and modelled load estimates (Source Catchments) for the 2020–21 water year from the Normanby Basin were 1.4 times above the long-term median (Figure 5-18). Total discharge for the whole of the Normanby Basin cannot be accurately calculated as there is no gauge on the Kennedy River or at the mouth of any of the three Normanby Basin distributaries, and so discharge has been estimated using the method described in Table 2-3. Over the 15-year period from 2006 to 2007:

- discharge has varied from 2,182 GL (2011–12) to 12,102 GL (2018–19)
- TSS loads ranged from 55 kt (2014–15) to 401 kt (2007–08)
- DIN loads ranged from 42 t (2011–12) to 266 t (2010–11)
- PN loads ranged from 124 t (2009–10) to 2,470 t (2018–19).

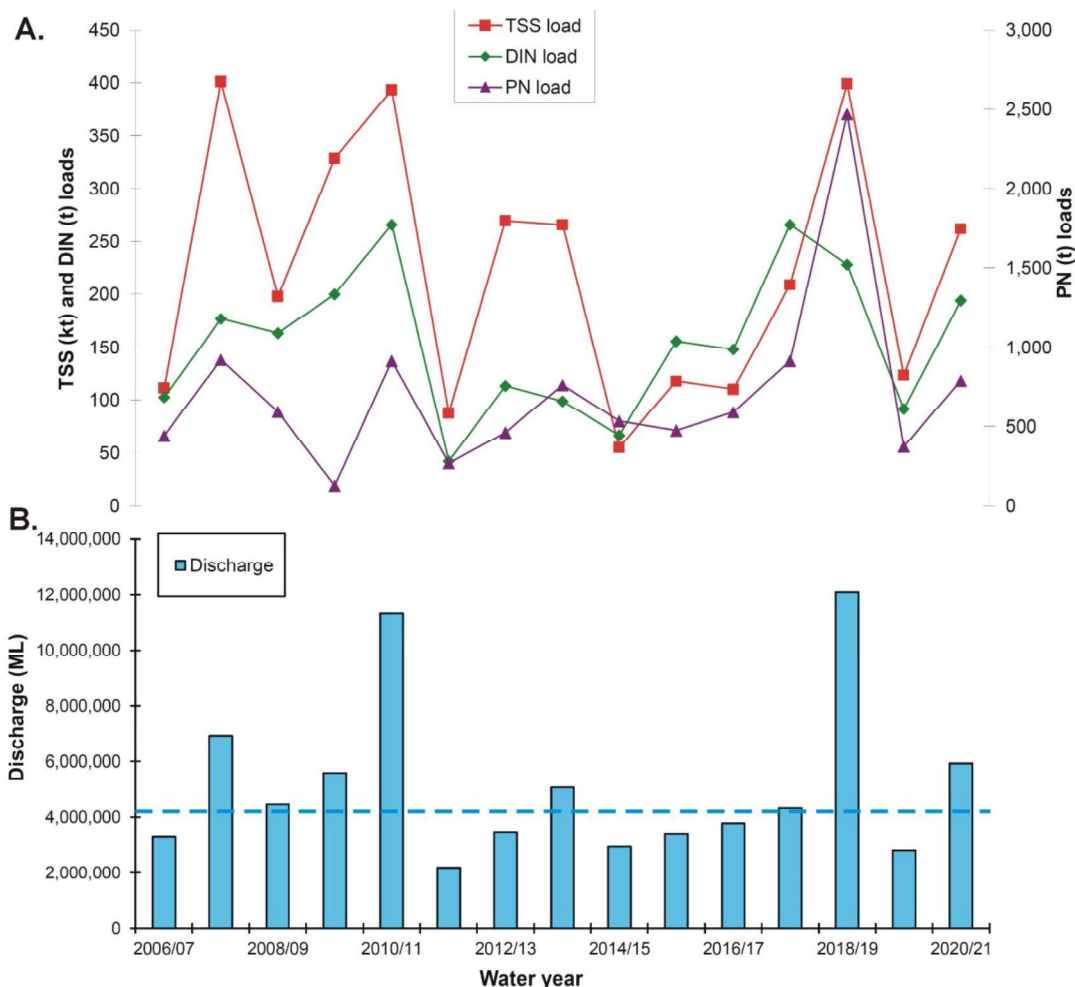


Figure 5-18: Modelled loads of (A) total suspended solids, dissolved inorganic (DIN) and particulate nitrogen (PN) and (B) discharge for the Normanby Basin. The loads reported here are a combination of ‘best estimates’ based on ‘up-scaled’ discharge and monitoring data from the Normanby River at Kalpowar gauging station (covers ~50% of the basin area). The dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality

The Normanby results include four sampling events (five at CI-01) during the wet season, including one that coincided with a flood event (26 February – 1 March 2021; Figure 5-16). Ambient water quality results are plotted against distance from the closest river mouth (Normanby, Bizant, or Kennedy) in Figure 5-19. Ambient results are compared against the GV for each water body in Table C-1.

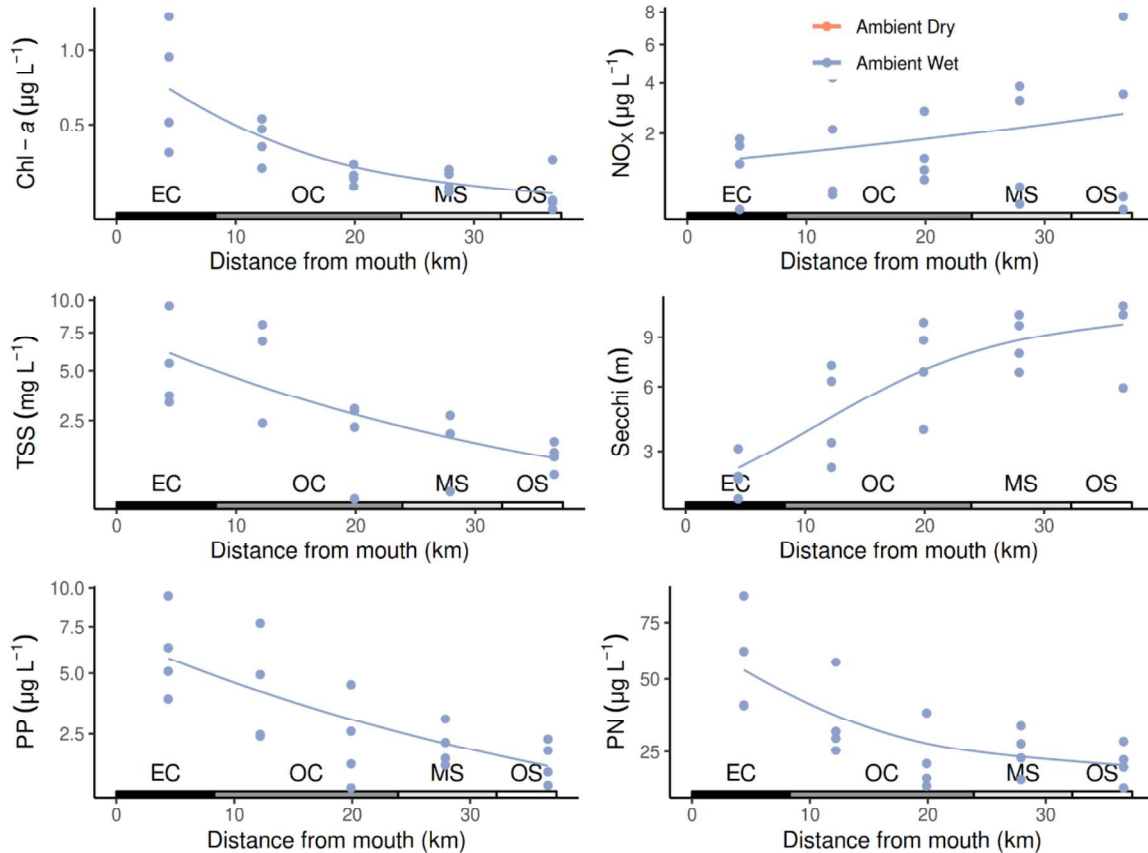


Figure 5-19: Water quality concentrations (surface and subsurface) and Secchi depth over distance (km) from river mouth for the Normanby focus region, all 2020–21 sampling dates.

Comparison of the 2020–21 ambient results with previous years and the GVs (Table C-1) highlights that:

- Overall, the water quality index for the Normanby scored “moderate”, with a “very poor” score for clarity due to TSS and Secchi depth results (Figure 5-20).
- NO_x concentrations exceeded the annual (offshore and midshelf) and wet season (open coastal and enclosed coastal) GVs for all sites and water bodies. However, samples collected in the wet season are not likely representative of annual medians.
- TSS concentrations and Secchi depths exceeded the annual and wet season GVs at all sites in the offshore, mid-shelf and open coastal water bodies.
- Mean Secchi depths increased in all water bodies compared to the previous year, most likely due to increased discharge.
- Median PP and PN concentrations exceeded the wet season GVs at some open coastal sites.

- For the second wet season in a row, Chl-a met the annual and wet season GVs at all Normanby transect sites and water bodies. This is in contrast to the high discharge 2018–19 wet season, when Chl-a concentrations were above the GVs in all water bodies.

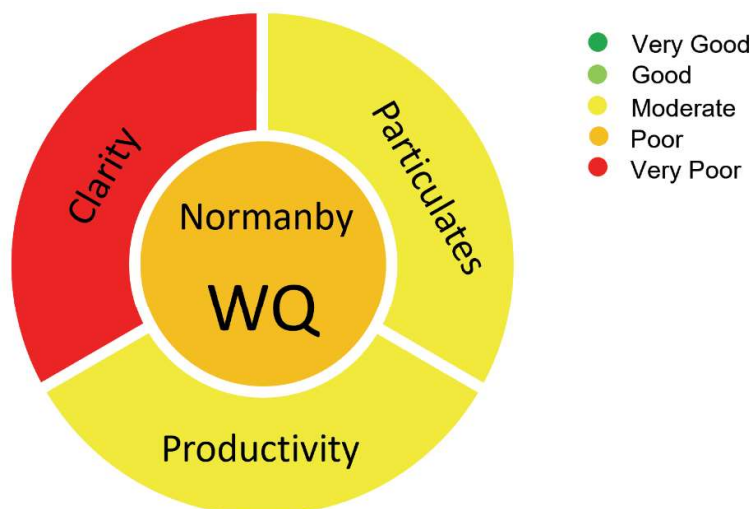


Figure 5-20: Normanby Annual WQ Index “coaster”. Calculations for index formulations are described in Appendix B.

Event water quality

Sampling conducted in late February/early March 2021 in partnership with Rinyirru Aboriginal Corporation and CSIRO coincided with the largest freshwater discharge event of the year (approx. 1417 GL total at Kalpowar Crossing gauge 105107A). It is difficult to estimate total river discharge associated with this event due to the lack of gauging on the Kennedy River. However, based on the total discharge measured at Kalpowar Crossing (gauge 105107A) and a comparison with flood events over the past 15 years (Howley *et al.*, 2018), this was an average magnitude event for the Normanby. Estuary and plume sampling occurred over 4 days (26 February – 1 March 2021) close to the peak of the event (Figure 5-16). A total of 27 samples were collected over the event, including 18 MMP samples at regular and event sampling sites, plus an additional 9 suspended sediment concentration (SSC) samples collected by Rinyirru Aboriginal Corporation at the Normanby estuary and Normanby and Kennedy river mouth sites.

Over the 4 days of sampling, SSC within the Normanby estuary fluctuated between 19 to 251 mg L⁻¹ (mean 139 mg L⁻¹). Within the adjacent flood plume, on 28 February, surface TSS decreased from 13 mg L⁻¹ at NR01 (salinity 9.0) to 0.5 mg L⁻¹ at NR06 (Corbett Reef, salinity 24.3). Interestingly, concentrations at all sites along the Normanby transect were approximately 3 times higher at depth than at the surface within the freshwater plume. Surface TSS/SSC at KR01 near the Kennedy River mouth ranged from 42 to 54 mg L⁻¹, decreasing along the Kennedy River transect to 3 mg L⁻¹ at KR02 and 1.1 mg L⁻¹ at CI01 (salinity 21.6). Similar to previous flood samples from Princess Charlotte Bay, higher concentrations of suspended sediments were discharged from the Kennedy River compared to the Normanby. Underway continuous flow sampling by CSIRO indicated that lower salinity, turbid floodwaters from the Normanby Basin dominated surface waters up to 200 km to the north of Princess Charlotte Bay on 1 March 2021 (Crowell *et al.*, 2021).

Chl-a concentrations also decreased along the Normanby transect, from a maximum of $1.4 \mu\text{g L}^{-1}$ at NR02 to $0.18 \mu\text{g L}^{-1}$ at Corbett Reef (NR06). Along the Kennedy transect, Chl-a ranged from 0.27 to $0.54 \mu\text{g L}^{-1}$.

Based on the analytical results and satellite images (Figure 5-21), it is evident that floodwater inundated coral reefs in Princess Charlotte Bay. However, nutrient and TSS/SSC concentrations at Cliff Island and Corbett Reef were not significantly elevated above average wet season concentrations, with the exception of DON at Corbett Reef. This is in contrast to previous flood sampling where nutrient and suspended sediment concentrations reaching offshore reefs were significantly elevated above ambient concentrations (Howley *et al.*, 2018).

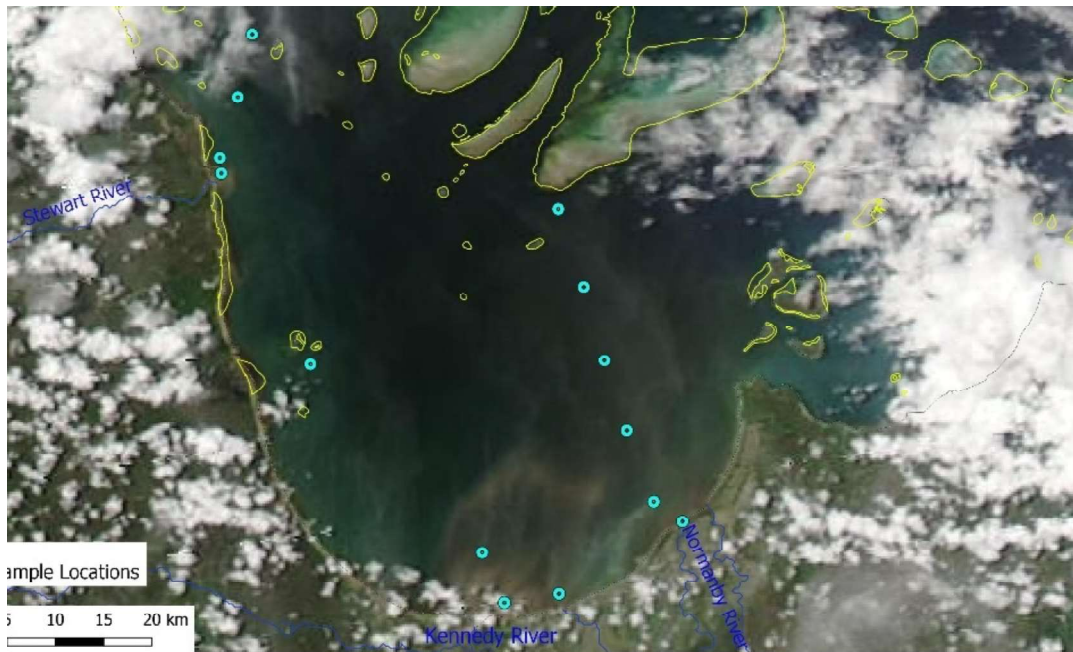


Figure 5-21: Satellite image of Kennedy and Normanby River flood plume on 23 February 2021 (3 days prior to sampling). Source: NASA MODIS Aqua.

5.1.4 Annan-Endeavour

The Annan-Endeavour focus area is influenced primarily by discharge from the Endeavour and Annan Rivers. Five sampling sites are located along transects from the two river mouths to mid-shelf reefs, representing a gradient in water quality (Figure 5-22). Additional sites ER01 and ER02 are sampled during events. In addition to manual sampling, dataloggers monitor continuous Chl-a fluorescence, turbidity and conductivity at Dawson Reef, 6 km from the mouth of the Annan River, and Forrester Reef 30 km north of the Endeavour River mouth (Figure 5-22).

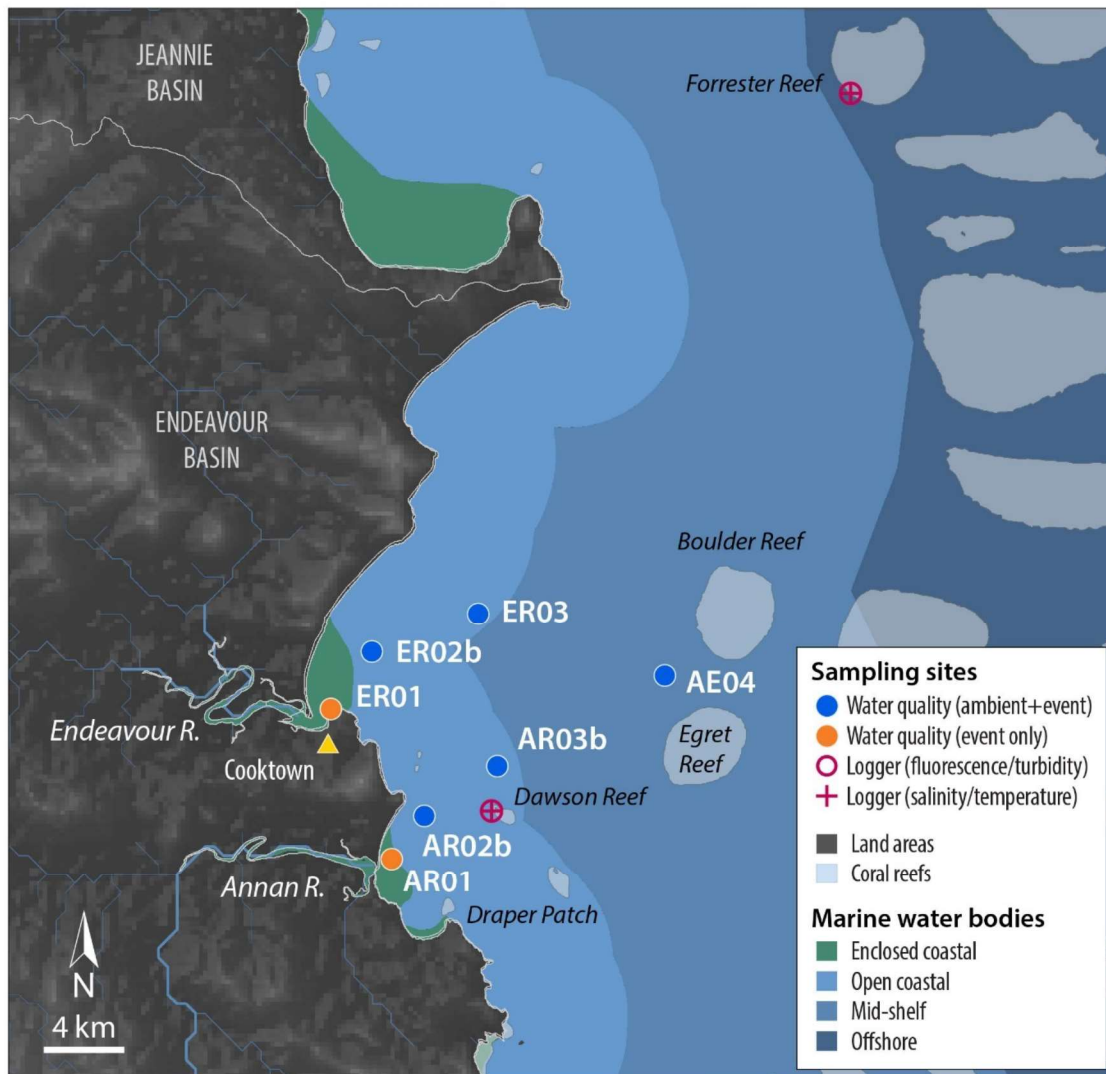


Figure 5-22: Water quality sampling sites in the Annan-Endeavour region shown with water body boundaries.

A total of 50 ambient surface and subsurface samples were collected from the Annan and Endeavour transect over 5 days between December 2020–May 2021. An additional 15 event samples were collected during relatively minor flood events in February and April 2021 (Figure 5-23). Thirteen additional samples were collected from the Dawson Reef and Forrester Reef dataloggers to calibrate turbidity/TSS and fluorescence/Chl-a logger measurements and laboratory data.

The estimated total discharge from the Endeavour Basin for the 2020–21 water year (1,552 GL) was just above the long-term median (Table 3-1, Figure 5-24 and Figure 5-25). The combined discharge and modelled loads estimated for the 2020–21 water year from the Endeavour Basin are shown in Figure 5-25. Over the 15-year period from 2006 to 2007:

- discharge has varied from 773 GL (2019–20) to 3,847 GL (2018–19)
- TSS loads have ranged from 39 kt (2019–20) to 192 kt (2018–19)
- DIN loads from 35 t (2019–20) to 173 t (2018–19)
- PN loads from 108 t (2019–20) to 539 t (2018–19).

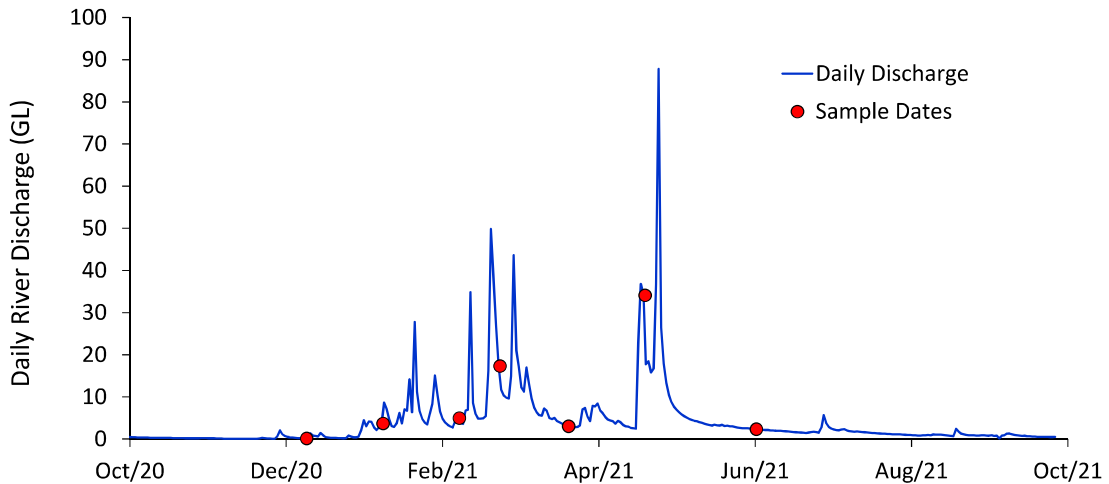


Figure 5-23: Daily discharge and sampling dates for the Endeavour Basin, combined (upscaled) values from the Annan River (gauge 107003A) and Endeavour River gauge (107001B) for the 2020–21 wet season.

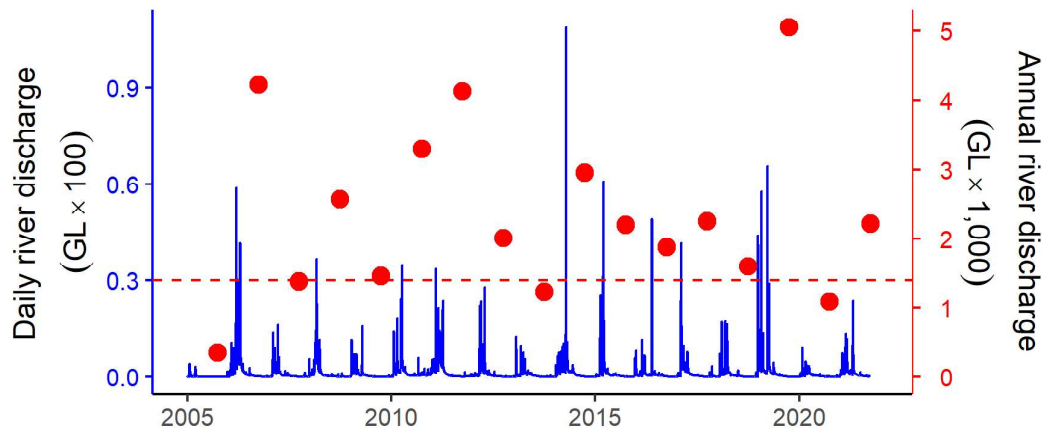


Figure 5-24: Long-term discharge for the Endeavour Basin, combined values from the Annan River (gauge 107003A) and Endeavour River (gauge 107001B). Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge. Method for estimation is described in Table 2-3.

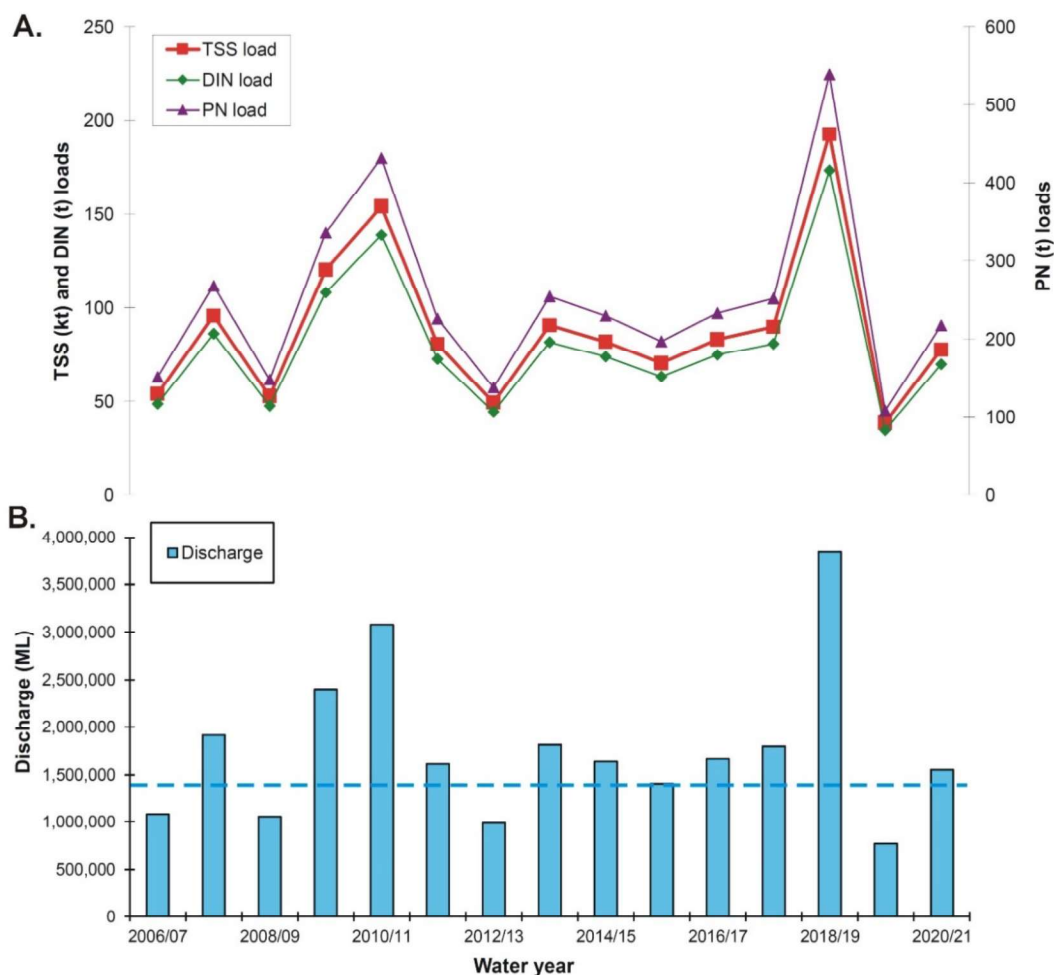


Figure 5-25. Loads of (A) total suspended solids, dissolved inorganic (DIN) and particulate nitrogen (PN) and (B) discharge for the Endeavour Basin from 2006 to 2021. The loads reported here the best estimates of annual mean concentration informed by nearest neighbour monitoring and by the Source Catchments modelling data and applied to each water year. Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality

Both ambient and event water quality results were plotted against distance from the mouths of the Annan or Endeavour River (Figure 5-26). Ambient mean and median values for each parameter are compared against the Eastern Cape York regional guidelines for the open coastal (ER02, ER03, AR02, AR03 & Dawson Reef), mid-shelf (AE04) and offshore (Forrester Reef) water bodies in Appendix C Table C-1.

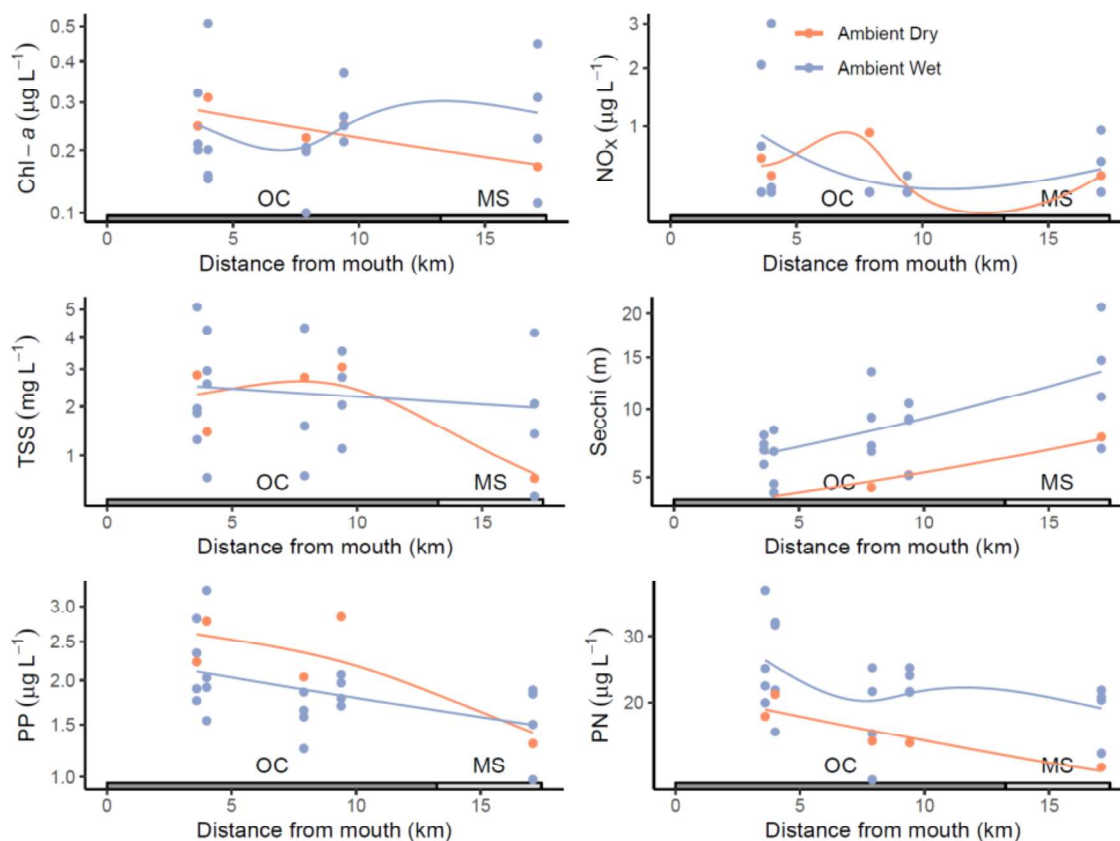


Figure 5-26: Water quality concentrations (surface and subsurface samples) and Secchi depth over distance from river mouth (km) for the Endeavour Basin focus region during ambient conditions (2020–21 water year). Note that data includes samples collected at varying distances from two river mouths (Annan and Endeavour), with each site plotted at the distance from the closest river. Complex regression lines result from this combination of data and varying river influences.

Comparison of the 2020–21 ambient results with previous years and the water quality GVs (Table C-1) highlights that:

- Overall, the water quality index scored “moderate” (Figure 5-27)
- Chl-a and PP met the GVs at all sites and water bodies.
- Median PN, PO₄ and NO_x concentrations exceeded the wet season GVs at most open coastal sites and annual GVs at the mid-shelf site (AE04).
- Median TSS exceeded the wet season and annual GVs at open coastal sites (ER02, ER03, AR02) but met the GV at AR03 (Dawson Reef) and AE04.
- Mean Secchi depth was less than the annual GV at all open coastal sites but met the GV at the midshelf water body (ER04).
- The annual median turbidity value at Dawson Reef (0.64 NTU) was less than the annual WQ GV (0.9 NTU). Mean turbidity at Dawson (1.39) increased slightly from 2019–20, but remained less than the annual mean from the 2018–19 record high discharge water year (1.63 NTU) (Table C-2)
- Median annual turbidity (0.25 NTU) at Forrester Reef was also well below the mid-shelf GV (0.8).
- Median Chl-a at Dawson & Forrester was also below the GVs.
- Wind driven sediment resuspension was responsible for the largest turbidity peak (>15NTU) and associated period of elevated Chl-a at Dawson Reef in March 2021 (Figure 5-28).

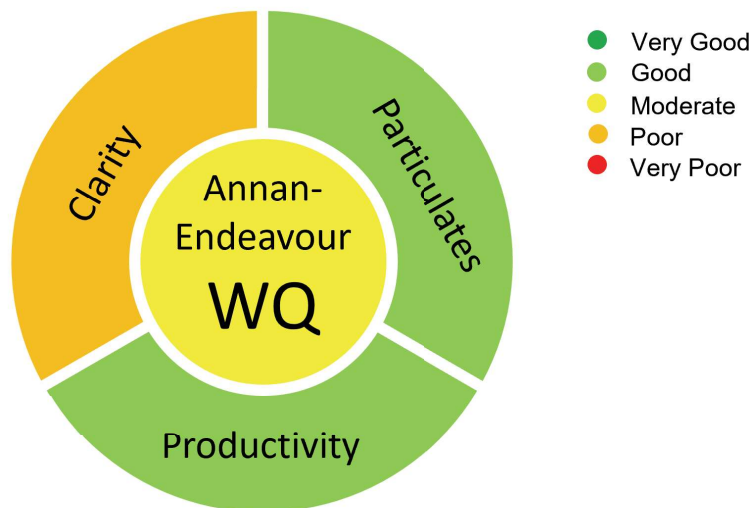


Figure 5-27: Annan-Endeavour Annual WQ Index “coaster”. Calculations for index formulations are described in Appendix B.

Event water quality

The 2020–21 wet season saw average rainfall in the Endeavour Basin, with several minor floods but relatively low daily discharge rates compared to above-average discharge years such as a 2018–19 (Figure 5-24). Flood event monitoring occurred along the Annan & Endeavour transects during minor flooding on 23 February (falling stage) and 21 April 2021 (Figure 5-23). Turbidity exceeded 500 NTU in the Annan estuary during both the February and April events, and elevated TSS was measured at Dawson Reef (open coastal) and Egret and Boulder mid-shelf reefs (site AE04) during the February event (4.8 and 5.5 mg L⁻¹ compared to ambient means of 2.2 and 1.6 mg L⁻¹ respectively). The FLNTU continuous turbidity dataloggers at Dawson and Forrester Reef also clearly showed the connectivity between turbid floodwater in the Annan and Endeavour estuaries and increased turbidity and Chl-*a* at reefs up to 30 km offshore (Figure 5-28). However, due to the relatively small magnitude of the wet season flood events, there was less flood influence at the mid-shelf Forrester Reef than during previous years, and Chl-*a* peaks at both reefs were lower than previous wet seasons. The most significant increase in turbidity and extended Chl-*a* increase was driven by high winds in March 2021 (Figure 5-28).

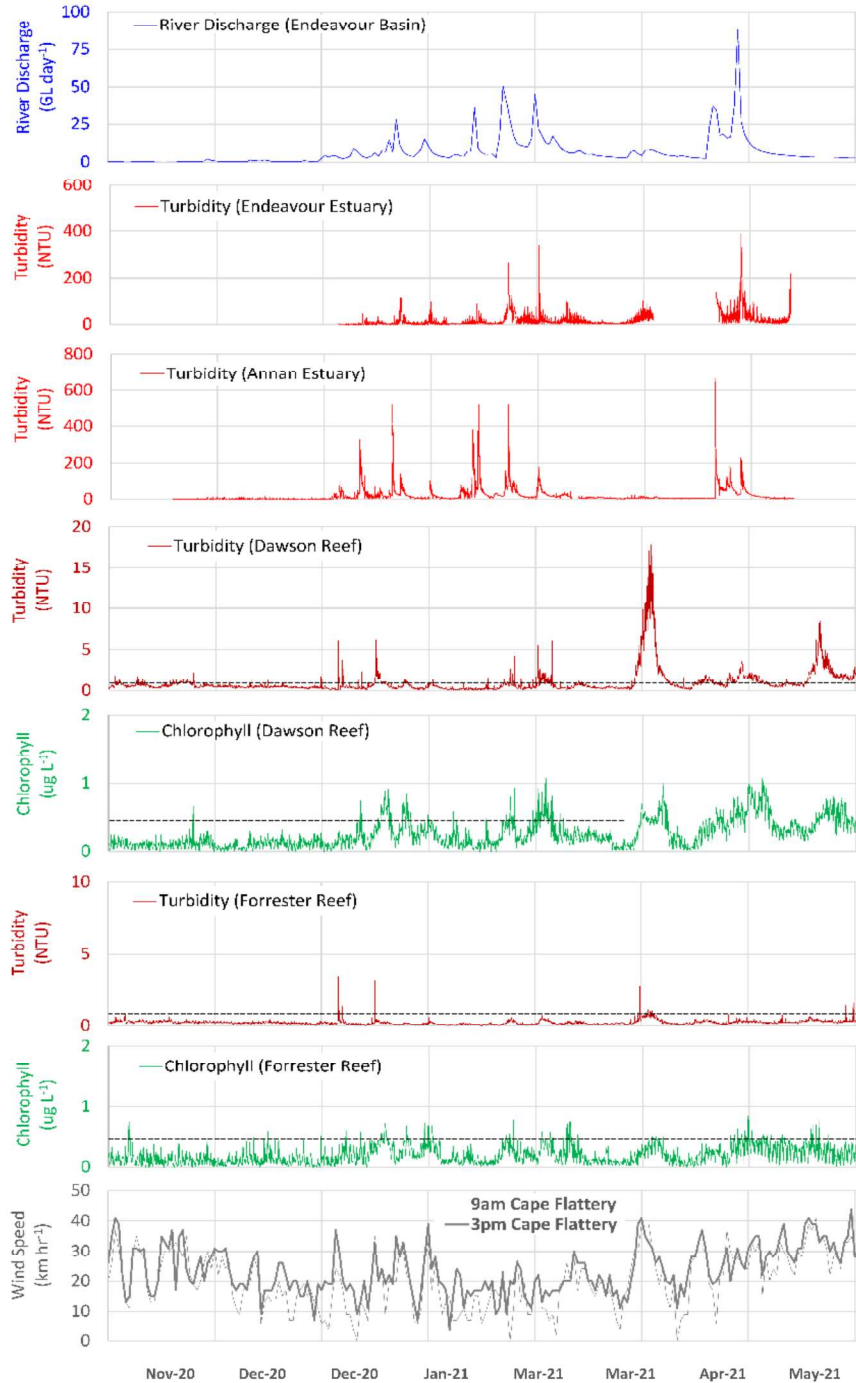


Figure 5-28: River discharge (combined Annan and Endeavour Rivers), turbidity measured on YSI EXO2s at the mouth of the Annan and Endeavour River, and turbidity and Chl-a fluorescence measured on the Wetlabs FLNTU at Dawson and Forrester Reefs over the 2020–21 wet season. Estuary turbidity (EXO2) data provided by CYWP and CSIRO. Dotted lines show wet season GVs.

5.2 Wet Tropics region

The Wet Tropics region is divided into three focus regions and results on the pressures and monitoring findings are presented separately for each.

5.2.1 Barron Daintree

This focus region contains the six sites of the ‘Cairns Transect’, which are sampled three times a year (Figure 5-29). This sampling design and frequency did not change in 2015 (unlike all other focus regions) as these sites are part of a long-term AIMS time-series.

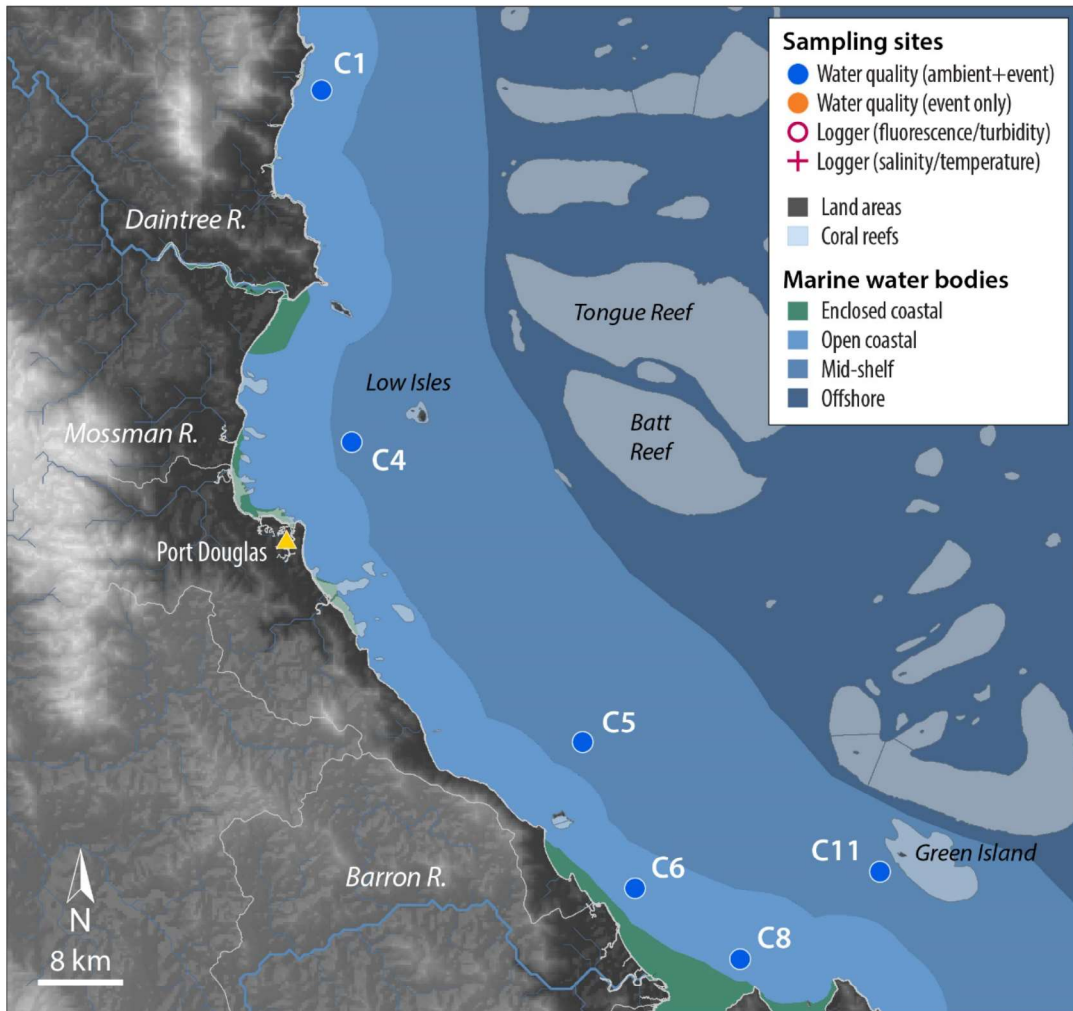


Figure 5-29: Sampling sites in the Barron Daintree focus region shown with water body boundaries

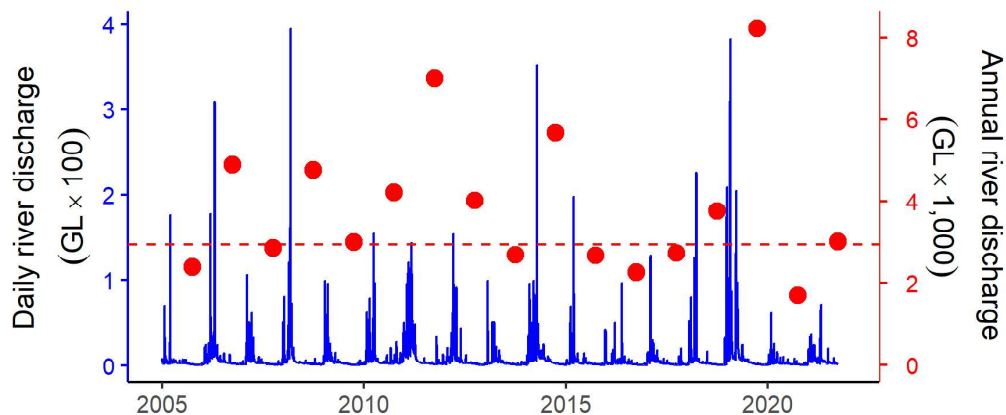


Figure 5-30: Combined discharge for the Barron (Myola gauge) and Daintree (Bairds gauge) Rivers. Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge.

The combined discharge and loads calculated for the 2020–21 water year from the Barron, Daintree, and Mossman Basins were close to the long-term median values (Figure 5-30; Figure 5-31; Table 3-1). Over the 16-year period:

- discharge has varied from 1,777 GL (2019–20) to 8,174 GL (2018–19)
- TSS loads ranged from 166 kt (2019–20) to 800 kt (2018–19)
- DIN loads ranged from 167 t (2019–20) to 758 t (2018–19)
- PN loads ranged from 444 t (2019–20) to 2,150 t (2018–19).

Of the three focus regions within the Wet Tropics NRM region, the Barron, Daintree and Mossman Basins commonly contribute the lowest discharge and consistent loads compared to the two focus regions to the south (i.e., Russell-Mulgrave and Johnstone Basins and the Tully-Murray and Herbert Basins).

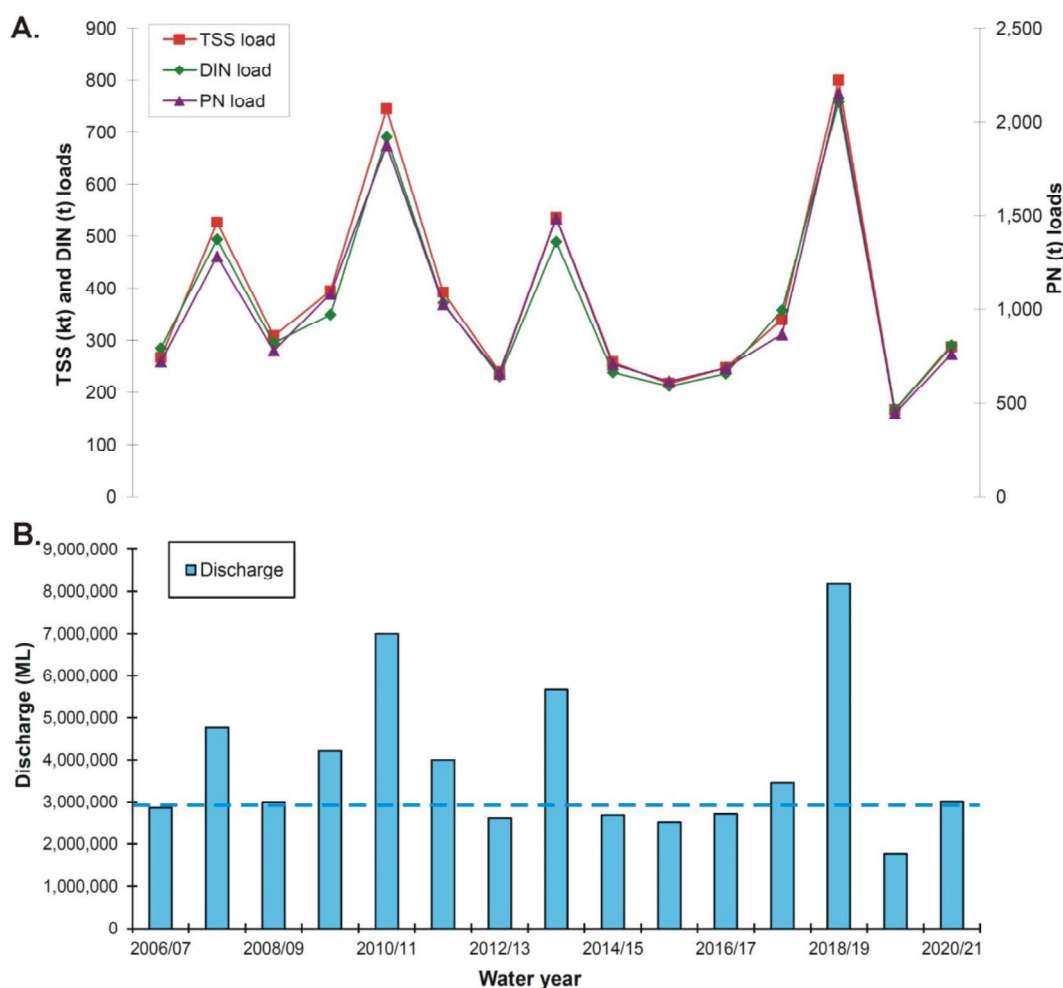


Figure 5-31: Loads of (A) TSS, DIN and PN and (B) discharge for the Barron, Daintree, and Mossman Basins from 2006–2021. The loads reported here are a combination of ‘best estimates’ for each basin based on ‘up-scaled discharge data from gauging stations, monitoring data (Barron River), the DIN model developed in Lewis *et al.* (2014) and annual mean concentrations and discharge from monitoring data or Source Catchments modelling data. The dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality and the in situ Water Quality Index

Long-term trends in water quality variables measured during ambient periods (i.e., not peak flood events) of the dry and wet seasons are presented in Figure 5-32. It is important to note that this trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points will have different values from raw data. This analysis is designed to detect **long-term** and **regional-scale** trends in water quality by removing the effect of short-term changes associated with weather and seasonal differences.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change (Figure 5-32). Site-specific statistics and comparison to GVs for all variables are available in Appendix C Table C-1. Mean concentrations of Chl-*a* and TSS have generally fluctuated around GVs (Great Barrier Reef Marine Park Authority, 2010) since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of both Chl-*a* and TSS have decreased and are now both below (meeting) water quality GVs. Mean concentrations of PO₄ have been relatively stable since the start of the MMP and show a downward trend in recent years, whereas mean NO_x concentrations have generally increased since 2005 and this trend has recently accelerated. Analysis of

trends shows that from 2016–2021, mean concentrations of PO_4 have declined and are currently below (meeting) GVs, while NO_x continues to be well above (exceeding) GVs.

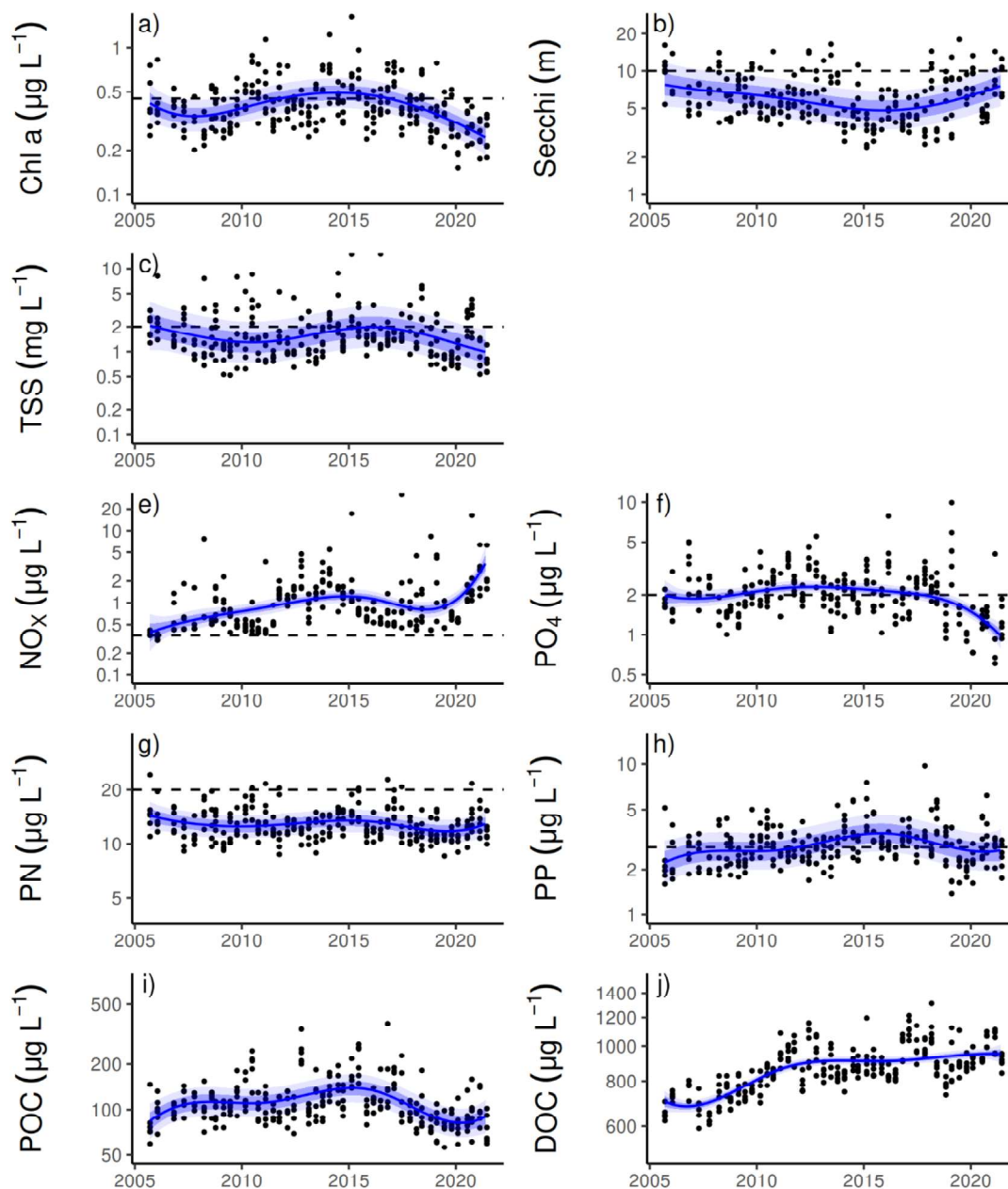


Figure 5-32: Temporal trends in water quality variables for the Barron Daintree focus region: a) chlorophyll *a* (Chl-*a*), b) Secchi depth, c) total suspended solids (TSS), d) nitrate/nitrite (NO_x), e) phosphate (PO_4), f) particulate nitrogen (PN), g) particulate phosphorus (PP), h) particulate organic carbon (POC) and i) dissolved organic carbon (DOC). Generalised additive mixed effect models (trends) are represented by blue lines with shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves, tides, and seasons after applying x-z detrending. Dashed horizontal reference lines indicate annual guidelines.

Mean Secchi depth declined (i.e., water clarity worsened) in previous years (until 2016), but analysis of trends shows that from 2016–2021, Secchi depth has increased (i.e., water clarity has improved) although it remains below (exceeding) the GV.

Mean concentrations of PN and PP have been relatively stable since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of PN have not significantly changed and remain below (meeting) GVs, while mean concentrations of PP have been relatively stable at values around the GVs.

Mean concentrations of POC have varied since 2005, and analysis of trends shows that from 2016–2021, POC may have decreased. Mean concentrations of DOC have increased dramatically since the inception of the MMP although trend analysis indicates they remained stable from 2016–2021.

The WQ Index is calculated using two different formulations to communicate: a) the long-term trend in water quality (based on the pre-2015 sampling design) and b) the annual condition of water quality (based on the post-2015 sampling design, which increased the power to detect change). For the Barron Daintree focus region (the Cairns Transect sites), no additional sites were added in 2015 and sampling is still conducted three times per year, unlike all other focus regions. The Methods section and Appendix B contain details of the calculations for both index formulations.

The long-term WQ Index has generally scored water quality as ‘good’ since 2005 with two years of ‘moderate’ in 2016–17 and 2017–18 water years. The long-term trend has been a small (i.e., changing by a single grade) but gradual decline in water quality from 2005–2018. Water quality appears to be trending towards improvement in the past three years (Figure 5-33a).

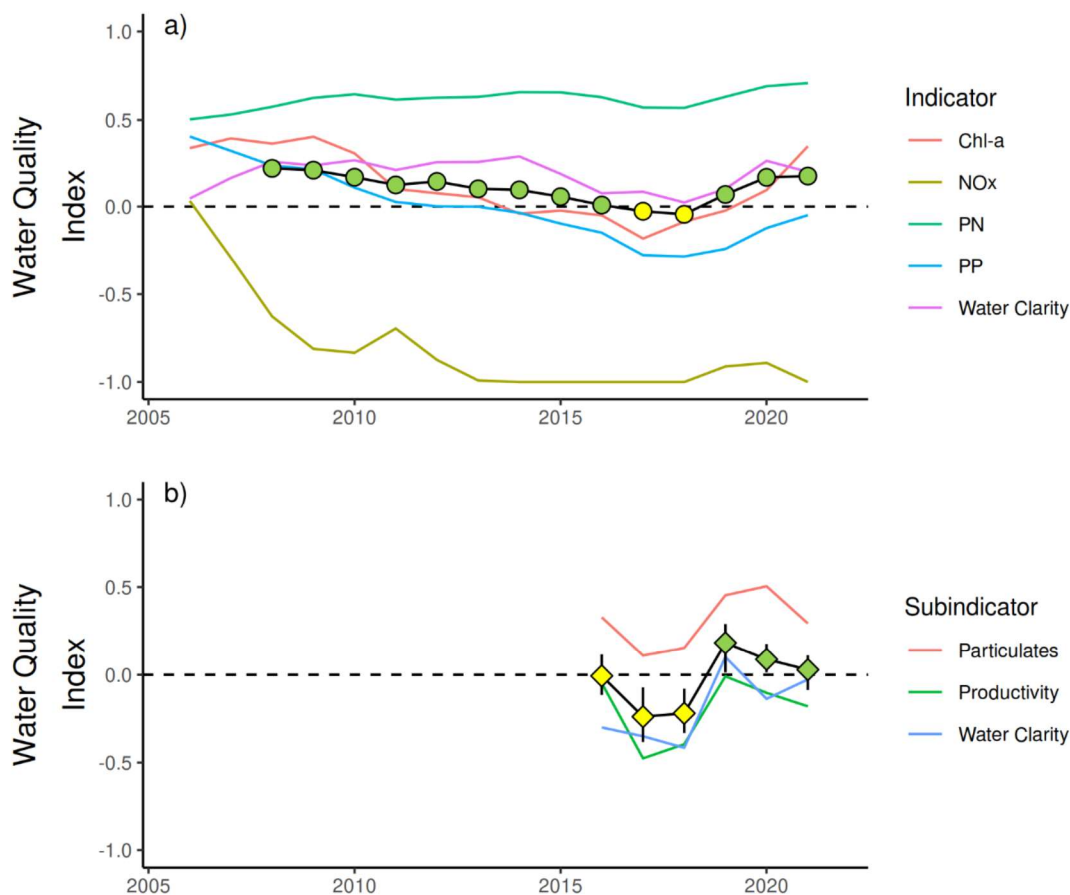


Figure 5-33: The Water Quality Index (WQ Index) for the Barron Daintree focus region. The WQ Index uses two formulations to communicate: a) long-term trend (based on pre-2015 sampling design) and b) the annual condition (based on post-2015 sampling design). WQ Index colour coding: ● / ◆ – ‘very good’; ○ / ◇ – ‘good’; ◐ / ◇ – ‘moderate’; ◑ / ◇ – ‘poor’; ◒ / ◇ – ‘very poor’. Indicators or sub-indicators that are used to calculate the WQ Index are shown as coloured lines on each plot. Error bars (vertical black lines) on the WQ Index represent the 95% quantile intervals. Calculations for both formulations are described in Appendix B.

The annual condition WQ Index scored water quality as ‘moderate’ during the 2015–18 water years and ‘good’ during the past three water years (Figure 5-33b). This version of the Index scores water quality parameters against GVs relevant to the season when samples are collected (wet versus dry GVs). River discharge was close to the long-term median in this focus region this year, which likely contributed to a ‘good’ score.

It is important to note that the two versions of the WQ Index are designed to answer separate questions and therefore differences in scores between the versions are expected.

Event water quality

No event sampling was conducted in the Barron Daintree focus area in 2020–21.

5.2.2 Russell-Mulgrave

The Russell-Mulgrave focus region is primarily influenced by discharge from the Russell-Mulgrave and Johnstone Basins and, to a lesser extent, by other rivers south of the focus region such as the Burdekin (Brodie *et al.*, 2013; Waterhouse *et al.*, 2017a). Three sites were sampled three times per year in this focus region until the end of 2014. Following the implementation of the revised MMP water quality sampling design in 2015, 12 monitoring sites are sampled in this focus region up to 10 times per year, with five sites sampled during both the dry and wet season and seven additional sites sampled during major flood events (Table A-1). The monitoring sites are located in a transect from the river mouth to mid-shelf waters, representing a gradient in water quality. Five sites are located in the open coastal water body, five sites are located in the mid-shelf water body, one site is in mid-estuarine waters, and one site is in enclosed coastal waters (Figure 5-34).

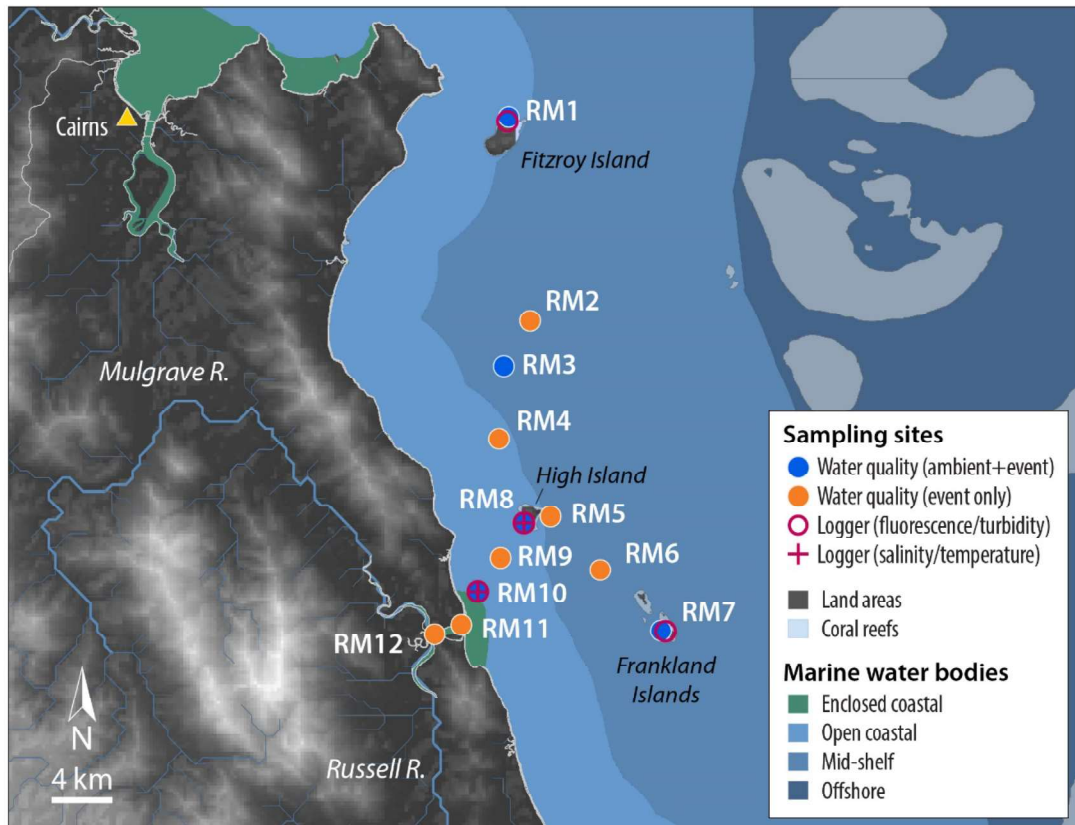


Figure 5-34: Sampling sites in the Russell-Mulgrave focus region, shown with the water body boundaries.

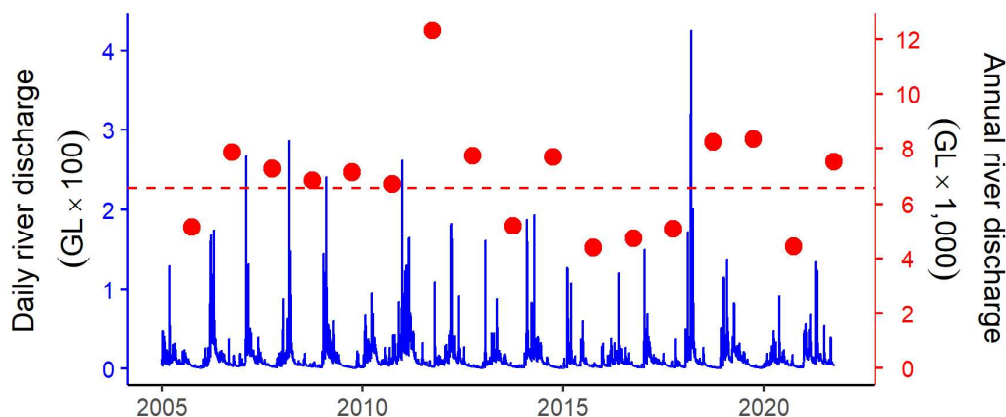


Figure 5-35: Combined discharge for the North and South Johnstone (Tung Oil and Central Mill gauges, respectively), Russell (Bucklands gauge) and Mulgrave (Peets Bridge gauge) Rivers. Daily (blue) and water year (October to September, red symbols) discharge is shown. Red dashed line represents the long-term median of the combined annual discharge.

The combined discharge volume of the Russell-Mulgrave and Johnstone Rivers was above the long-term median for the 2020–21 water year and was similar to the annual discharge from the 2013–14 water year (Figure 5-35).

The combined discharge and loads calculated for the 2020–21 water year from the Russell-Mulgrave and Johnstone Basins were in the average to higher range to that recorded over the past decade (Figure 5-36). Over the 16-year period:

- discharge has varied from 4,372 GL (2014–15) to 12,335 GL (2010–11)
- TSS loads ranged from 251 kt (2014–15) to 725 kt (2010–11)
- DIN loads ranged from 744 t (2014–15) to 2,145 t (2010–11)
- PN loads ranged from 840 t (2014–15) to 2423 t (2010–11).

Of the three focus regions within the Wet Tropics NRM region, the Russell-Mulgrave and Johnstone Basins collectively contribute similar discharge and loads to the Tully-Murray and Herbert Basins during low to average discharge years, although the latter basins contribute higher values (particularly DIN) during the high discharge years such as in 2008–09 and 2010–11 water years.

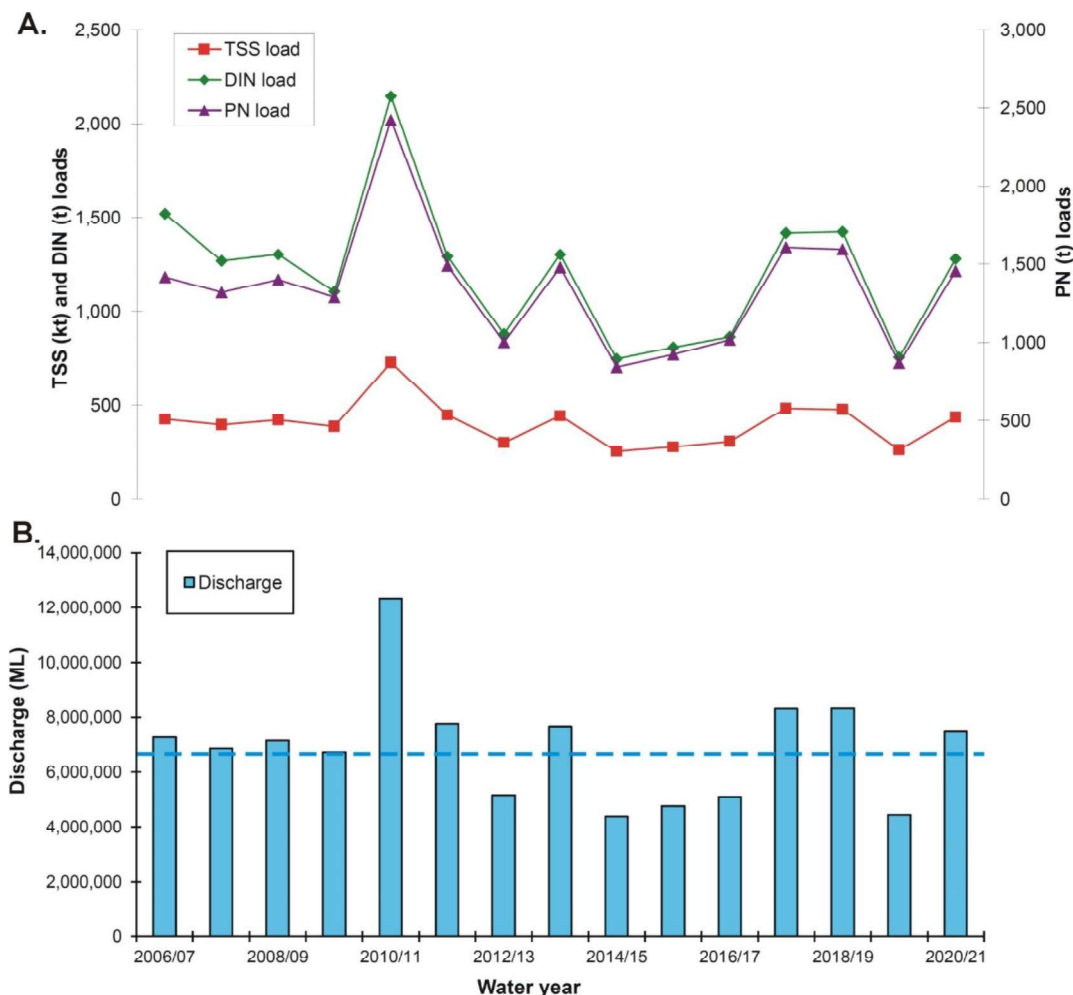


Figure 5-36: Loads of (A) TSS, DIN and PN and (B) discharge for the Russell, Mulgrave and Johnstone Basins from 2006 to 2021. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (Johnstone River), the DIN model developed in Lewis *et al.* (2014) and annual mean concentrations and discharge from monitoring data or Source Catchments modelling data. Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality and the in situ Water Quality Index

Water quality showed trends along the sampling transect (cross-shelf gradient in northerly direction). Sites located nearest to the river mouth (river mouth = 0 km) had high concentrations of NO_x and particulate nutrients (PN and PP), which declined with distance away from the river mouth, reaching low levels in mid-shelf waters (Figure 5-37, Appendix C Table C-2). Concentrations of Chl-*a* and TSS showed a similar pattern to nutrient concentrations and tended to decline with distance from the river mouth. Secchi depths were low at sites near the river mouth (water clarity was poor) and increased (water clarity improved) with distance from the river mouth. These spatial patterns are consistent with those observed in 2019–20.

Seasonal differences in water quality were small for most variables. Concentrations of NO_x , TSS, Chl-*a* and PP were similar between wet and dry seasons, though PN was slightly lower in the dry season (Figure 5-37). Secchi depths were similar in the wet season and the dry.

There was likely little influence of river discharge on mid-shelf waters during the 2020–21 water year, which was demonstrated by wet and dry season values converging in mid-shelf waters (for PN).

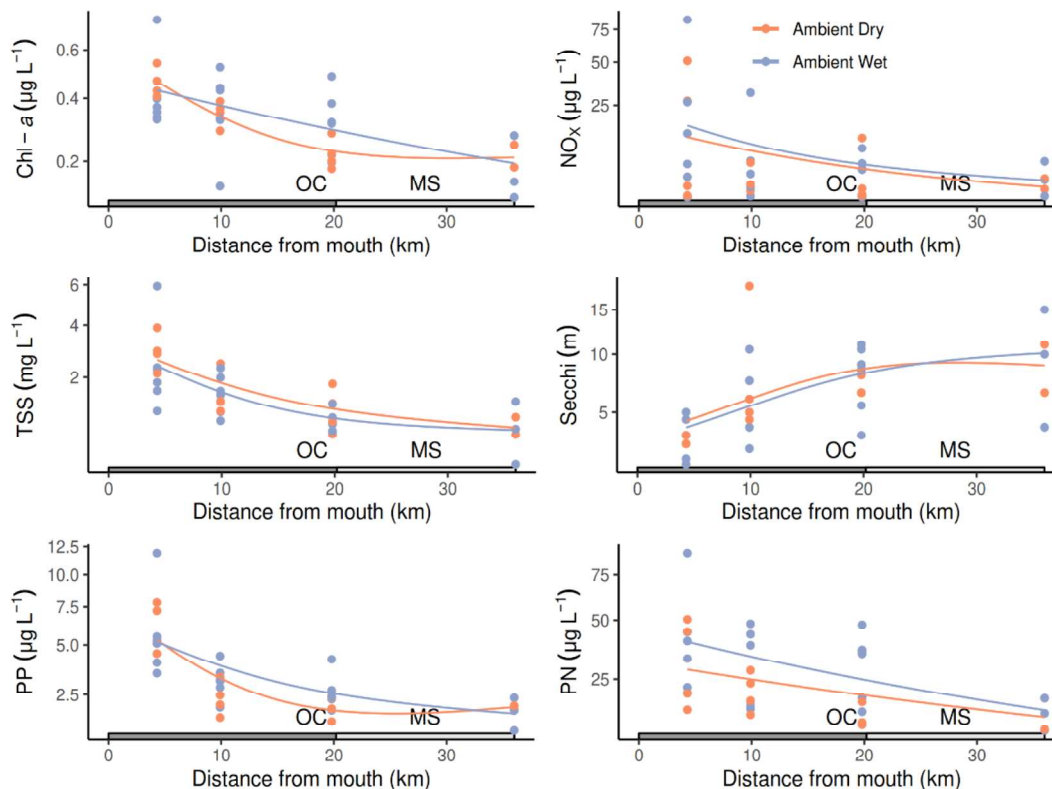


Figure 5-37: Water quality variables measured during ambient and event sampling in 2020-21 along the Russell-Mulgrave focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the Russell-Mulgrave river mouth. Water body classifications are shown along the x-axes: open coastal (OC) and mid-shelf (MS). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

Long-term trends in water quality variables measured during ambient periods (for example, not during peak flood events) of the dry and wet seasons are presented in Figure 5-38. It is important to note that this trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points will have different values compared to raw data. This analysis is designed to detect **long-term** and **regional-scale** trends in water quality by removing the effect of short-term changes associated with weather and seasonal differences.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change (Figure 5-38). Site-specific statistics and comparison to GVs for all variables are available in Appendix C Table C-1. Mean concentrations of Chl-*a* and TSS have generally fluctuated around GVs (Great Barrier Reef Marine Park Authority, 2010) since the start of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of both Chl-*a* and TSS have decreased and are now both below (meeting) water quality GVs at most sites. FLNTU turbidity (Figure 5-38a) and fluorometer Chl-*a* (Figure 5-38b) have,

however, remained steady at around guideline values, reflecting slightly different sampling locations and technologies, so these apparent improving trends should be treated with caution.

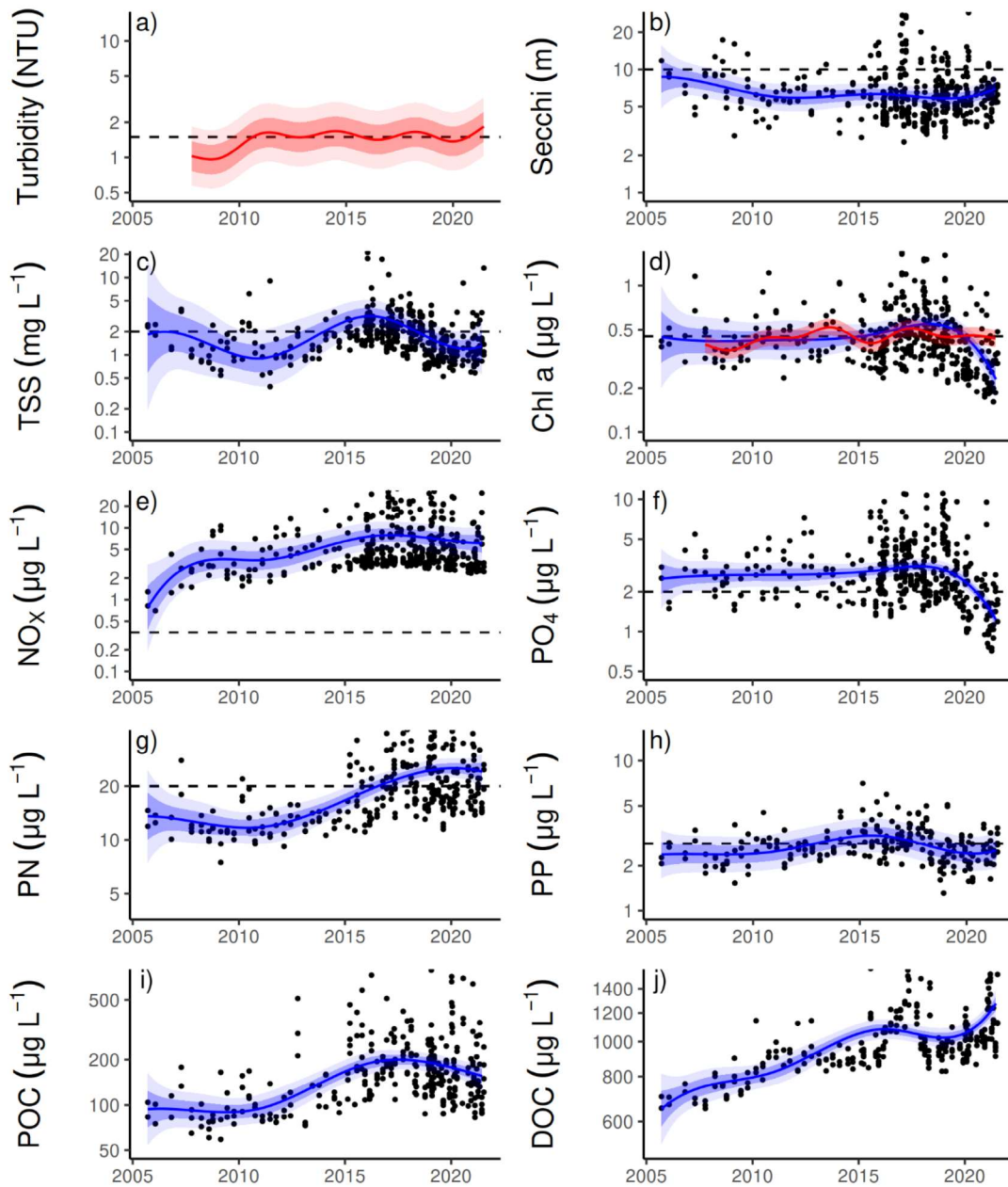


Figure 5-38: Temporal trends in water quality variables for the Russell-Mulgrave focus region: a) turbidity, b) Secchi depth, c) total suspended solids (TSS), d) chlorophyll *a* (Chl-*a*), e) nitrate/nitrite (NO_x), f) phosphate (PO_4), g) particulate nitrogen (PN), h) particulate phosphorus (PP), i) particulate organic carbon (POC) and j) dissolved organic carbon (DOC). Generalised additive mixed effect models (trends) are represented by blue lines with shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves, tides, and seasons after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, and individual records can be found in Appendix C Figure C-1. Dashed horizontal reference lines indicate annual guidelines.

Mean concentrations of PO₄ have been relatively stable since the inception of the MMP, but analysis of trends shows that from 2016–2021 concentrations have declined and are currently below (meeting) GVs at most sites. Mean concentrations of NO_x have generally increased since 2005 and analysis of trends shows that from 2016–2021 concentrations have remained stable and are currently well above (exceeding) GVs. Mean Secchi depth declined (i.e., water clarity worsened) since the inception of the MMP, but analysis of trends shows that from 2016–2021, Secchi depth has remained stable and below (exceeding) the GV.

Mean concentrations of PN and PP have varied around the GV since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of PN have likely increased and continue to be above (exceeding) GVs at most sites, while mean concentrations of PP have decreased and are currently below (meeting) GVs at most sites. Mean concentrations of POC and DOC dramatically increased since monitoring began in 2005. Analysis of trends shows that from 2016–2021, POC has decreased slightly, while DOC has continued to increase (after a pause from 2018-2020).

The WQ Index is calculated using two different formulations to communicate: a) the long-term trend in water quality (based on the pre-2015 sampling design) and b) the annual condition of water quality (based on the post-2015 sampling design, which increased the power to detect change). The Methods section and Appendix B contain details of the calculations for both index formulations.

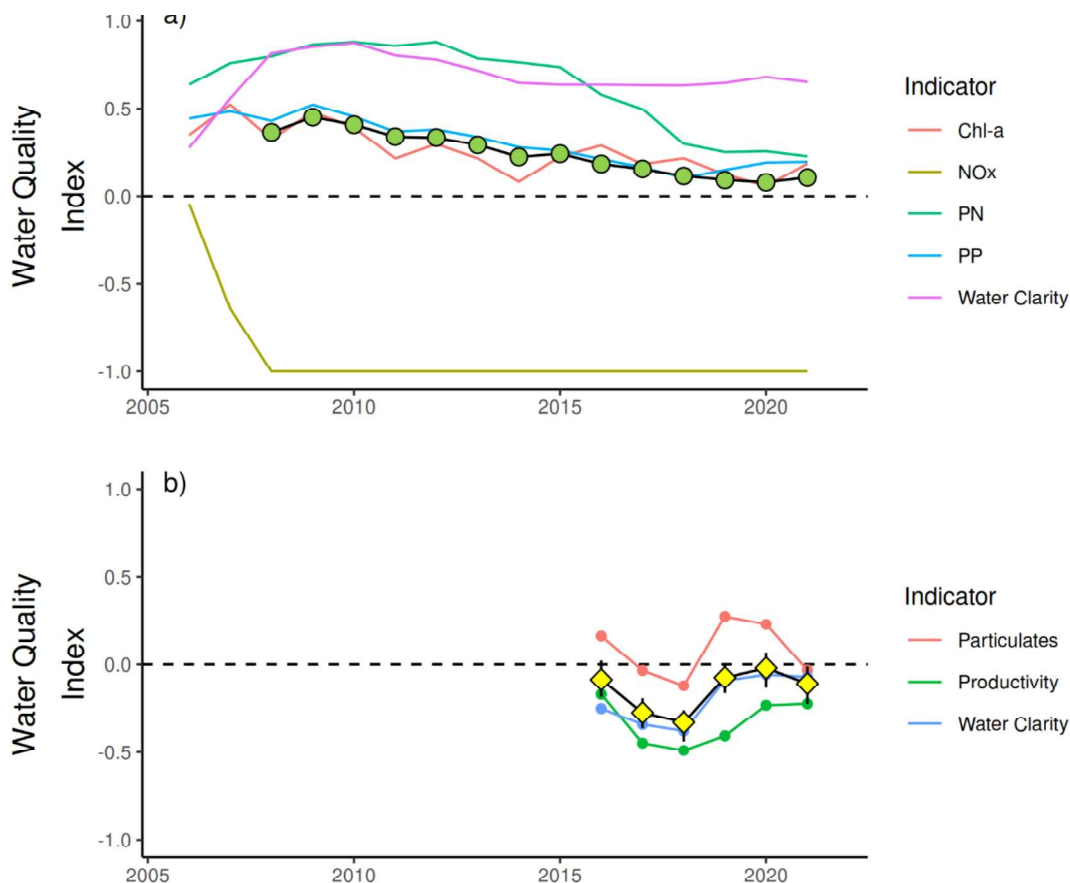


Figure 5-39: The Water Quality Index (WQ Index) for the Russell-Mulgrave focus region. The WQ Index uses two formulations to communicate: a) long-term trend (based on pre-2015 sampling design) and b) the annual condition (based on post-2015 sampling design). WQ Index colour coding: ● / ◆ – ‘very good’; ○ / ◇ – ‘good’; ● / ◆ – ‘moderate’; ● / ◆ – ‘poor’; ● / ◆ – ‘very poor’. Indicators or sub-indicators that are used to calculate the WQ Index are shown as coloured lines on each plot. Error bars (vertical black lines) on the WQ Index represent the 95% quantile intervals. Calculations for both formulations are described in Appendix B.

The long-term WQ Index has scored water quality as ‘good’ since 2008; however, this Index has shown a small (i.e., changing within a grade) but gradual decline in water quality since 2009 (Figure 5-39a). This downward trend has generally been driven by trends in PN, PP, and Chl-a indicators.

The annual condition WQ Index scored water quality as ‘moderate’ for the past six years (Figure 5-39b). This version of the Index scores water quality parameters against GVVs relevant to the season when samples are collected (wet versus dry GVVs) and includes additional sites in the open coastal water body to better characterise areas affected by river discharge.

It is important to note that the two versions of the WQ Index are designed to answer separate questions and therefore differences in scores between the versions are expected.

Event water quality

No event sampling was conducted in the 2020–21 wet season in the Russell-Mulgrave focus area. An event sampling trip was attempted in May but the roads were cut off and the boat ramps were not accessible.

5.2.3 Tully

The Tully focus area is primarily influenced by discharge from the Tully-Murray and Herbert Rivers and, to a lesser extent, by the Burdekin River in large flow years (Brodie *et al.*, 2013).

One site was sampled in this focus area three times per year until the end of 2014. Following the implementation of the revised MMP water quality sampling design in 2015, 11 monitoring sites are sampled in this focus region up to 10 times per year, with six sites sampled during both the dry and wet seasons and five additional sites sampled during major flood events Table A-1. The monitoring sites are located in a transect from the river to mid-shelf waters, representing a gradient in water quality. Seven sites are located in the open coastal water body, one site is located in the mid-shelf water body, one site is in mid-estuarine waters, and two sites are in lower estuarine waters (Figure 5-40).

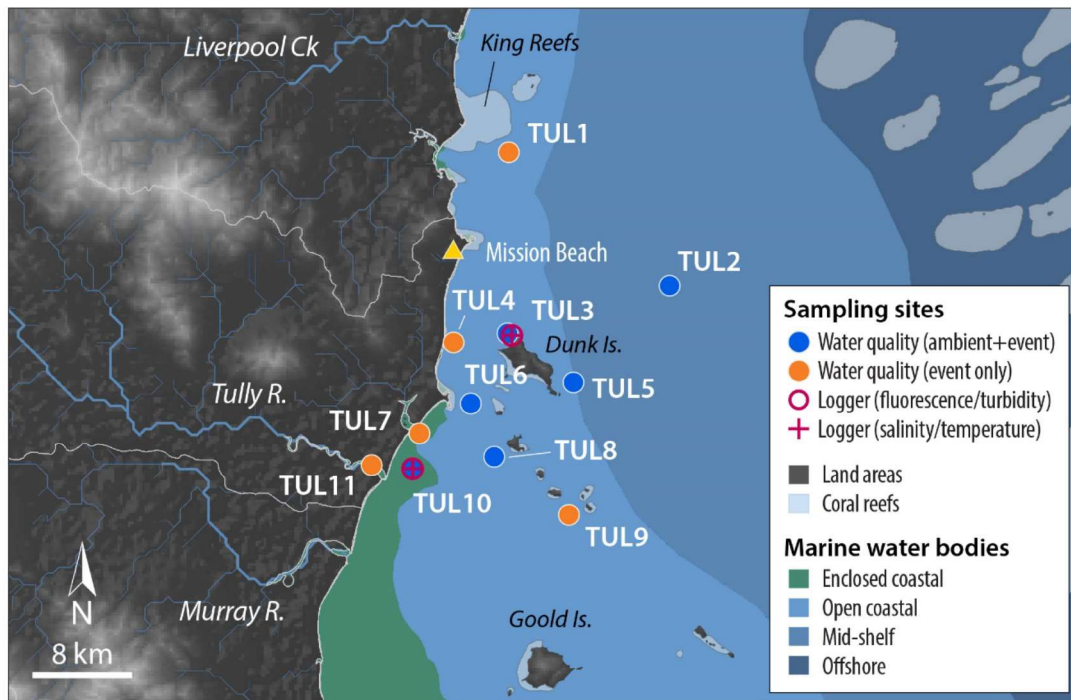


Figure 5-40: Sampling sites in the Tully focus area, shown with the water body boundaries.

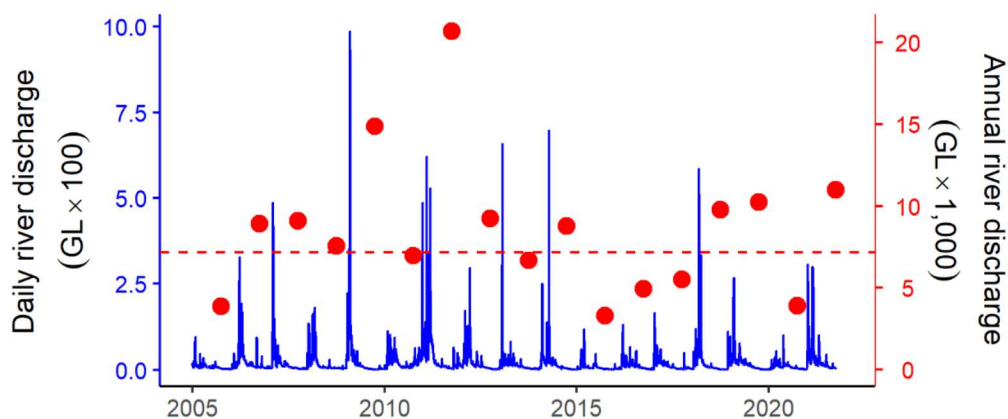


Figure 5-41: Combined discharge for Tully (Euramo gauge) and Herbert (Ingham gauge) Rivers. Daily (blue) and water year (October to September, red) discharge is shown. Red dashed line represents the long-term median of the combined annual discharge. Please note as this is the combined discharge, high flows in one river will not necessarily be visible in the graph.

The combined discharge and loads calculated for the 2020–21 water year from the Tully, Murray, and Herbert Basins were over 1.5 times the long-term median (Figure 5-41). Over the 16-year period:

- discharge has varied from 3,647 GL (2014–15) to 20,738 GL (2010–11)
- TSS loads ranged from 213 kt (2014–15) to 1,598 kt (2010–11)
- DIN loads ranged from 1,022 t (2014–15) to 5,214 t (2010–11)
- PN loads ranged from 664 t (2014–15) to 4,666 t (2010–11).

Of the three focus regions within the Wet Tropics NRM region, the Tully, Murray, and Herbert Basins collectively contribute similar discharge and TSS and PN loads to the Russell, Mulgrave, and Johnstone Basins during low-to-moderate discharge years. However, the Tully, Murray, and Herbert Basins contribute higher values during the high discharge years such as in 2008–09 and 2010–11 as well as generally higher DIN loads in the average to above-average discharge years (Figure 5-42).

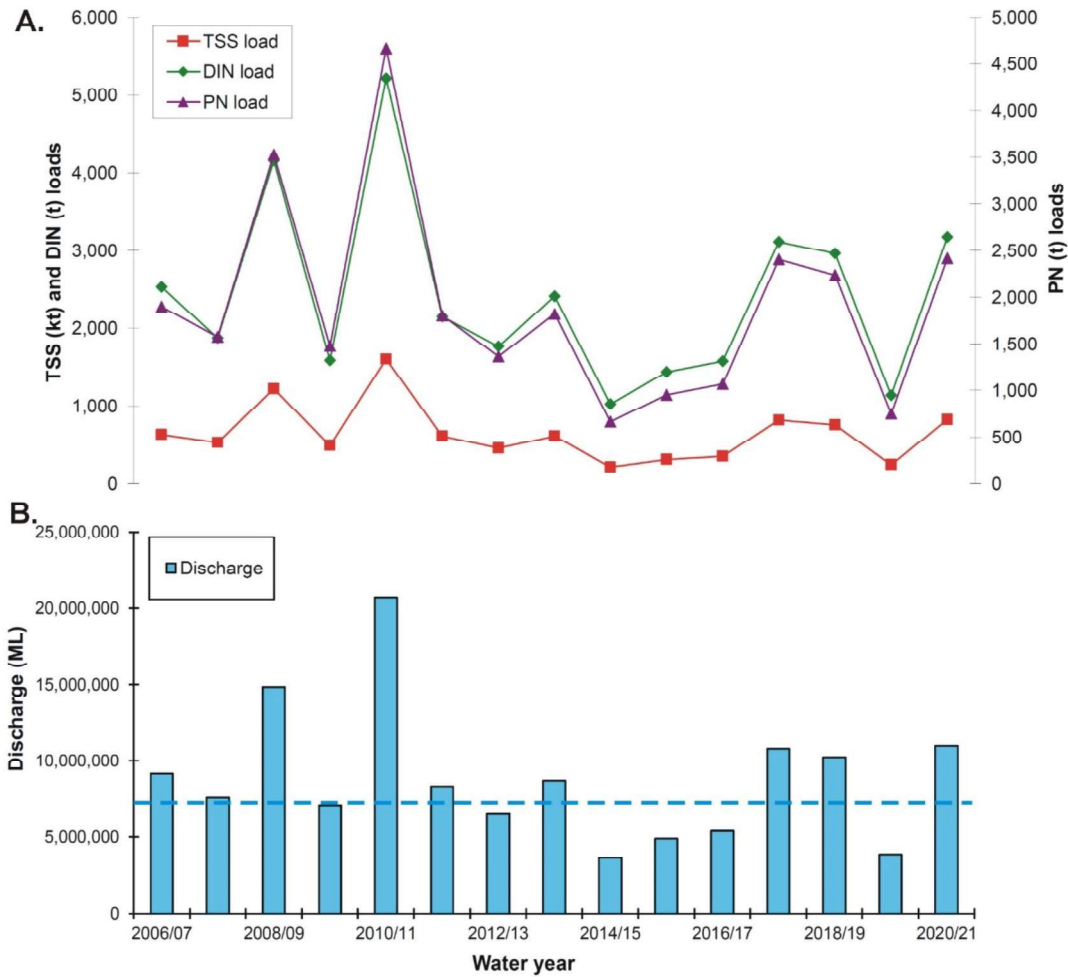


Figure 5-42: Loads of (A) TSS, DIN and PN and (B) discharge for the Tully, Murray, and Herbert Basins from 2006–07 to 2019–21. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (Tully and Herbert Rivers), the DIN model developed in Lewis *et al.* (2014) and annual mean concentrations and discharge from monitoring data or Source Catchments modelling data. The dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality and the in situ Water Quality Index

Water quality showed trends along the sampling transect (cross-shelf gradient in northerly direction). Sites located nearest to the river mouth (river mouth = 0 km) had high concentrations of particulate nutrients (PN and PP), particularly in the wet season, and declined with distance away from the river mouth, reaching low levels in mid-shelf waters (Figure 5-43, Appendix C Table C-2). Concentrations of Chl-*a* and TSS showed a similar pattern to particulate nutrient concentrations, declining with distance from the river mouth. Secchi depths were low at sites near the river mouth (water clarity was poor) and increased (water clarity improved) with distance from the river mouth, with little seasonal difference. Concentrations of NO_x declined strongly from the river mouth in the wet season, but showed no cross-transect pattern in the dry.

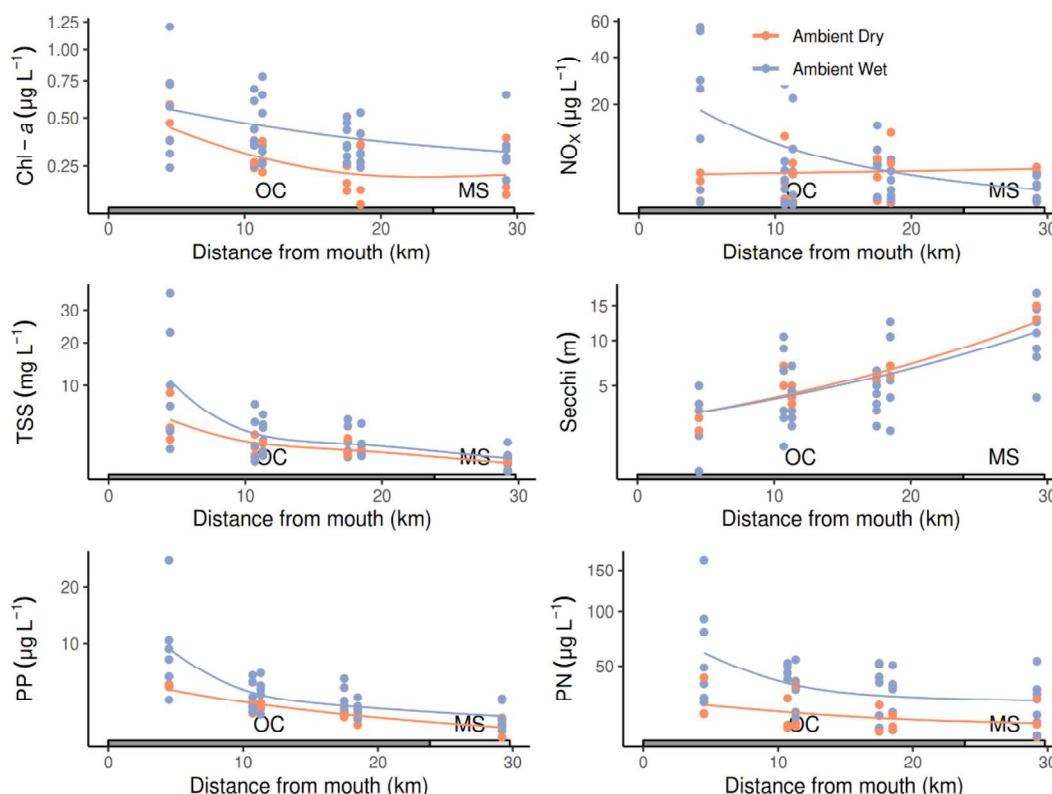


Figure 5-43: Water quality variables measured during ambient and event sampling in 2020-21 along the Tully focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the Tully River mouth. Water body classifications are shown along the x-axes: open coastal (OC) and mid-shelf (MS). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

Seasonal differences were prominent for NO_x and PN, reflecting the above-average river discharges. Near the river mouth, seasonal differences were also observed for PP and TSS

Long-term trends in water quality variables measured during ambient periods (for example, not during peak flood events) of the dry and wet seasons are presented in Figure 5-44. It is important to note that this trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points will have different values compared to raw data. This analysis is designed to detect **long-term** and **regional-scale** trends in water

quality by removing the effect of short-term changes associated with weather and seasonal differences.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change (Figure 5-44). Site-specific statistics and comparison to GVs for all variables are available in Appendix C Table C-2. Mean concentrations of Chl-*a* and TSS have generally fluctuated around GVs (Great Barrier Reef Marine Park Authority, 2010) since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of both Chl-*a* and TSS have decreased and are now both below (meeting) water quality GVs at most sites. Fluorometer Chl-*a* (red line in Figure 5-44d) does not reflect this trend – this is an effect of the different measurement technology and location and single fluorometric logging site.

Mean concentrations of PO₄ have been relatively stable since the inception of the MMP, but analysis of trends shows that from 2016–2021 concentrations have declined and are currently below (meeting) GVs at all sites. Mean concentrations of NO_x have generally increased since 2008 and analysis of trends shows that from 2016–2021 concentrations have slightly decreased but remain well above (exceeding) GVs.

Mean Secchi depth has been relatively stable since the inception of the MMP, and analysis of trends shows that from 2016–2021, Secchi depth has slightly increased (water clarity improved) although it currently remains below (exceeding) the GV.

Mean concentrations of PN and PP have been relatively stable and close to GVs since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of PN have increased and continue to be above (exceeding) GVs, while mean concentrations of PP have also declined slightly and are currently below (meeting) GVs. Mean concentrations of POC and DOC generally increased since 2008. Analysis of trends shows that from 2016–2021 POC has remained stable while DOC has resumed increasing after a pause.

The WQ Index is calculated using two different formulations to communicate: a) the long-term trend in water quality (based on the pre-2015 sampling design) and b) the annual condition of water quality (based on the post-2015 sampling design, which increased the power to detect change). The Methods section and Appendix B contain details of the calculations for both index formulations.

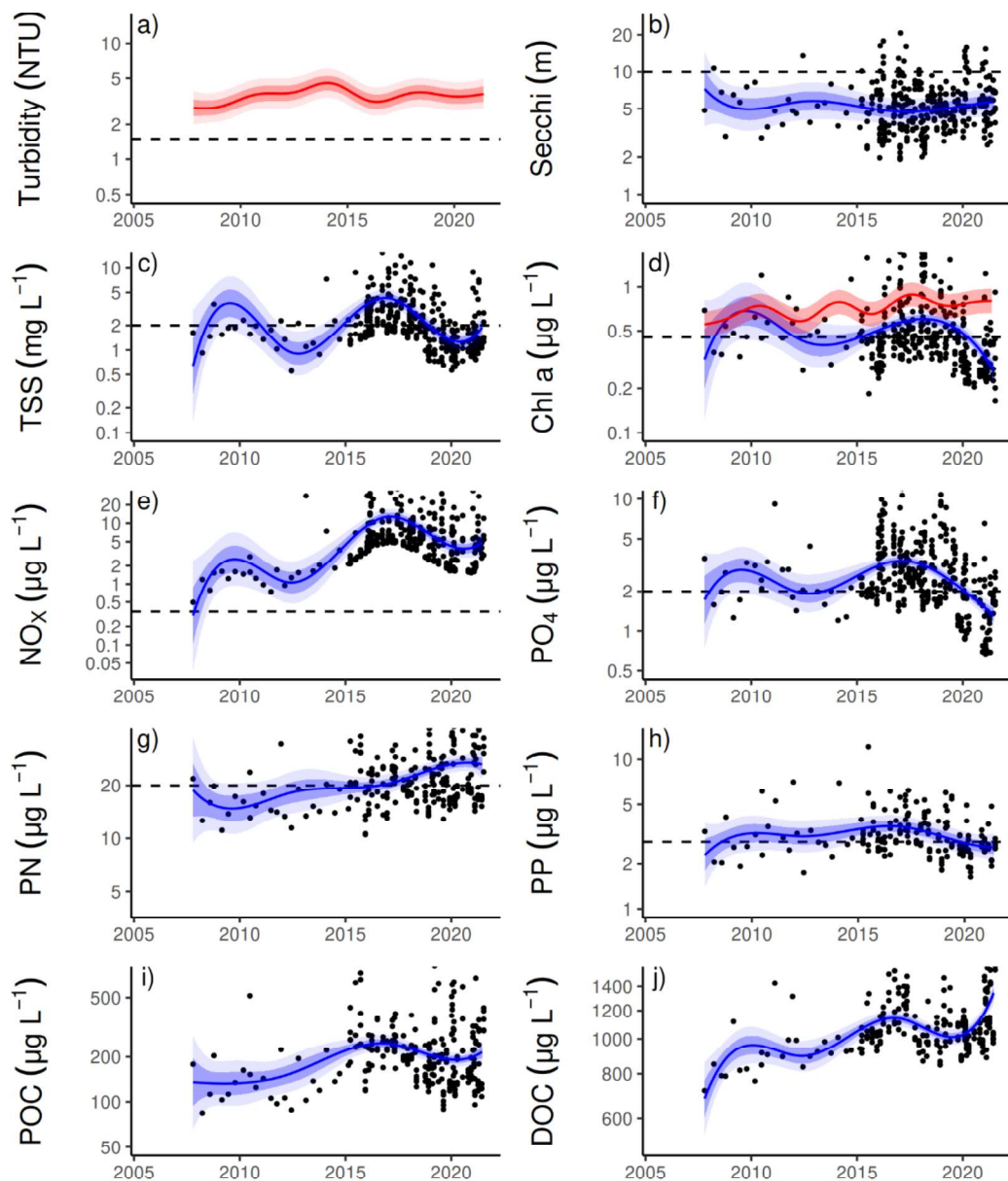


Figure 5-44: Temporal trends in water quality variables for the Tully focus region: a) turbidity, b) Secchi depth, c) total suspended solids (TSS), d) chlorophyll *a* (Chl-*a*), e) nitrate/nitrite (NO_x), f) phosphate (PO_4), g) particulate nitrogen (PN), h) particulate phosphorus (PP), i) particulate organic carbon (POC) and j) dissolved organic carbon (DOC). Generalised additive mixed effect models (trends) are represented by blue lines with shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves, tides, and seasons after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, and individual records can be found in Appendix C Figure C-1. Dashed horizontal reference lines indicate annual guidelines.

The long-term WQ Index has scored water quality as ‘moderate’ or ‘poor’ since 2010 (Figure 5-45a). The long-term trend has varied since the inception of the MMP but has shown a small (for example, change by a single grade) decline over the time-series. This downward trend has generally been driven by trends in water clarity, PN, PP, and Chl-a indicators.

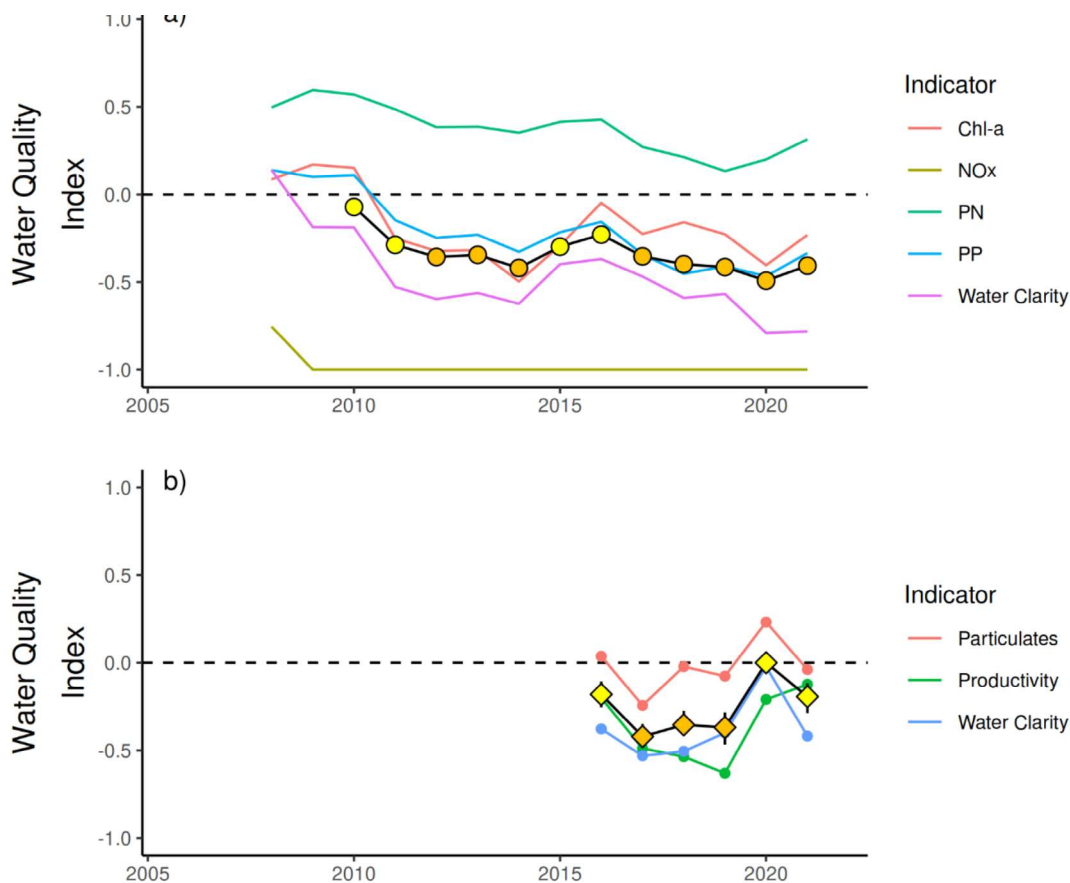


Figure 5-45: The Water Quality Index (WQ Index) for the Tully focus region. The WQ Index uses two formulations to communicate: a) long-term trend (based on pre-2015 sampling design) and b) the annual condition (based on post-2015 sampling design). WQ Index colour coding: ● / ◆ – ‘very good’; ○ / ◇ – ‘good’; ● / ◆ – ‘moderate’; ○ / ◇ – ‘poor’; ● / ◆ – ‘very poor’. Indicators or sub-indicators that are used to calculate the WQ Index are shown as coloured lines on each plot. Error bars (vertical black lines) on the WQ Index represent the 95% quantile intervals. Calculations for both formulations are described in Appendix B.

The annual condition WQ Index scored water quality as ‘poor’ for the previous three years and ‘moderate’ for the 2019–20 and 2020–21 water years (Figure 5-45b). The score for the 2019–20 water year was much higher than previous years, probably due to low discharge that year. The score for 2020–21 is still ‘moderate’ but has returned to a value closer to the long-term mean. This version of the Index scores water quality parameters against GVs relevant to the season when samples are collected (wet versus dry GVs) and includes additional sites in the open coastal water body to better characterise areas affected by river discharge.

It is important to note that the two versions of the WQ Index are designed to answer separate questions and therefore differences in scores between the versions are expected.

Event water quality

The Tully River had three flow events that exceeded the minor flood level over the 2020–21 water year as shown in the discharge data (Figure 5-46) and satellite imagery (Figure 5-47). The largest event peaked just below the moderate flood level on 19 February 2021 and this flood plume was subject to event sampling one day after this peak. Routine sampling of the Tully focus area occurred on 27 February 2021 at the tail end of the event. In addition, routine sampling of the Tully focus area coincided with the peak of the third flow event (21 April 2021) and hence samples were somewhat influenced by plume waters (Figure 5-46). Here we present the water quality data over these three sampling campaigns. The satellite images over the wet season provide an indication of the different flow and resuspension events over the water year in the Tully focus area (see Section 4.3.2 for further information).

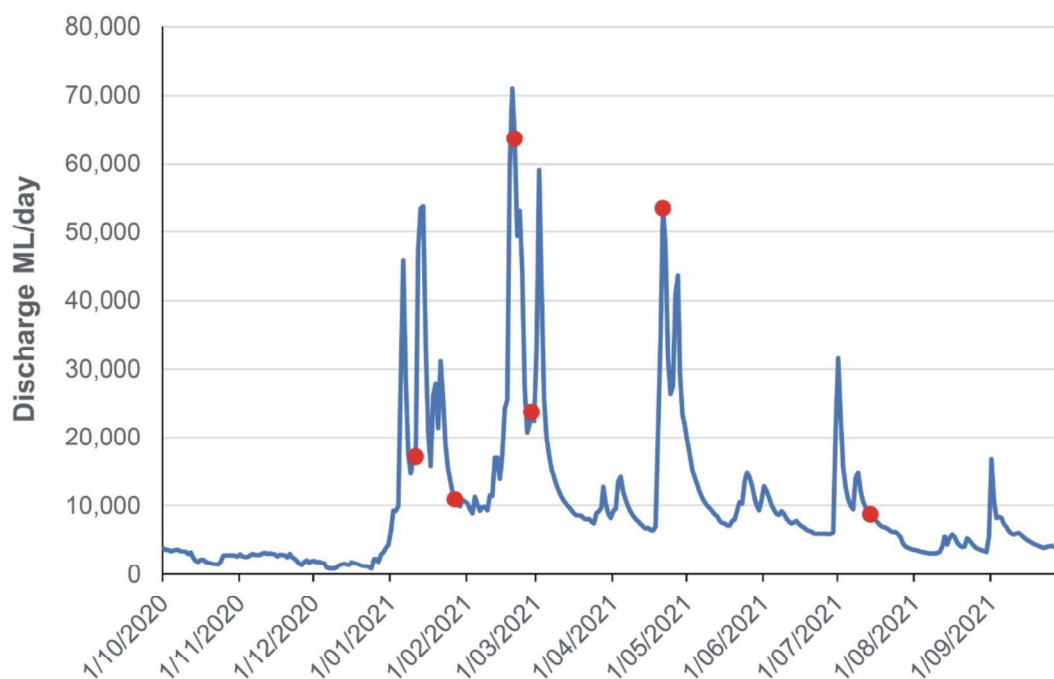


Figure 5-46: Tully River at Euramo flow gauge record for the 2020–21 water year. Periods of water quality sampling by JCU are marked as red dots.



Figure 5-47: Satellite images of the Tully focus area during the 2021 wet season. The images coincide with the periods: 4 days after the largest flow event (23 Feb), periods of lower flows but higher resuspension (4 March and 15 March 2021) and 7 days following the final flood event of the season which also coincided with strong winds (28 April 2021).

The water quality data for the Tully focus area showed clear trends in the wet season and flood plume samples collected over the inshore-offshore sites and over the salinity gradient (Figure 5-48 and Figure 5-49). The sampling also provided important insights on the difference between the surface and depth samples which have been separated in the plots. In general, the TSS, nitrate (Figure 5-48) and PN and PP (Figure 5-49) concentrations declined over the surface samples collected over the salinity gradient. The first plume sampled in the wet season (20 February) coincided with relatively fine (i.e. low winds) conditions and the plume was observed to be largely confined to the surface waters. Hence, the surface samples from 20 February 2021 had much higher concentrations than the depth samples due to the increased river influence (i.e. lower salinities) and little (if any) wave driven resuspension. For the following two sampling periods, the few outlier samples for TSS, PN and PP which had much higher concentrations than corresponding samples collected at similar salinities, were exclusively collected from the deeper sections of the water column. In these cases, most of the samples were from the relatively shallow and exposed Tully River mouth site (<9 m depth) and likely attributed to either sediment resuspension from the bottom or a concentrated nepheloid plume layer.

The highest chlorophyll *a* concentrations were generally $> 0.5 \mu\text{g.L}^{-1}$ and peaked at $1.3 \mu\text{g.L}^{-1}$ (Figure 5-48), were measured in the 15 to 25 salinity range which is generally consistent with previous monitoring data. The concentrations were more variable after the 25 salinity zone and ranged between ~ 0.2 and $0.6 \mu\text{g.L}^{-1}$.

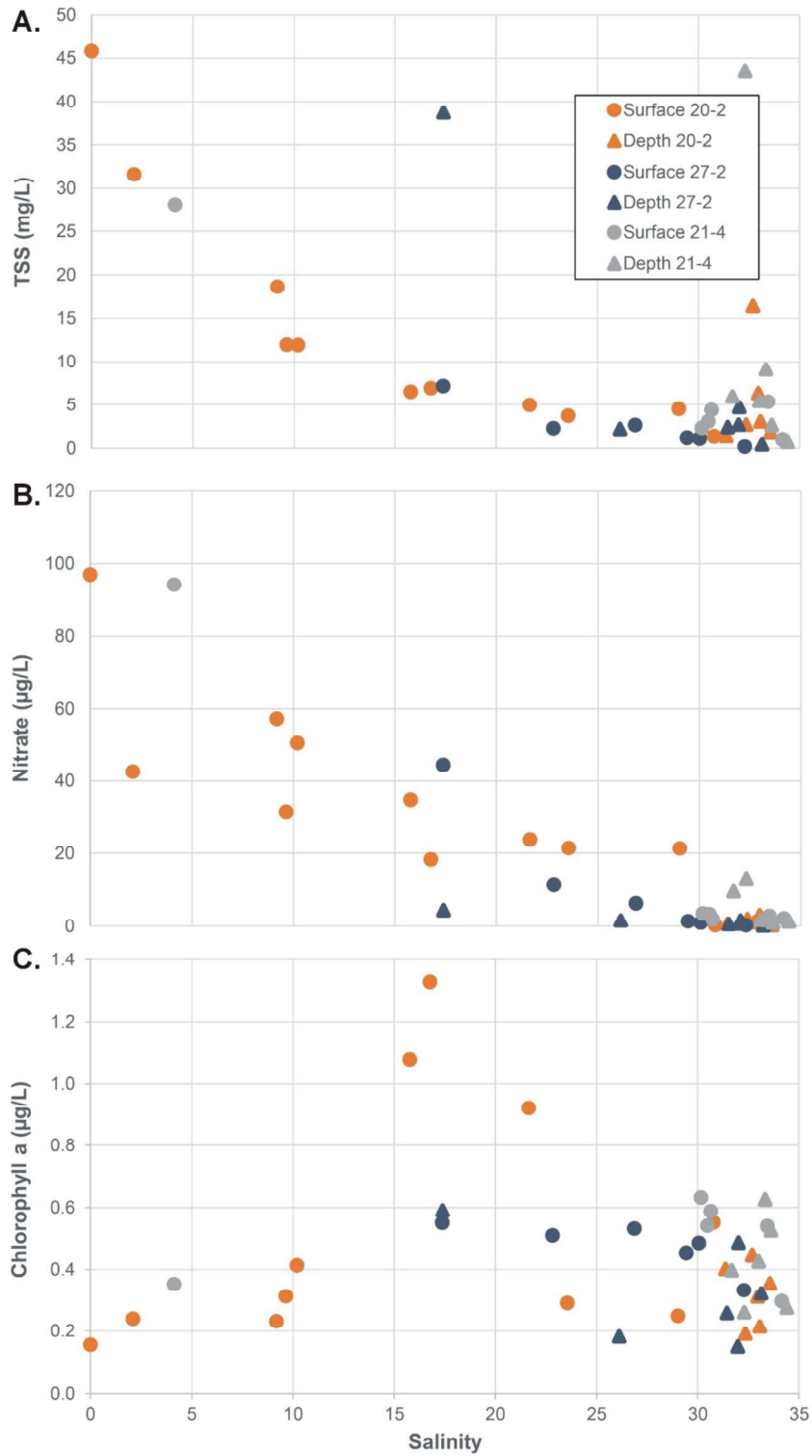


Figure 5-48: Water quality data from the Tully focus region under the influence of flood plumes over the 2020–21 wet season including (a) TSS, (b) nitrate and (c) chlorophyll a plotted over the salinity gradient. Surface samples are plotted as circles and depth samples as triangles.

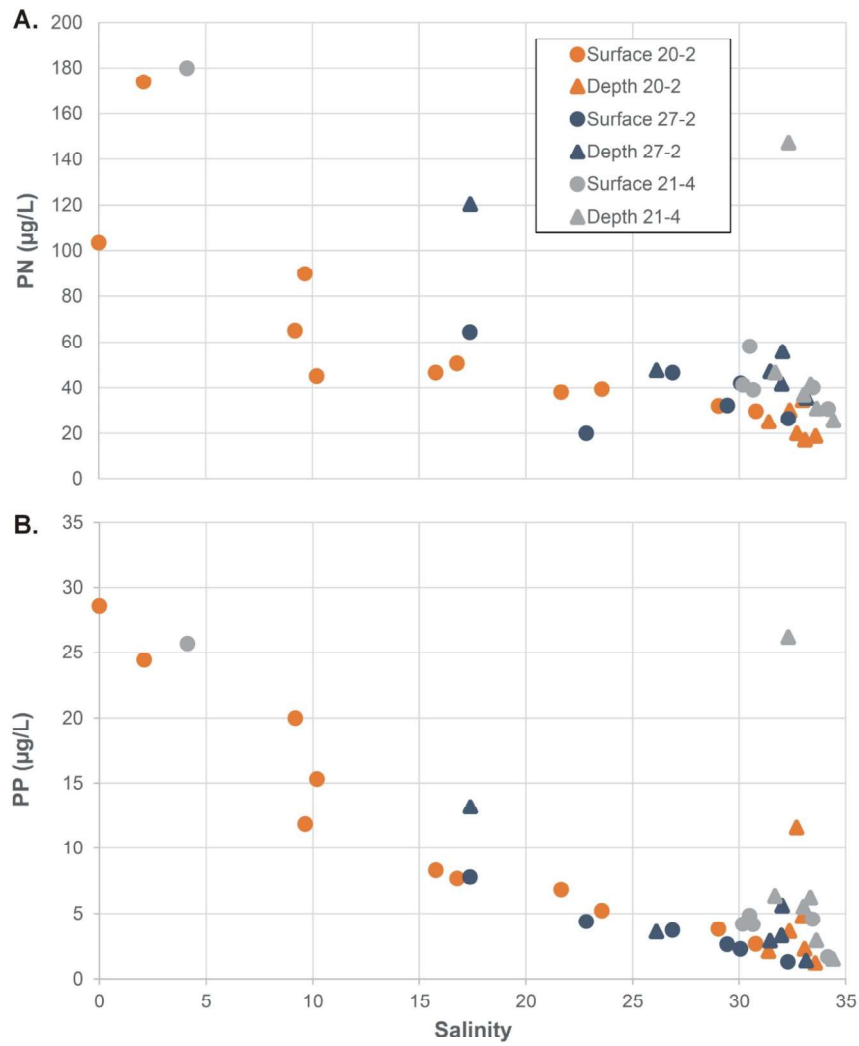


Figure 5-49: Water quality data from the Tully focus region under the influence of flood plumes over the 2020–21 wet season including (a) PN and (b) PP plotted over the salinity gradient. Surface samples are plotted as circles and depth samples as triangles.

5.3 Burdekin region

Three sites were sampled in this focus area three times per year until the end of 2014. Following the implementation of the revised MMP water quality sampling design in 2015, 15 sites are sampled in this focus region up to nine times per year, with six sites sampled during both the dry and wet seasons and nine additional sites sampled during major flood events (Table A-1). The monitoring sites are located in a transect away from the river mouth in a north-westerly direction, representing a gradient in water quality. Eight sites are located in the open coastal water body, two sites are located in the mid-shelf water body, and five sites are in enclosed coastal waters (Figure 5-50).

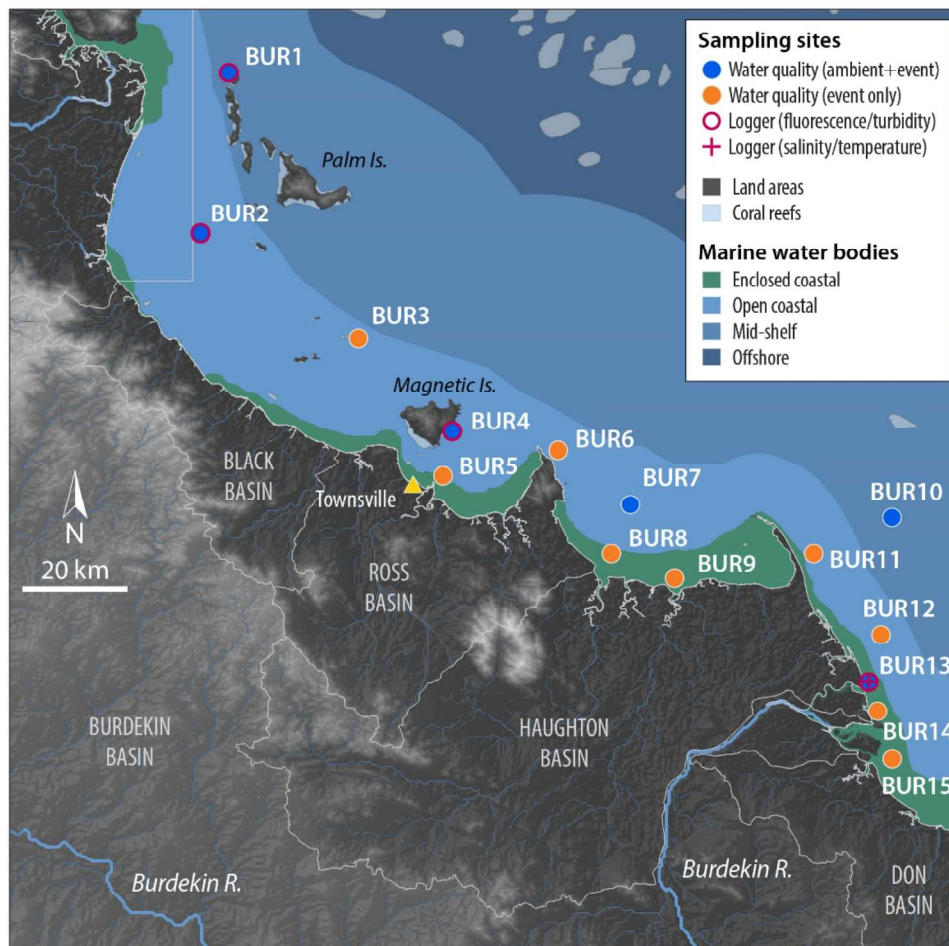


Figure 5-50: Sampling sites in the Burdekin focus area, shown with the water body boundaries.

The total discharge for the Burdekin region in 2020–21 was over 1.5 times the long-term median (Figure 5-51; Table 3-1). The combined discharge and loads calculated for the 2020–21 water year from the Burdekin and Haughton Basins were in the higher range over the past decade (Figure 5-52). Over the 16-year period:

- discharge has varied from 998 GL (2014–15) to 36,811 GL (2010–11)
- TSS loads ranged from 272 kt (2013–14) to 14,970 kt (2007–08)
- DIN loads ranged from 205 t (2014–15) to 3,031 t (2018–19)
- PN loads ranged from 539 t (2013–14) to 21,937 t (2007–08).

During the very large discharge years (2007–08, 2008–09, 2010–11 and 2018–19), the Burdekin and Haughton Basins (dominated by the Burdekin Basin) produced by far the highest loads of TSS and PN compared to any of the other focus regions. In contrast, the DIN loads are either similar to or lower than the basins of the Wet Tropics and Mackay-Whitsunday regions during the high discharge years and much lower during the lower discharge years.

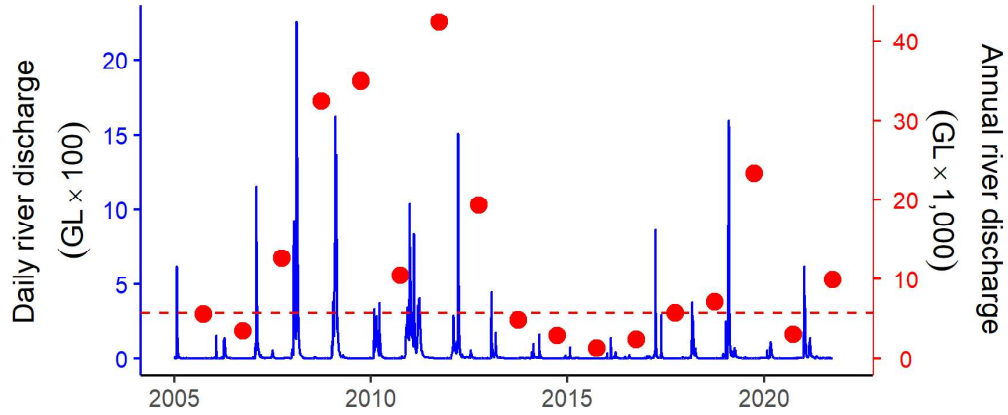


Figure 5-51: Total discharge for the Burdekin region (Table 2-3). Daily (blue) and water year (October to September, red) discharge is shown. Red dashed line represents the long-term median annual discharge.

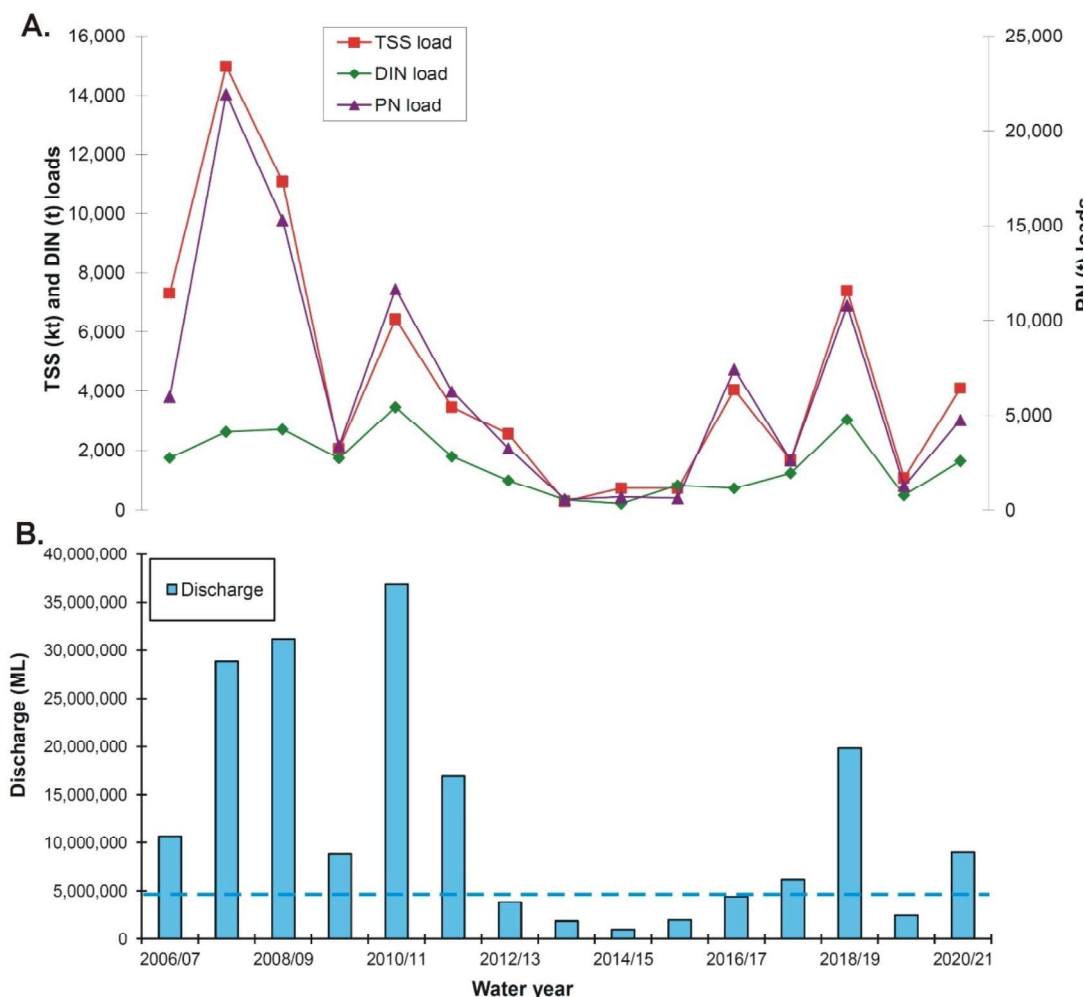


Figure 5-52: Loads of (A) TSS, DIN and PN and (B) discharge for the Burdekin and Haughton Basins from 2006–07 to 2020–21. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (Burdekin River), and annual mean concentrations and discharge from monitoring data or Source Catchments modelling data. Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

Ambient water quality and the in situ Water Quality Index

Water quality showed trends along the sampling transect (Burdekin mouth to Palm Island group). Sites located nearest to the river mouth (river mouth = 0 km) had high concentrations of TSS, Chl-*a*, and particulate nitrogen (PN) all year, and high concentrations of particulate phosphorus (PP) and NO_x during the wet season, which declined with distance away from the river mouth (Figure 5-53, Appendix C Table C-1). Secchi depths were low at sites near the river mouth (water clarity was poor) and increased (water clarity improved) with distance from the river mouth. Concentrations of NO_x and PP during the dry season were variable along the transect and did not show clear patterns.

Seasonal differences in water quality were present for some variables. Ambient monitoring during the wet season showed greater values of NO_x and PN than during the dry season

(Figure 5-53). Concentrations of TSS and Chl-*a* were similar between wet and dry seasons, as were Secchi depths.

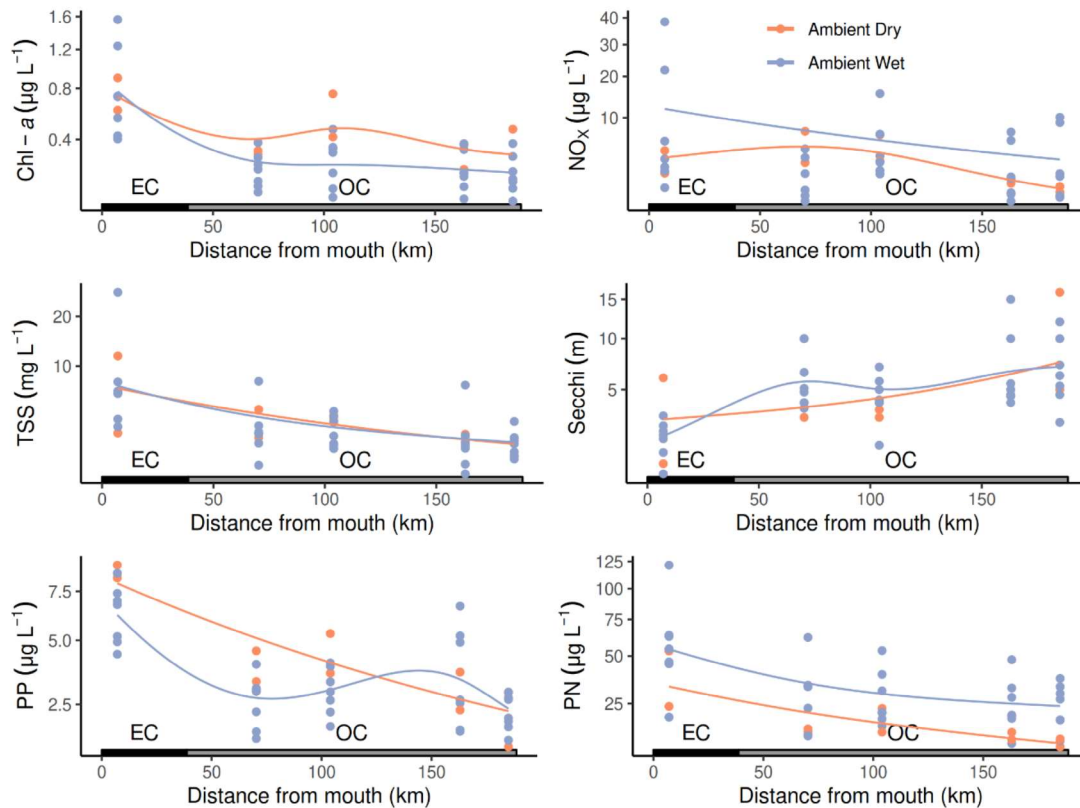


Figure 5-53: Water quality variables measured during ambient and event sampling in 2020-21 along the Burdekin focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the Burdekin River mouth. Water body classifications are shown along the x-axes: Enclosed coastal (EC) and open coastal (OC). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

Long-term trends in water quality variables measured during ambient periods (i.e., not during peak flood events) of the dry and wet seasons are presented in Figure 5-54. It is important to note that this trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points will have different values compared to raw data. This analysis is designed to detect **long-term** and **regional-scale** trends in water quality by removing the effect of short-term changes associated with weather and seasonal differences.

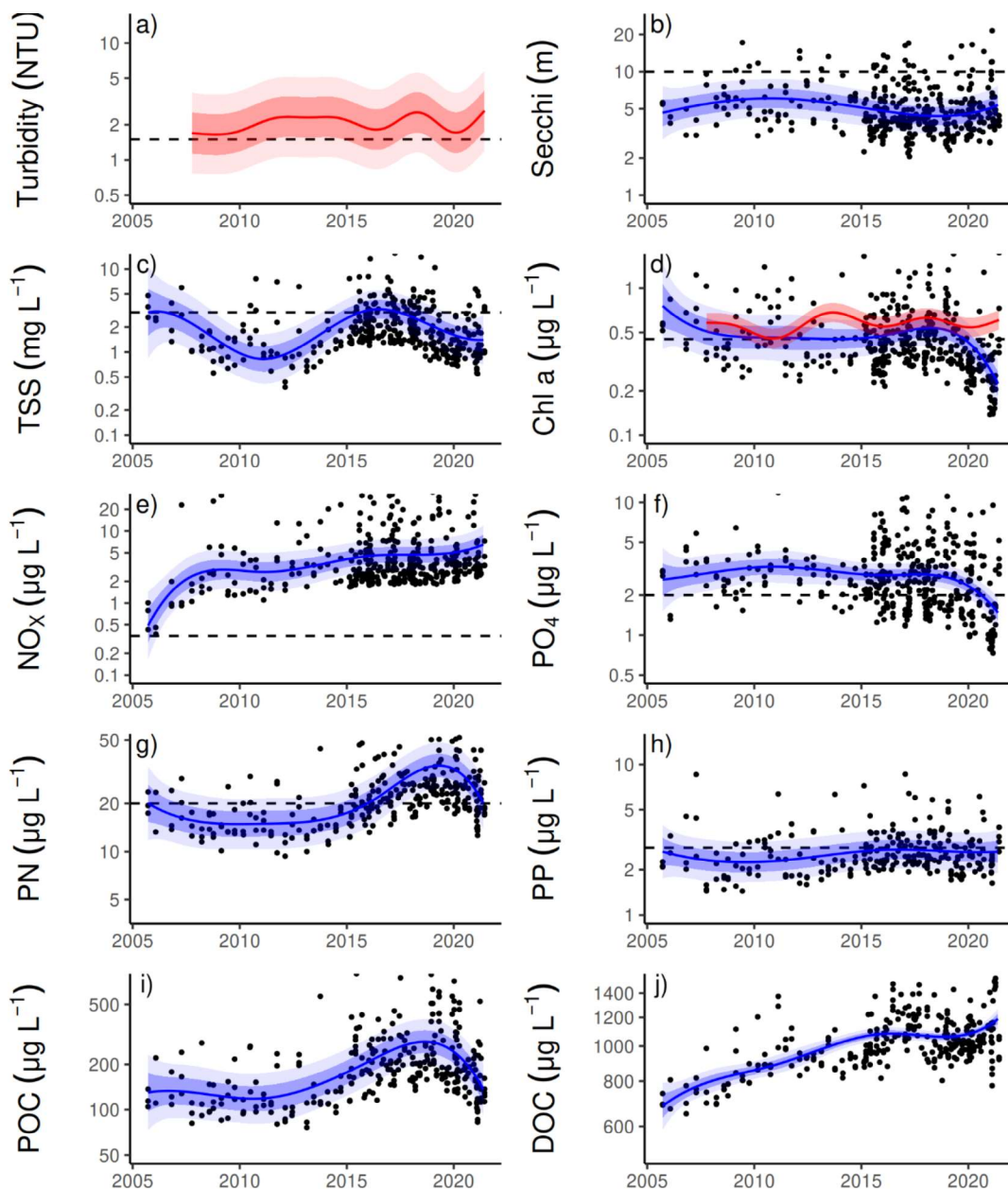


Figure 5-54: Temporal trends in water quality variables for the Burdekin focus region: a) turbidity, b) Secchi depth, c) total suspended solids (TSS), d) chlorophyll *a* (Chl-*a*), e) nitrate/nitrite (NO_x), f) phosphate (PO_4), g) particulate nitrogen (PN), h) particulate phosphorus (PP), i) particulate organic carbon (POC) and j) dissolved organic carbon (DOC). Generalised additive mixed effect models (trends) are represented by blue lines with shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves, tides, and seasons after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, and individual records can be found in Appendix C Figure C-1. Dashed horizontal reference lines indicate annual guidelines.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change (Figure 5-54). Site-specific statistics and comparison to GVs for all variables are available in Appendix C Table C-1. Mean concentrations of Chl-*a* and TSS have generally fluctuated around GVs (Great Barrier Reef Marine Park Authority, 2010) since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of both Chl-*a* and TSS have decreased and are now both below (meeting) water quality GVs at all sites.

Mean concentrations of PO₄ have been relatively stable since the inception of the MMP, and analysis of trends shows that from 2016–2021 concentrations have slightly declined and are currently around GVs. Mean concentrations of NO_x have been gradually increasing since 2008 and analysis of trends shows that from 2016–2021 concentrations have continued on this trajectory and have continued to be well above (exceeding) GVs.

Mean Secchi depth has been relatively stable since the inception of the MMP, and analysis of trends shows that from 2016–2021, Secchi depths have remained stable and are currently below (exceeding) the GV. Mean concentrations of PN have varied around GVs since 2010, while PP concentrations have been relatively stable and close to GVs since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of PN and PP did not change significantly however PN continues to be above (exceeding) the GV while PP is currently below (meeting) the GV. Mean concentrations of POC and DOC have generally increased since 2005. Analysis of trends shows that from 2016–2021, POC and has decreased slightly while DOC has continued to increase.

The WQ Index is calculated using two different formulations to communicate: a) the long-term trend in water quality (based on the pre-2015 sampling design) and b) the annual condition of water quality (based on the post-2015 sampling design, which increased the power to detect change). The Methods section and Appendix B contain details of the calculations for both index formulations.

The long-term WQ Index has scored water quality as ‘good’ or ‘moderate’ since 2008 (Figure 5-55a). The long-term trend has shown a small (for example, change by a single grade) decline over the time-series since 2010. This downward trend has generally been driven by trends in PN and PP indicators.

The annual condition WQ Index scored water quality as ‘good’ for the 2019–20 water year (which was characterised by below-average river discharge) but returned to ‘moderate’ in 2020–21, as in each of the earlier four years (Figure 5-55b). This version of the Index scores water quality parameters against GVVs relevant to the season when samples are collected (wet versus dry GVVs) and includes additional sites in the open coastal water body to better characterise areas affected by river discharge.

It is important to note that the two versions of the WQ Index are designed to answer separate questions and therefore differences in scores between the versions are expected.

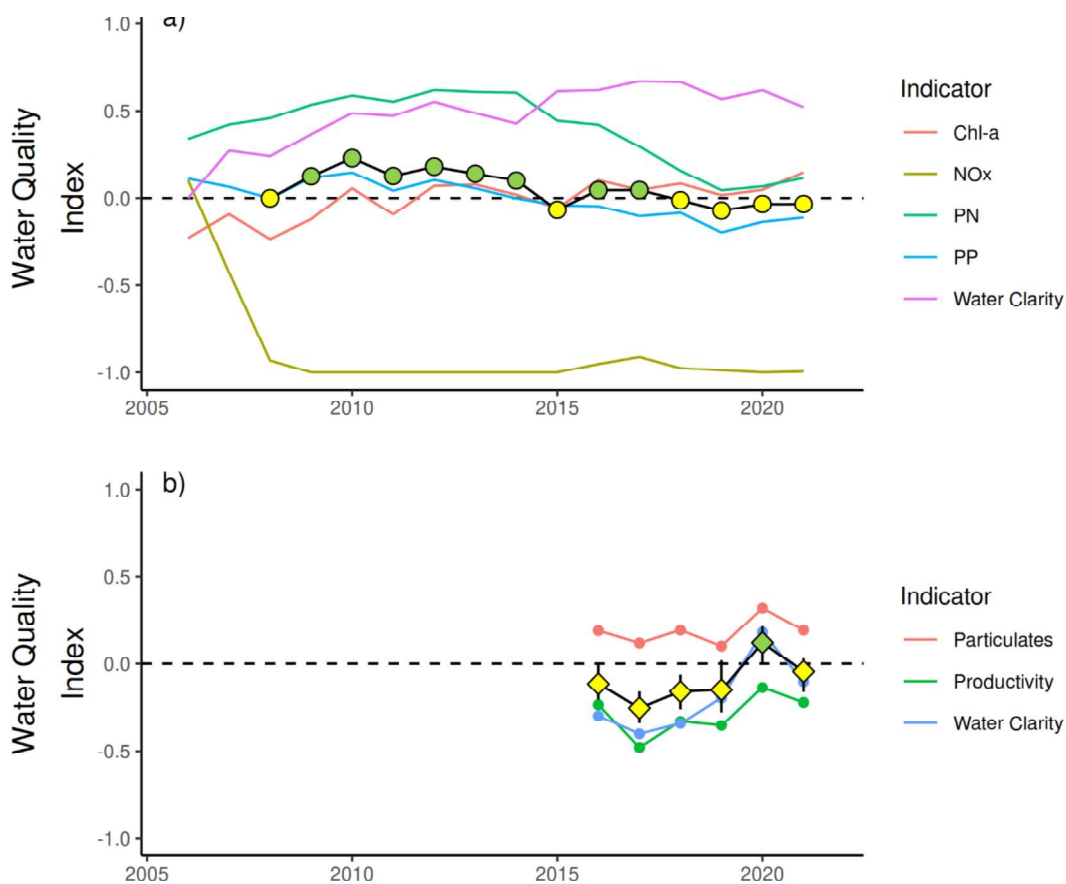


Figure 5-55: The Water Quality Index (WQ Index) for the Burdekin focus region. The WQ Index uses two formulations to communicate: a) long-term trend (based on pre-2015 sampling design) and b) the annual condition (based on post-2015 sampling design). WQ Index colour coding: ● / ◆ – ‘very good’; ○ / ◇ – ‘good’; ● / ◆ – ‘moderate’; ○ / ◇ – ‘poor’; ● / ◆ – ‘very poor’. Indicators or sub-indicators that are used to calculate the WQ Index are shown as coloured lines on each plot. Error bars (vertical black lines) on the WQ Index represent the 95% quantile intervals. Calculations for both formulations are described in Appendix B.

Event water quality

No event sampling was conducted in the 2020–21 wet season in the Burdekin focus area.

5.4 Mackay-Whitsunday region

The Mackay-Whitsunday region comprises four major river basins, the Proserpine, O'Connell, Pioneer, and Plane Basins. The region is also potentially influenced by runoff from the Fitzroy River during extreme events or through longer-term transport and mixing.

Three sites were sampled in this focus area three times per year until the end of 2014. From 2015, 11 sites are sampled in this focus region up to five times per year, with five sites sampled during both the dry and wet seasons and six additional sites sampled during major flood events (Table A-1). The sites are located in a transect from the O'Connell River mouth to open coastal waters, representing a gradient in water quality. Ten sites are located in the open coastal water body and one site is in enclosed coastal waters (Figure 5-56).

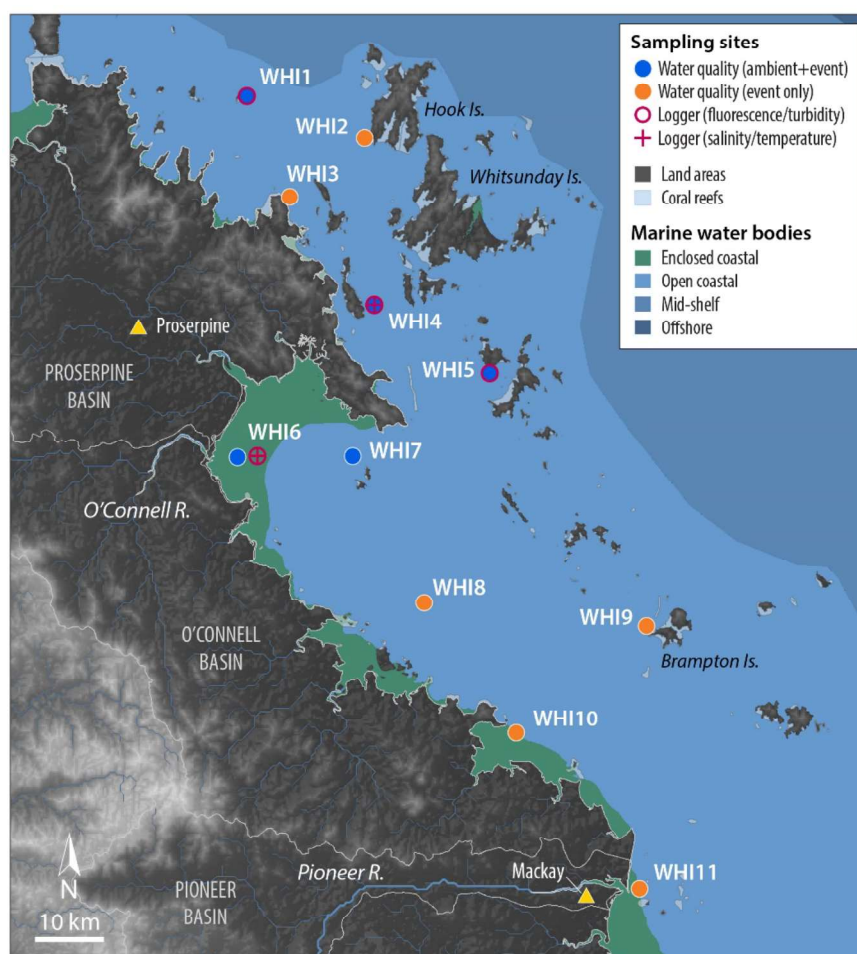


Figure 5-56: Sampling sites in the Mackay-Whitsunday focus area, shown with the water body boundaries.

Annual discharge for the Mackay-Whitsunday region was well below the long-term median levels (Figure 5-56) and was similar to discharge during the 2017–18 water year. Annual discharge from the individual basins were around or below half of the long-term median values (Table 3-1).

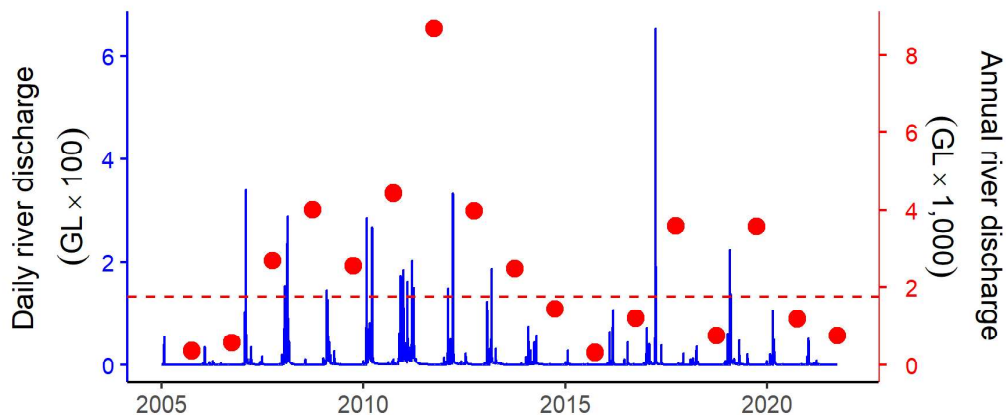


Figure 5-57: Combined discharge for the Mackay-Whitsunday focus region. Daily (blue) and water year (October to September, red) discharge is shown. Red dashed line represents the long-term median of the combined annual discharges. See Table 2-3 for a list of flow gauge data used. Please note as this is the combined discharge, high flows in one river will not necessarily be visible in the graph.

The combined discharge and loads calculated for the 2020–21 water year from the Proserpine, O’Connell, Pioneer and Plane Basins (Figure 5-58) were similar to that measured in the 2017–18 and were among the lowest recorded over the past decade. Over the 16-year period:

- discharge has varied from 337 GL (2014–15) to 8,675 GL (2010–11)
- TSS loads ranged from 38 kt (2014–15) to 1,702 kt (2010–11)
- DIN loads ranged from 87 t (2014–15) to 1,732 t (2010–11)
- PN loads ranged from 125 t (2014–15) to 4,936 t (2010–11).

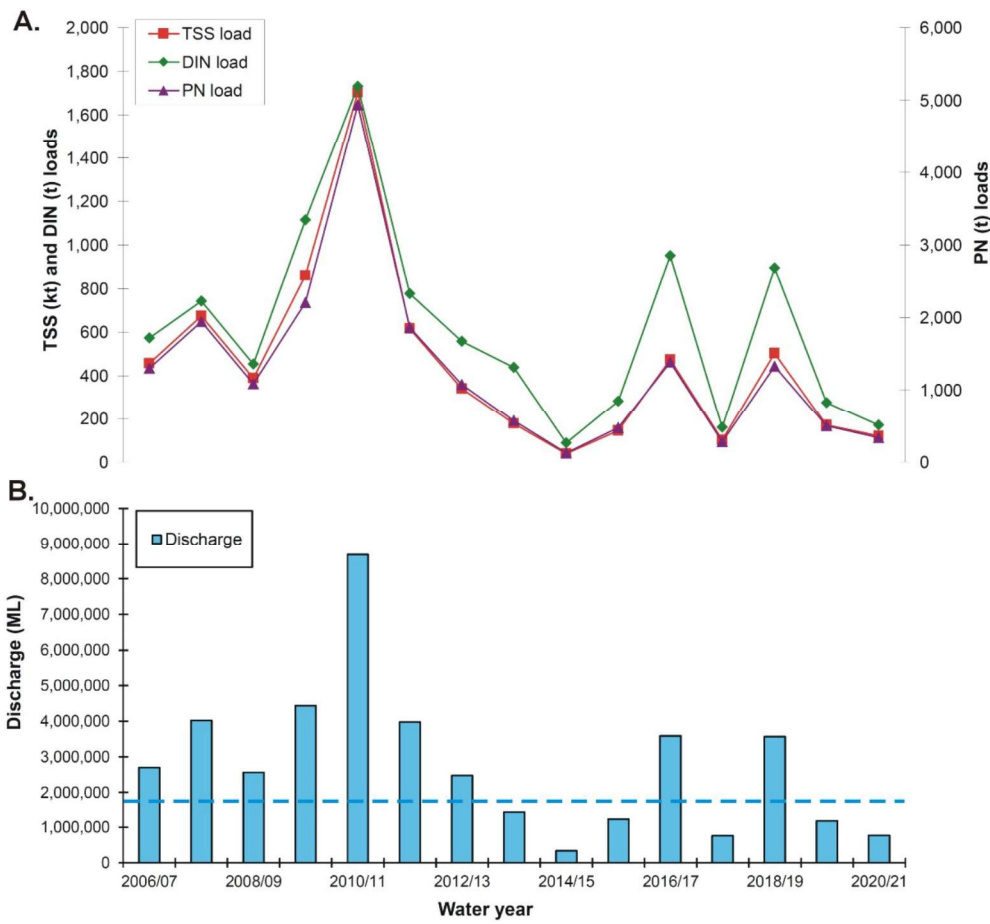


Figure 5-58: Loads of (A) TSS, DIN and PN and (B) discharge for the Proserpine, O'Connell, Pioneer, and Plane Basins from 2006–07 to 2020–21. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled' discharge data from gauging stations, monitoring data (O'Connell and Pioneer Rivers and Sandy Creek), and annual mean concentrations and discharge from monitoring data or Source Catchments modelling data. Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes

Ambient water quality and the in situ Water Quality Index

Water quality showed trends along the sampling transect (O’Connell mouth to open coastal waters). The site located in the enclosed coastal water body (river mouth = 0 km) had high concentrations of TSS (dry season), Chl-*a*, and particulate nutrients (PN and PP), which declined with distance away from the river mouth (Figure 5-59, Table E-2). NO_x varied along the transect in both wet and dry seasons. Secchi depths were low at sites near the river mouth (water clarity was poor) and increased (water clarity improved) with distance from the river mouth. Concentrations of TSS, NO_x, and Secchi depth were highly variable in this focus region, which is likely related to its large tidal range and physical oceanographic characteristics.

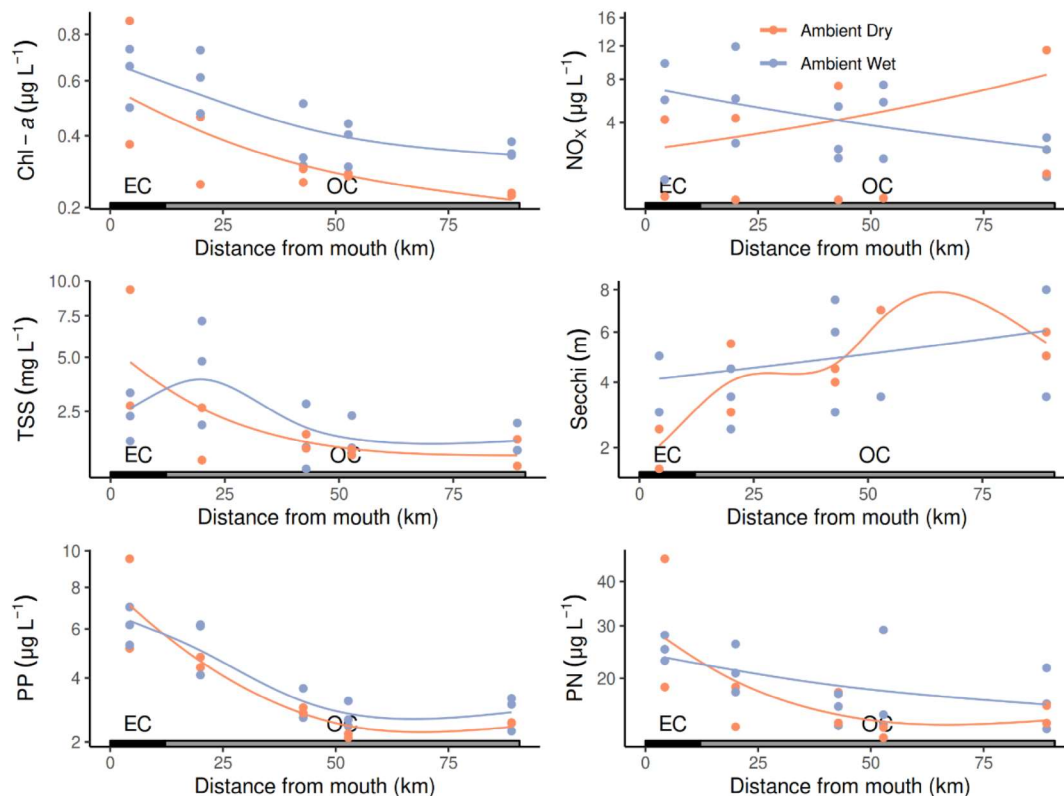


Figure 5-59: Water quality variables measured during ambient and event sampling in 2020-21 along the Mackay-Whitsunday focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the O’Connell River mouth. Water body classifications are shown along the x-axes: Enclosed coastal (EC) and open coastal (OC). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

Seasonal differences in water quality were present for some variables. Ambient monitoring during the wet season showed greater values of Chl-*a* (most sites), while concentrations of PN, PP and TSS were similar in both seasons (Figure 5-59).

Long-term trends in water quality variables measured during ambient periods (for example, not during peak flood events) of the dry and wet seasons are presented in Figure 5-60. It is important to note that this trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points will have different values compared to raw data. This analysis is designed to detect **long-term** and **regional-scale** trends in water

quality by removing the effect of short-term changes associated with weather and seasonal differences.

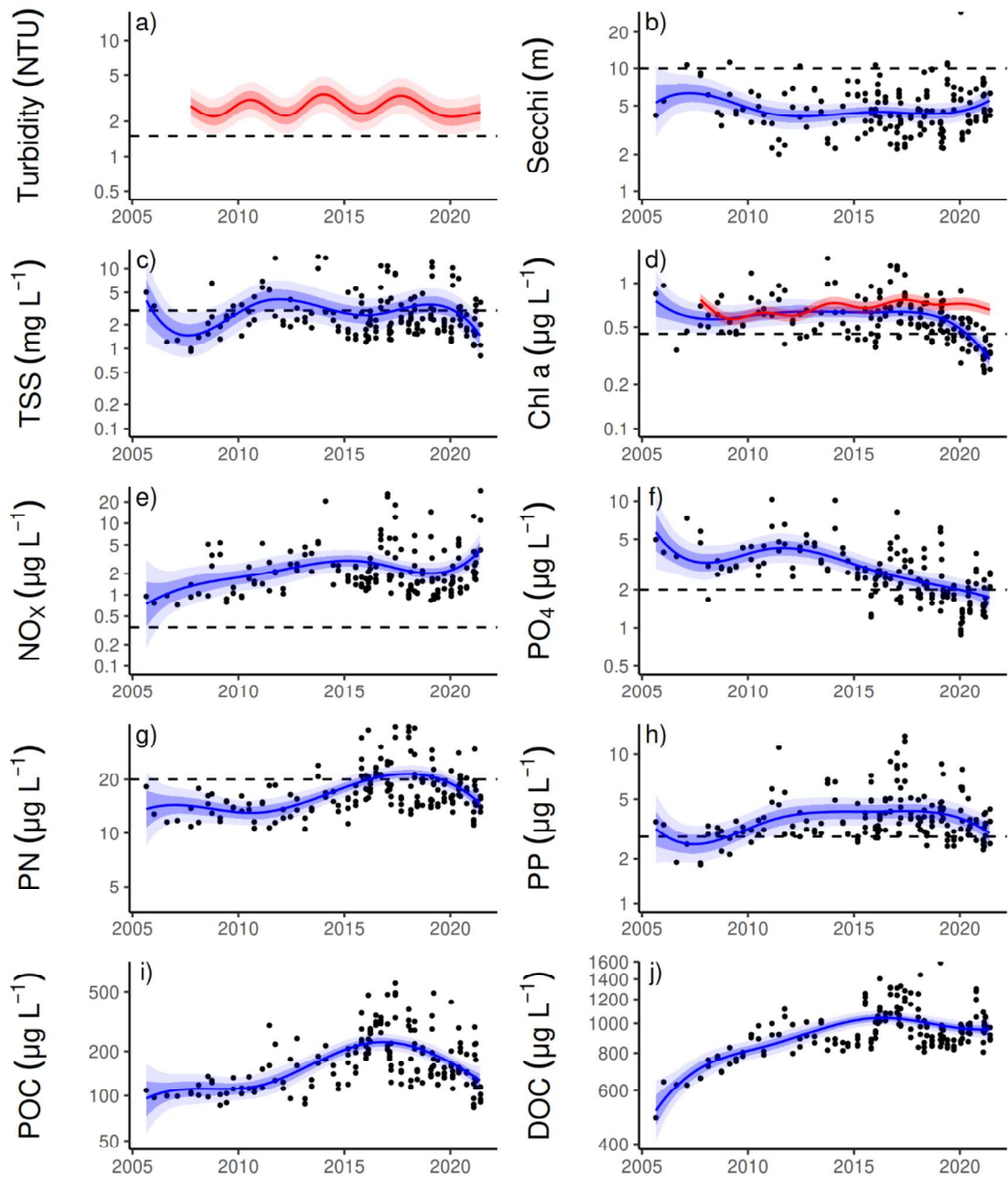


Figure 5-60: Temporal trends in water quality variables for the Mackay-Whitsunday focus region: a) turbidity, b) Secchi depth, c) total suspended solids (TSS), d) chlorophyll a (Chl-a), e) nitrate/nitrite (NO_x), f) phosphate (PO_4), g) particulate nitrogen (PN), h) particulate phosphorus (PP), i) particulate organic carbon (POC) and j) dissolved organic carbon (DOC). Generalised additive mixed effect models (trends) are represented by blue lines with shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves, tides, and seasons after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, and individual records can be found in Appendix C Figure C-1. Dashed horizontal reference lines indicate annual guidelines.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change (Figure 5-60). Site-specific statistics and comparison to GVs for all variables are available in Appendix C Table C-1. Mean concentrations of Chl-*a* and TSS have generally fluctuated around GVs (Great Barrier Reef Marine Park Authority, 2010) since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of TSS have improved slightly and are currently meeting Guideline Values (GVs), while concentrations of Chl-*a* have also improved slightly and are now slightly below (meeting) GVs.

Mean concentrations of PO₄ have markedly declined since the inception of the MMP, and analysis of trends shows that from 2016–2021 concentrations have continued to decline and are currently close to GVs. Mean concentrations of NO_x have been relatively stable since 2010 and analysis of trends shows that from 2016–2021 concentrations have slightly increased and continue to be well above (exceeding) GVs.

Mean Secchi depth has been relatively stable since 2008, and analysis of trends shows that from 2016–2021, Secchi depths have remained stable and are currently below (exceeding) the GV.

Mean concentrations of PN and PP have varied around the GV since the inception of the MMP. Analysis of trends shows that from 2016–2021, mean concentrations of both PN and PP have improved slightly and PN is now below (meeting) the GV while PP is just above (exceeding) the GV. Mean concentrations of POC have varied while concentrations of DOC have generally increased since 2005. Analysis of trends shows that from 2016–2021, POC and DOC have decreased slightly.

The WQ Index is calculated using two different formulations to communicate: a) the long-term trend in water quality (based on the pre-2015 sampling design) and b) the annual condition of water quality (based on the post-2015 sampling design, which increased the power to detect change). The Methods section and Appendix B contain details of the calculations for both index formulations.

The long-term WQ Index has scored water quality as 'moderate' or 'poor' since 2008 (Figure 5-61a). The long-term trend has shown a small (for example, change by a single grade) decline over the time-series since 2008. This downward trend has generally been driven by trends in water clarity, PN, and PP indicators, especially over the period 2008–2016.

The annual condition WQ Index scored water quality as 'moderate' or 'poor' for the previous five years and 'moderate' for the 2020–21 water year (Figure 5-61b). This version of the Index scores water quality parameters against GVs relevant to the season when samples are collected (wet versus dry GVs) and includes additional sites in the open coastal water body to better characterise areas affected by river discharge.

It is important to note that the two versions of the WQ Index are designed to answer separate questions and therefore differences in scores between the versions are expected.

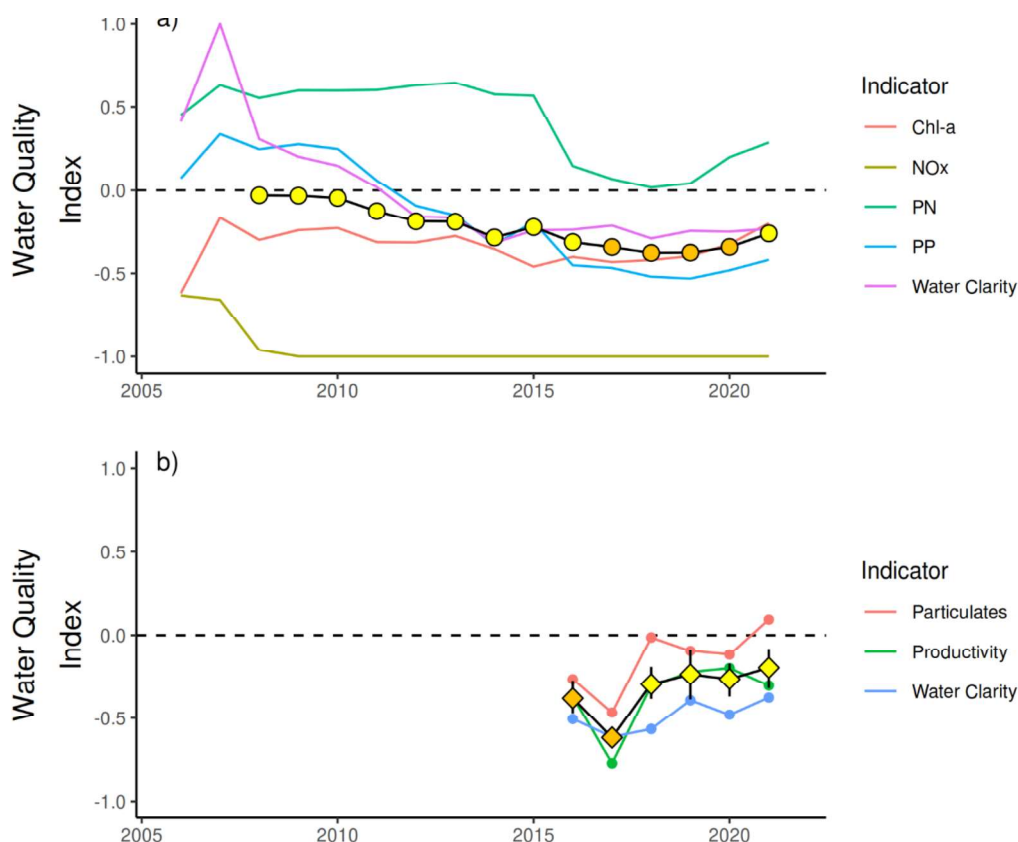


Figure 5-61: The Water Quality Index (WQ Index) for the Mackay-Whitsunday focus region. The WQ Index uses two formulations to communicate: a) long-term trend (based on pre-2015 sampling design) and b) the annual condition (based on post-2015 sampling design). WQ Index colour coding: ● / ◆ – ‘very good’; ○ / ◇ – ‘good’; ● / ◆ – ‘moderate’; ● / ◆ – ‘poor’; ● / ◆ – ‘very poor’. Indicators or sub-indicators that are used to calculate the WQ Index are shown as coloured lines on each plot. Error bars (vertical black lines) on the WQ Index represent the 95% quantile intervals. Calculations for both formulations are described in Appendix B.

Event water quality

No event sampling was conducted in the 2020–21 wet season in the Mackay-Whitsunday focus area.

Pesticide monitoring results

Three sites were monitored at Flat Top Island, Repulse Bay and Sandy Creek in the Mackay-Whitsunday region.

The time-averaged concentrations of 25 pesticides analysed are presented in Appendix C-7. Consistent with results from previous monitoring years, the pesticides detected most frequently and at the highest concentrations were diuron, atrazine and hexazinone, with maximum concentrations of 64 ng/L, 13 ng/L and 27 ng/L respectively.

No exceedances of individual pesticide guideline values were detected in the wet season in 2020–21. All detections were below guideline levels derived to be protective of 99% of species.

The highest msPAF score was adopted as the overall score for a region/site (Table C-9, Appendix C-7). The maximum risk of exposure to mixtures of pesticides was low at all three sites: protective of at least 95% of species (i.e., 1% to ≤5% of species affected). The risk

throughout the region was very low in most months of the wet season: protective of $\geq 99\%$ of species (i.e., $\leq 1\%$ of species affected) (Table C-9, Appendix C-7).

6 Discussion

6.1 Long-term changes in water quality

Previous work has demonstrated that to detect trends in water quality and distinguish between long-term changes and natural variability, decadal time scales are required (Henson *et al.*, 2016). After more than a decade of continuous sampling, there is evidence that most focus regions have experienced gradual declines in water quality since 2008, although there are early indications that water quality may be improving in at least one focus region, the Barron-Daintree.

In addition, year-to-year and seasonal differences in water quality are a key feature of this monitoring dataset. This is an important point, as it demonstrates that while overall multi-year water quality may be considered ‘good’ relative to guideline values, inshore ecological communities can experience periods of ‘very poor’ water quality in relation to episodic events such as river discharge (McKenzie *et al.*, 2020; Petus *et al.*, 2014a, b, 2016; Thompson *et al.*, 2020). Ecological community response to such disturbances is confounded by other factors such as organism sensitivity and resilience; this complexity results in difficulty in directly linking river inputs to ecological community change.

The results for 2020–21 followed typical patterns of water quality in the inshore Reef, which generally show distinct gradients away from river mouths, with elevated levels of most parameters closest to the coast. Seasonal differences in water quality during 2020–21 were more prominent for some variables and subregions than others. These gradients are influenced over short time periods by flood events and sediment resuspension, and over longer time periods by complex interactions between physical and biogeochemical processes (Schaffelke *et al.*, 2017). Such dynamics are a part of the natural Reef ecosystem, albeit under lower levels of input of river-derived material than at present (Kroon *et al.*, 2012).

A statistical analysis of the past 5 years of MMP water quality data showed significant variability between years and locations. Most variation was explained by temporal factors (for example, seasons, years, and river flow), highlighting the variable nature of the ecosystem, with regional aspects (such as latitude, land use on adjacent catchments, proximity to rivers, and resuspension) explaining a smaller amount of the variation.

Our analyses of long-term monitoring data from coastal waters of the Reef suggest that some variables showed no long-term net increases or decreases in concentration, whereas other variables have increased in concentration over time. This analysis is not yet possible in the Cape York focus region which has only been routinely sampled for five years.

In the majority of the Wet Tropics, Burdekin, and Mackay-Whitsunday focus regions:

- TSS:
 - Both meeting and exceeding GVs for the 2020–21 water year for different regions
 - Concentrations improving (lower) in recent years (2016–2021)
- Chl-a:
 - Meeting GVs for the 2020–21 water year
 - Concentrations improving (lower) in recent years (2016–2021)
- NO_x:
 - Exceeding GVs for the 2020–21 water year
 - Concentrations stable or worsening (higher) in recent years (2016–2021)
- PO₄:
 - Both meeting and exceeding GVs for the 2020–21 water year for different regions
 - Concentrations improving (lower) in recent years (2016–2021)

- PN:
 - Exceeding GVs for the 2020–21 water year
 - Concentrations stable or worsening (higher) in recent years (2016–2021)
- PP:
 - Generally exceeding GVs for the 2020–21 water year
 - Concentrations stable or improving (lower) in recent years (2016–2021)
- Secchi depth:
 - Exceeding GVs for the 2020–21 water year
 - Values stable or improving (greater) in recent years (2016–2021)

Previous water quality monitoring reports highlighted the large increases that had occurred in organic carbon concentrations (DOC and POC) since the beginning of the MMP. Monitoring results from the past few years suggest that POC is presently stable or declining in all focus regions, but that DOC may have resumed its increasing trend. The causes and implications of these changes are discussed in previous reports (Gruber *et al.*, 2019) and remain unclear until further process-based experiments can be conducted.

Analysis of the longer-term trends of the remote sensing datasets show high variability between monitoring years, driven by a range of factors and in particular, river discharge. For this report, Sentinel-3 satellite images of the reef and the Forel-Ule colour scale (FU, 21 colour classes) were used to produce map Reef water types instead of the MODIS imagery and the wet season colour scale (wet season, 6 colour classes). The results for the 2020–21 wet season were consistent with previous years, and indicated similar conditions to mean long-term conditions, or in some southern areas, were consistent with characteristics of drier years. Anomalies were identified in the extent of the tertiary water types for the third year in a row and highlighted the complexity of water quality characteristics in the region, and the need for greater understanding of the other potential drivers to that variability (such as wind, currents, upwelling and temperature). The dry season pilot study (Appendix E) demonstrated the potential of the FU colour scale for mapping water colour patterns in the dry season, showing that methods developed as part of the MMP can be adjusted to produce both dry and wet season monitoring products. This would be particularly useful to better understand the conditions and physical influences that can be detrimental or promote the recovery of Reef habitats throughout the year.

The complexity of long-term changes in water quality highlights the importance of maintaining and further developing a range of monitoring, processing and modelling tools supporting the integrated design of the MMP Inshore Water Quality Program. The results examining flood event and ambient conditions coupled with other research programs within the Reef lagoon provide important insights on water quality in the Reef. For example, remote sensing products highlight the spatial and temporal influence of river plumes during the wet season within the Reef lagoon and help to identify where coastal ecosystems may be at risk from exposure to elevated levels of pollutants (Devlin *et al.*, 2015; Petus *et al.*, 2014a, b, 2016) or chronic reduced light levels (Petus *et al.*, 2019). Recent studies highlight the influence of river discharge and associated constituents on water clarity in the inshore and mid-shelf Reef waters in the months following flood events using satellite photic depth data (Fabricius *et al.*, 2014, 2016) or a combination of *in situ* and satellite-derived data (Petus *et al.*, 2019).

The capacity to link coastal water quality to end-of-catchment loads and the ability to estimate the potential impacts of flood plumes on reef ecosystems are based on the spatial and temporal extent of available water quality data. Long-term coastal water quality patterns are complex and influenced by many factors including oceanographic forcing, climate change, and the impact of severe storms. As predictive tools such as the eReefs hydrodynamic and biogeochemical models are further progressed for practical applications such as these, the ability to report on these objectives will continue to improve.

In addition to data needs, there are several key knowledge needs that will help improve the ability to predict and manage linkages between land management and marine water quality. Further research is required on the rates of key biogeochemical processes (in addition to information on concentrations) operating in the coastal ocean, including the production and consumption rates of carbon, nitrogen, and phosphorus species. Recent work suggests that organic nutrient pools may serve as a major nitrogen and phosphorus source for phytoplankton production in the Reef lagoon (Lønborg *et al.*, 2017), and that particulate nitrogen derived from river discharge may be more bioavailable than previously thought (Lewis *et al.*, 2020). Further research on organic and particulate nutrient pools is needed to determine how these sources compare with nitrate in supporting phytoplankton production. Addressing these knowledge needs will provide greater ability to interpret patterns in coastal water quality and greater confidence that management action has delivered improvement in water quality.

6.2 Water quality and effects on marine communities

Water quality comprises the sediment, nutrient, and contaminant concentrations present in a water body. Water quality characteristics have an effect on certain physico-chemical properties such as water clarity (light attenuation) and key ecological processes including rates of primary productivity (especially in phytoplankton) and nutrient cycling. In addition to anthropogenic stressors described in Section 3, the Reef lagoon is influenced by many natural drivers and pressures that affect suspended nutrient and sediment concentrations including: the upwelling of deeper Coral Sea waters onto the continental shelf (Benthuisen *et al.*, 2016; Furnas and Mitchell 1996); resuspension of bottom sediments by wind and waves (Orpin *et al.*, 1999); extreme weather conditions such as cyclones (Dufois *et al.*, 2017); and nitrogen fixation by cyanobacteria (Messer *et al.*, 2017).

Overall, land-derived run-off is considered to be the largest source of 'new' nutrients to the inshore Reef (Bartley *et al.*, 2017; Furnas *et al.*, 2011). However recent work has highlighted the potential role of marine nitrogen fixation as a nitrogen source of similar or greater magnitude, that may have increased as a result of catchment loads of phosphorus and micronutrients (Erlher *et al.*, 2020; Bell, 2021). These contributions need to be better understood in the Reef. Water quality parameters in the Reef vary along cross-shelf and latitudinal gradients, with inshore reefs experiencing year-round elevated suspended sediment concentrations and (with the exception of the Cape York region) elevated Chl-*a* concentrations compared to offshore reefs (Furnas *et al.*, 2005; Schaffelke *et al.*, 2012). Reefs in the central and southern regions also experience elevated concentrations of dissolved inorganic nutrients compared to northern reefs (Furnas *et al.*, 2005), although nutrient concentrations can show considerable year-to-year and seasonal variability (Schaffelke *et al.*, 2012). Water quality variables in the inshore Reef are dynamic and reflect differences in inputs, transport, and many simultaneous biological and chemical processes.

Thirty-five major rivers drain into the Reef lagoon, and the average annual export of sediments, nutrients, and herbicides from these catchments to the coastal zone has increased more than 5-fold since European settlement (Kroon *et al.*, 2012). River loading has large spatial and temporal variation, with the contribution of individual rivers differing substantially along the coast (Wolff *et al.*, 2018) and during periods of high rainfall (Schroeder *et al.*, 2012; Waterhouse *et al.*, 2017a).

Local environmental conditions, such as water quality, influence the benthic communities including seagrasses and corals found in coastal and inshore waters of the Reef. Collectively, inshore coral reefs differ markedly from those found in clearer, offshore waters (for example, Done, 1982; Wismer *et al.*, 2009). The premise underpinning the Reef 2050 Plan is that loads of nutrients, sediments and pesticides delivered by rivers contribute to declining Reef ecosystem health (Schaffelke *et al.*, 2017) and suppress ecological resilience. A review of the potential effects of water quality on seagrass and coral communities can be found in the MMP

reports specific to ecological monitoring (McKenzie *et al.*, 2021; Thompson *et al.*, 2021). However, the direct link between land-runoff, pollutant loads, and Reef ecosystem response remains difficult to measure in the context of the complexities such as regional variation, time lags and the other drivers, activities and pressures noted above. The MMP plays an important role in providing further evidence to improve understanding of these linkages.

The *2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef* concluded that: ‘Key Great Barrier Reef ecosystems continue to be in poor condition. This is largely due to the collective impact of land runoff associated with past and ongoing catchment development, coastal development activities, extreme weather events and climate change impacts such as the 2016 and 2017 coral bleaching events...’. Furthermore, ‘the decline of marine water quality associated with land-based run-off from the adjacent catchments is a major cause of the current poor state of many of the coastal and marine ecosystems of the Great Barrier Reef. Water quality improvement has an important role in ecosystem resilience’ (Waterhouse *et al.*, 2017b). The data presented in this report will contribute to the review and assessment of the evidence for the 2022 iteration of the Scientific Consensus Statement.

6.3 Pesticides

There is little difference in the overall pesticide risk category calculated for 2020–21 and the previous year (Waterhouse *et al.* 2021). The maximum risk category was low at all three sites in both years. For both Flat Top Island and Repulse Bay, the pesticide risk has declined from moderate in 2018–19, and from very high and high at Flat Top Island in 2017–18 and 2016–17, respectively (Thai *et al.*, 2020). Although two herbicides (Pendamethalin and Chlorphrifos) included in 2019–20 were not assessed this year, the risk calculation is unlikely to have been affected markedly, based on their toxicity and concentration levels in previous years.

It is important to consider the adequacy of samples and timing of flow events when interpreting results within and between years. Passive samplers provide a time-averaged estimates of pesticide concentration data so if peaks are short the high concentrations are masked to some extent. Sampling particularly needs to occur when maximum concentrations of pesticides enter marine waters. This is often during the first flush of land-based run-off from rivers, or during early wet season flood events. Wind and tide will also play a role in where pesticides reach.

We cross-checked pesticide concentration peaks in nearby rivers to confirm the flow capture and determine whether any samplers were lost during critical periods. Catchment Loads Monitoring Program data revealed that diuron concentrations in the Pioneer River at Dumbleton (wqi.eagle.io) were high on 23 November (one day), in the period from 29 December 2020 to 10 January 2021, and again 24 to 31 March 2021. Deployment and retrieval records show that these peaks were split across different samples. This is likely to have partially masked higher concentrations. Reported concentrations do increase in correlation with highs from river sampling, although remaining at low or very low risk, and well below guidelines. Sandy Creek was the only site with a lost sampler this year. The loss did coincide with part of the high January period, however the first flush, as well as most of the high period, was captured in the previous deployment which still returned a low risk of exposure.

The hydrology and sampling coverage also needs consideration when evaluating trends. Recent eReefs modelling of pesticide dispersal in the Reef by CSIRO will be able to account for these factors, and significantly increase our understanding of risks to the Reef posed by pesticides in land-based run-off in the future.

Evaluating data on loads in rivers and risk at the end of catchment, monitored by the Catchment Loads Monitoring Program, would be a more direct evaluation of whether any

improved water quality in the Mackay-Whitsunday reflects changes in land management practices.

6.4 Management response

Concern about the effects of land-based run-off first triggered the Australian and Queensland governments to formulate the Reef Water Quality Protection Plan for catchments adjacent to the Reef in 2003 (Australian and Queensland governments, 2003). In 2015, the Australian and Queensland governments released the *Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan), updated in 2018 (Commonwealth of Australia, 2018). The Reef 2050 Plan identifies seven themes (ecosystem health, biodiversity, heritage, water quality, community benefits, economic benefits and governance) for managing the Great Barrier Reef World Heritage Area. The *Reef 2050 Water Quality Improvement Plan 2017–2022* (Reef 2050 WQIP) (Queensland and Australian governments, 2018a) delivers the water quality theme within the Reef 2050 Plan. The plan is a joint commitment of the Australian and Queensland governments and identifies actions that will help minimise the risk to the Reef from a decline in the quality of water entering the Reef lagoon from its adjacent catchments. It builds on three previous iterations of the Reef Water Quality Protection Plan (2003, 2009 and 2013). The long-term (2050) outcome for the plan is that '*Good water quality sustains the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health and benefits communities*'.

The actions in the Reef 2050 WQIP support the implementation of improved land management practices in Reef catchments that are expected to result in measurable improvements in the downstream water quality of creeks and rivers. These actions should, with time, also lead to improved water quality in the inshore Reef, although system-scale changes may occur on decadal timescales (Lefcheck *et al.*, 2018). Recent assessments question whether these actions will be sufficient to ensure the resilience of the Reef ecosystems into the future (Bartley *et al.*, 2014; Kroon *et al.*, 2014, 2016) and suggest that additional options involving system restoration may be required (Waterhouse *et al.*, 2017b).

The *Paddock to Reef Integrated Monitoring, Modelling and Reporting Program* (Paddock to Reef program) serves as a framework to evaluate and report progress on Reef 2050 WQIP targets. The MMP is an integral part of this overarching program and provides physico-chemical and ecological data to measure the condition and trend of Reef inshore water quality and ecosystems. The Paddock to Reef program was reviewed and updated in 2018 with the design extended to 2022. The revised scope of the program aligns with the expanded scope of the Reef 2050 WQIP and is complementary to and supportive of the Reef 2050 Plan, regional water quality improvement plans and the associated monitoring and reporting programs i.e., the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) and Regional Report Cards.

Sustained improvements in the marine water quality of the inshore Reef have not yet been observed in the MMP Inshore Water Quality program. The complexity of the relationship between land-based runoff and water quality, the influence of inter-annual variability, the progress of changed management practice adoption, and the expected slow response timeframes between land-based changes and marine water quality all contribute to this lack of observed change. Continued water quality monitoring and modelling of the Reef lagoon will be fundamental to detecting and tracking changes in response to management actions and interventions.

7 Conclusions












This section provides major conclusions from water quality monitoring efforts in nine focus areas spanning four NRM regions. Table 7-1 provides a high-level summary by NRM region.

Results showed variable responses to the average to above-average river discharges and end-of-catchment pollutant loads of 2020–21. The river discharges in all focus regions of the Reef except the Mackay-Whitsunday region were above the long-term median during the 2020–21 wet season.

The main findings for each NRM region are highlighted below and are separated into results from ambient (routine sampling during wet and dry seasons) and event-based (sampling during flood events) monitoring.

Table 7-1: Summary of results for some of the primary indicators measured in the MMP Inshore Water Quality program, 2020–21. * Arrows indicate difference relative to long-term patterns: area exposed in 2020–21 similar (difference ≤ 5%) to long-term patterns. decrease in area exposed (difference > 5%), increase in area exposed (difference >5 %), coral reef, seagrass.

Focus area	Drivers and Pressures		Remote sensing mapping and modelling		Water Quality Index	
	Cyclone activity (Category, timing)	River discharge (ref to LT median)	Area (in %) exposed to a potential risk*	Area (in %) exposed to the highest potential risk (categories III and IV)#	Annual	Trend
Reef wide	Cyclone Kimi (low, early Jan) Cyclone Lucas (low, late Jan) Cyclone Niran (low, late Feb - early Mar)	<1.5	<ul style="list-style-type: none"> • Reef: 11% (+7%) in coral area exposed to lowest cat of risk (II). Likely related to in Cape York regions. 	<ul style="list-style-type: none"> • Reef: 3% , 28% • <2% , 19% <p>→ Only inshore Reef waters and habitats, with the largest proportion in the enclosed coastal waters.</p>	na	na
Cape York	Cyclone Kimi (low, early Jan) Cyclone Lucas, (low, late Jan)	1.5 -2	<ul style="list-style-type: none"> • Note (+17%) in coral area exposed to lowest cat of risk (II). 	<ul style="list-style-type: none"> • CY: 3% , 19% • <2% , with the largest proportion in the enclosed coastal waters. 	Moderate	na
Wet Tropics	Cyclone Kimi (low, early Jan) Cyclone Niran (low, late Feb - early Mar)	<1.5	<ul style="list-style-type: none"> • WT: 16% 	<ul style="list-style-type: none"> • WT: 3% , -65% • <2% , with the largest proportion in the enclosed coastal waters. 	Moderate	Declined 2008–2018, improved past 3 years
Burdekin	na	1.5 -2	<ul style="list-style-type: none"> • B: 11% 	<ul style="list-style-type: none"> • B: 3% , 46% • <2% , with the largest proportion in the enclosed coastal waters. 	Moderate	Declined gradually since 2010, stable in recent years
Mackay-Whitsunday	na	<1.5	<ul style="list-style-type: none"> • MW: -15% 	<ul style="list-style-type: none"> • MW: 3% , 36% • 2% , with the largest proportion in the enclosed coastal waters. 	Moderate	Declined since 2008, stable in recent years, improved this year

Focus area	Drivers and Pressures		Remote sensing mapping and modelling		Water Quality Index	
	Cyclone activity (Category, timing)	River discharge (ref to LT median)	Area (in %) exposed to a potential risk*	Area (in %) exposed to the highest potential risk (categories III and IV)#	Annual	Trend
Fitzroy	na	<1.5	<p>F: 9%  • Note  (-11%) in seagrass area exposed the highest category of risk (IV)</p> <p>F: 3%  2%  , 33%  → Only inshore Fitz waters and habitats, with the largest proportion in the enclosed coastal waters.</p>	<p>F: 3%  2%  , 33%  → Only inshore Fitz waters and habitats, with the largest proportion in the enclosed coastal waters.</p>	Good (see Appendix D)	Good (see Appendix D)
Burnett-Mary	na	<1.5	<p>BM: <3% </p>	<p>BM: <1%  , 19%  → Only inshore BM waters and habitats</p>	na	na

7.1 Cape York

As this was only the fifth year of sampling in the Cape York region under the MMP, no long-term trends have been evaluated.

Discharge from rivers in the Cape York focus regions in 2020–21 period was above the long-term median discharge for all sub-regions. However, rainfall was generally consistent over the wet season and did not result in any above average magnitude flood events. As a result of the relatively high total discharge but general lack of major flooding, there was some decline in water quality compared to the previous (2019–20) below-average wet season, but significant water quality improvements compared to the record discharge 2018–19 wet season. Overall, the water quality index score for each sub-region was moderate, with the exception of the Normanby Basin, which scored “poor”.

Ambient water quality:

Enclosed coastal, open coastal and mid-shelf waters (for those parameters with guidelines):

- Chl-*a* and PP met the water quality GVs at most sites for all Cape York sub-regions.
- NO_x exceeded the GVs at most sites and sub-regions.
- Secchi depth was less than (did not meet) the minimum GV at most sites and sub-regions. However, monitoring occurred primarily during the wet season and means are compared against annual guidelines.
- TSS, PO₄ and PN comparisons against GVs were mixed, with some sites and sub-regions meeting the GVs (Table 7-2).
- Mean and median turbidity and Chl-*a* met the annual and wet season GVs at Dawson and Forrester Reefs FLNTU datalogger sites.
- A “poor” water quality index score at the Normanby sub-region was driven by both TSS and Secchi depth GV exceedances. Two average magnitude flood events influenced water quality across Princess Charlotte Bay over the wet season, contributing to the high TSS concentrations.

Table 7-2: Cape York summary information – exceedance of guideline values: exceeding (✘) or meeting (✔) annual guideline values.

Water quality variable	Pascoe	Stewart	Normanby	Annan-Endeavour
NO _x	✘	✘	✘	✘ ✔ (mixed)
PO ₄	✔	✔	✘ ✔ (mixed)	✘ ✔ (mixed)
PN	✔	✘	✘ ✔ (mixed)	✘
PP	✔	✔	✔	✔
TSS	✔	✔	✘	✘ ✔ (mixed)
Secchi depth	✘	✘	✘	✘ ✔ (mixed)
Chl- <i>a</i>	✔	✔	✔	✔

Event water quality

- Flood monitoring in the Normanby sub-region over late February early March documented typically high concentrations of TSS in the Normanby & Kennedy estuaries (mean 139), with floodwater influences on salinity and turbidity measured as far as 200 km to the north of the river mouths.
- Turbidity exceeded 500 NTU in the Annan estuary during relatively minor February and April flood events. Elevated TSS (5.5 mg L⁻¹) was measured at mid-shelf reefs (site AE04) during the February event. Flooding resulted in increased turbidity and Chl-*a* concentrations for short periods at inshore reefs such as Dawson Reef, 6 km from the mouth of the Annan River (measured by *in situ* continuous dataloggers). However, in contrast to previous years, there was little floodwater connectivity between the Annan-Endeavour rivers and Forrester Reef located 30 km to the north.
- Approximately 85% of the Cape York region was not exposed to a potential risk, similar to long-term patterns, and only 1% (483 km²) of the region was exposed to the highest risk category IV. Approximately 15% (or 14,277 km²) of the total area of the Cape York region, including 24% (2,443 km²) of the region's coral reefs and 63% (1,670 km²) of the seagrasses were exposed to a potential risk. However, only the inshore Cape York waters, seagrass and coral habitats were exposed to the highest categories of potential risk (III and IV), with the largest proportion located in the region's enclosed coastal waters. Areas exposed were globally similar to the long-term patterns, but there was an increase in the coral area exposed to the lowest potential risk category (II: +17%). Mid-shelf and offshore Cape York reefs and seagrasses were exposed to the lower potential risk category II or to no / very low risk.

7.2 Wet Tropics

Discharge from the Daintree, Mossman, and Barron Basins was close to the long-term median in 2020–21, after a very low discharge year in 2019–20. Discharge from the Russell-Mulgrave and Johnstone Basins was also close to the long-term average in 2020–21, while discharge in the Tully region was around 1.5 times the long-term median in 2020–21.

Ambient water quality

Enclosed coastal, open coastal, and mid-shelf waters (for those parameters with guidelines):

In most regions of the Wet Tropics, annual water quality guidelines were exceeded for most water quality variables, except for Chl-*a* and PO₄, which met guidelines in all focus regions. Over the period from 2016 to 2021, many water quality variables are showing signs of an improving trend (Table 7-3).

Water Quality Index scores have shown a long-term trend of gradual decline but have seen improvement over the past three years. For the 2020–21 water year, the Annual Condition Water Quality Index score was 'moderate'.

Table 7-3: Wet Tropics summary information – exceedance of guideline values: exceeding (✖) or meeting (✔); annual guideline values and trend (2016–2021): Deteriorating (⬇️), improving (⬆️) or stable (⬚).

Water quality variable	Barron-Daintree	Russel-Mulgrave	Tully
NO _x	✖ ⬇️	✖ ⬚	✖ ⬆️
PO ₄	✔ ⬆️	✔ ⬆️	✔ ⬆️

PN	 	 	 
PP	 	 	 
TSS	 	 (most sites) 	 
Secchi depth	 	 	 
Chl-a	 	 	 
DOC			
POC			

Wet season and event water quality

- There were three flood events influencing the Wet Tropics region during the 2020–21 wet season.
- 84% of the Wet Tropics region was not exposed to a potential risk, similar to long-term patterns, and only 1% (or 399 km²) of the region was exposed to the highest risk category IV. Approximately 16% (or about 5000 km²) of the total area of the Wet Tropics region, including 4% (86 km²) of the region's coral reefs and 99% (229 km²) of the seagrasses were exposed to a potential risk. However, only the inshore Wet Tropics waters, seagrass and coral habitats were exposed to the highest categories of potential risk (III and IV), with the largest proportion located in the region's enclosed coastal waters. Mid-shelf and offshore Wet Tropics reefs and mid-shelf Wet Tropics seagrasses were largely exposed to no / very low risk. The areas were similar to the long-term average areas (changes <5%).

7.3 Burdekin

The combined discharge and loads calculated for the 2020–21 water year from the Burdekin and Haughton Basins were around 1.5 times the long-term median, after a very low discharge year in 2019–20.

Ambient water quality

Enclosed coastal, open coastal, and mid-shelf waters (for those parameters with guidelines):

In the Burdekin region many water quality parameters were not meeting guideline values except for Chl-a. the trends in some variables have deteriorated over the past 5 years (NO_x and PN) however most variables were either stable or improving over the period (Table 7-4).

Water Quality Index scores have shown a long-term trend of decline since 2008 but have been stable over the past few years. For the 2020–21 water year, Annual Condition Water Quality Index scores were 'moderate' and have declined since the 2019–20 water year.

Table 7-4: Burdekin region summary information – exceedance of guideline values: exceeding (✘) or meeting (✔); annual guideline values and trend (2016–2021): Deteriorating (↓), improving (↑) or stable (↔).

Water quality variable	Burdekin
NO _x	✘ ↓
PO ₄	✘ ↑
PN	✘ ↔
PP	✘ / ✔ ↔
TSS	✘ ↑
Secchi depth	✘ ↑
Chl-a	✔ ↑
DOC	↓
POC	↑

Wet season and event water quality

- There was one major flood event influencing the Burdekin region during the 2020–21 wet season.
- Approximately 89% of the Burdekin region was not exposed to a potential risk, similar to long-term patterns, and only 1% or 584 km² of the region was exposed to the highest risk category IV. Approximately 11% (or about 5,300 km²) of the total area of the Burdekin region, including 2% (53 km²) of the region's coral reefs and 92% (649 km²) of the seagrasses were exposed to a potential risk. However, only the inshore Burdekin waters, seagrass and coral habitats were exposed to the highest categories of potential risk (III and IV), with the largest proportion located in the region's enclosed coastal waters. Mid-shelf Burdekin seagrasses were largely exposed to the lowest potential risk category (III), while mid-shelf and offshore Burdekin reefs were largely exposed to no / very low risk. These areas were similar to the long-term average area (< 5% difference).

7.4 Mackay-Whitsunday

The combined discharge and loads calculated for the 2020–21 water year from the Proserpine, O'Connell, Pioneer and Plane Basins were below long-term median values and were among the lowest recorded over the past decade.

Ambient water quality

Enclosed coastal and open coastal waters (for those parameters with guidelines):

In the Mackay-Whitsunday region most water quality parameters were not meeting guideline values except for Chl-a and TSS at most sites that were monitored. Trends over

the last 5 years indicate that all variables were either stable or improving over the period (Table 7-5)

Water Quality Index scores have shown a long-term trend of decline since 2008 but have been stable over the past few years. For the 2020–21 water year, Water Quality Index scores were 'moderate'.

Table 7-5: Mackay-Whitsunday summary information – exceedance of guideline values: exceeding (✖) or meeting (✔); annual guideline values and trend (2016–2021): Deteriorating (⬇️), improving (⬆️) or stable (↔️).

Water quality variable	Mackay-Whitsunday
NO _x	✖ ⬇️
PO ₄	✖ ⬆️
PN	✖ ⬆️
PP	✖ ⬆️
TSS	✔ ⬆️
Secchi depth	✖ ↔️
Chl- <i>a</i>	✔ ⬆️
DOC	↔️
POC	⬆️

Wet season and event water quality

- There were no major flood events in the Mackay-Whitsunday region during the 2020–21 wet season.
- Approximately 85% of the Mackay-Whitsunday region was not exposed to a potential risk, similar to long-term patterns, and only 1% (or 426 km²) of the region was exposed to the highest risk category IV. Approximately 15% (or about 7,200 km²) of the total area of the Mackay-Whitsunday region, including 6% (206 km²) of the region's coral reefs and 92% (282 km²) of the seagrasses were exposed to a potential risk, with the largest proportion located in the region's enclosed coastal waters. However, only the inshore Mackay-Whitsunday waters, seagrass and coral habitats were exposed to the highest categories of potential risk (III and IV). Mid-shelf and offshore Mackay-Whitsunday reefs were exposed to no / very low risk. These areas were globally similar to the long-term average areas (<5% difference), and there was a decrease in the total region area exposed to the lowest potential risk category (II: -7%).

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Appendix A: Water quality site locations and frequency of monitoring

Table A-1: Description of the water quality sites sampled by AIMS, JCU and CYWMP during 2020–21. Sites in bold font were part of the ambient monitoring design from 2005 to 2015. The proposed number of visits is shown in black text, while the actual number of visits is shown in brackets in red text.

Site Location	Logger Deployment		Ambient sampling at fixed sites: proposed (actual)		Event-based sampling
	Turbidity and chlorophyll	Salinity	Number of times site is visited/year by AIMS	Number of times site is visited/year by JCU/ CYWMP	Additional surface-sampling/year by JCU/ CYWMP
Cape York					
Normanby-Kennedy transect					
Kennedy mouth					3 (Surface sampling only)
Kennedy inshore					2 (Surface sampling only)
Cliff Islands				4 (Sampling 2 depths) (4)	
Bizant River mouth					1 (Surface sampling only)
Normanby River mouth					1 (Surface sampling only)
Normanby inshore				4 (Sampling 2 depths) (4)	1 (Surface sampling only)
NR-03				4 (Sampling 2 depths) (4)	
NR-04				4 (Sampling 2 depths) (4)	
NR-05				4 (Sampling 2 depths) (4)	
Corbett Reef				4 (Sampling 2 depths) (4)	
Pascoe transect					
Pascoe mouth north				5 (Sampling 2 depths) (5)	
Pascoe mouth south				5 (Sampling 2 depths) (5)	
PR-N2				5 (Sampling 2 depths) (5)	
PR-N3					
PR-N5					
PR-N6					
PR-S2.5				5 (Sampling 2 depths) (5)	
Middle Reef				5 (Sampling 2 depths) (5)	
PR-S5				5 (Sampling 2 depths) (5)	
Annan and Endeavour transect					
Annan mouth					2 (Surface sampling only)
Walker Bay				5 (Sampling 2 depths) (5)	2 (Surface sampling only)
Dawson Reef	√			5 (Sampling 2 depths) (5)	2 (Surface sampling only)
Endeavour mouth					2 (Surface sampling only)
Endeavour north shore				5 (Sampling 2 depths) (5)	2 (Surface sampling only)
Endeavour offshore				5 (Sampling 2 depths) (5)	2 (Surface sampling only)

Site Location	Logger Deployment		Ambient sampling at fixed sites: proposed (actual)		Event-based sampling
NRM region	Turbidity and chlorophyll	Salinity	Number of times site is visited/year by AIMS	Number of times site is visited/year by JCU/ CYWMP	Additional surface-sampling/year by JCU/ CYWMP
Egret and Boulder Reef				5 (Sampling 2 depths) (5)	2 (Surface sampling only)
Forrester Reef	√				
Stewart transect					
Stewart mouth					
SR-02				5 (Sampling 2 depths) (4)	
SR-03				5 (Sampling 2 depths) (4)	
SR-04				5 (Sampling 2 depths) (4)	
Hannah Island				5 (Sampling 2 depths) (4)	
Wet Tropics					
Cairns Long-term transect					
Cape Tribulation			3 (Sampling 2 depths) (3)		
Port Douglas			3 (Sampling 2 depths) (3)		
Double Island			3 (Sampling 2 depths) (3)		
Yorkey's Knob			3 (Sampling 2 depths) (3)		
Fairlead Buoy			3 (Sampling 2 depths) (3)		
Green Island			3 (Sampling 2 depths) (3)		
Russell-Mulgrave Focus Area					
Fitzroy Island West	√		5 (Sampling 2 depths) (5)		
RM2					
RM3			5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	
RM4					
High Island East					
Normanby Island					
Frankland Group West (Russell Island)	√		5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	
High Island West	√	√	5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	
Palmer Point					
Russell-Mulgrave River mouth mooring	√	√	5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	
Russell-Mulgrave River mouth					
Russell-Mulgrave junction [River]					
Tully Focus Area					
King Reef					1 (Surface sampling only)
East Clump Point			5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	1 (Sampling 2 depths)
Dunk Island North	√	√	5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	1 (Sampling 2 depths)

Site Location	Logger Deployment		Ambient sampling at fixed sites: proposed (actual)		Event-based sampling
NRM region	Turbidity and chlorophyll	Salinity	Number of times site is visited/year by AIMS	Number of times site is visited/year by JCU/ CYWMP	Additional surface-sampling/year by JCU/ CYWMP
South Mission Beach					1 (Surface sampling only)
Dunk Island South East			5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	1 (Sampling 2 depths)
Between O'Shanter and Timana			5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	1 (Sampling 2 depths)
Hull River mouth					1 (Surface sampling only)
Bedarra Island			5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	1 (Sampling 2 depths)
Triplets					1 (Surface sampling only)
Tully River mouth mooring	√	√	5 (Sampling 2 depths) (5)	5 (Sampling 2 depths) (5)	1 (Sampling 2 depths)
Tully River					1 (Surface sampling only)
Burdekin					
Burdekin Focus Area					
Pelorus and Orpheus Island West	√		4 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (5)	
Pandora Reef	√		4 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (5)	
Cordelia Rocks					
Magnetic Island (Geoffrey Bay)	√		4 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (5)	
Inner Cleveland Bay					
Cape Cleveland					
Haughton 2			4 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (5)	
Haughton River mouth					
Barratta Creek					
Yongala IMOS NRS	√	√	4 (Sampling 2 depths) (4)		
Cape Bowling Green					
Plantation Creek					
Burdekin River mouth mooring	√	√	4 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (5)	
Burdekin Mouth 2					
Burdekin Mouth 3					
Mackay-Whitsunday					
Whitsunday focus area					
Double Cone Island	√		5 (Sampling 2 depths) (5)		
Hook Island W					
North Molle Island					
Pine Island	√	√	5 (Sampling 2 depths) (5)		

Site Location	Logger Deployment		Ambient sampling at fixed sites: proposed (actual)		Event-based sampling
NRM region	Turbidity and chlorophyll	Salinity	Number of times site is visited/year by AIMS	Number of times site is visited/year by JCU/ CYWMP	Additional surface-sampling/year by JCU/ CYWMP
Seaforth Island	√		5 (Sampling 2 depths) (5)		
OConnell River mouth	√	√	5 (Sampling 2 depths) (5)		
Repulse Islands dive mooring			5 (Sampling 2 depths) (5)		
Rabbit Island NE					
Brampton Island					
Sand Bay					
Pioneer River mouth					

The 2020–21 water year is only the fifth year of sampling for the Cape York region. In consultation between CYWMP, AIMS and the Authority, both the analytical laboratory and the number of sites sampled in Cape York changed in 2020. The site changes were made because:

- AIMS and CYWMP assessed the sites at each sub-region and determined that there was little variability between some sites; therefore, a reduction in the number of sites within each sub-region was reasonable;
- Some sites in the enclosed coastal zone (particularly the Normanby sites) were impossible to access during low or mid-tides, thus these sites were being skipped on occasion; and
- Shallow enclosed coastal sites were subject to highly variable conditions, including tidal flushing and wind and tide-driven sediment resuspension. This made it difficult to interpret data during “ambient” periods.
- The switch to the AIMS laboratory methods required more intensive sampling effort including extra samples collected at each site, and more labour-intensive filtering (PN, PP, PC, TSS). The additional time requirements made it impossible to sample all sites and filter samples the same day (a QC requirement).

Appendix B: Water quality monitoring methods

B-1 Comparison with Reef Water Quality Guideline values

The Water Quality Guidelines provide a useful framework to interpret the water quality measurements obtained through the MMP. Table B-1 gives a summary of the Guideline Values (GVs) for water quality variables in four cross-shelf water bodies (Great Barrier Reef Marine Park Authority, 2010). The MMP design prior to 2015 included sites in the open coastal and mid-shelf water bodies. The MMP design post-2015 now includes sites from all four water bodies.

At present, the Water Quality Guidelines do not define GVs for dissolved inorganic nutrients (nitrate and phosphate) in the Reef lagoon as these nutrients are rapidly cycled through uptake and release by biota and are variable on small spatial and temporal scales (Furnas *et al.*, 2005, 2011). Due to this high variability, their concentrations did not show as clear spatial patterns or correlations with coral reef attributes as the other water quality parameters that were included in the Guidelines and are considered to be more representative of nutrient availability integrated over time (De'ath and Fabricius, 2010). However, the Queensland Water Quality Guidelines (Department of Environment and Resource Management [DERM], 2009) identify GVs for dissolved inorganic nutrients in marine water bodies. Guideline values for dissolved inorganic nutrients and turbidity (in enclosed coastal waters) were drawn from Queensland Water Quality Guidelines or provided by the Authority. Site-specific GVs for all water quality variables are shown in Appendix C Table C-8.

Table B-1: Guidelines values for four cross-shelf water bodies from the Water Quality Guidelines for the Great Barrier Reef Marine Park (Great Barrier Reef Marine Park Authority, 2010). Guidelines for some values come from other sources, as indicated below.

Parameter	Unit	Enclosed coastal		Open coastal		Mid-shelf		Offshore	
		Wet Tropics	Central Coast	Wet Tropics	Central Coast	Wet Tropics	Central Coast	Wet Tropics	Central Coast
Chlorophyll <i>a</i> *	µg L ⁻¹	2.0	2.0	0.45	0.45	0.45	0.45	0.40	0.40
Particulate nitrogen*	µg L ⁻¹	n/a	n/a	20.0	20.0	20.0	20.0	17.0	17.0
Particulate phosphorus*	µg L ⁻¹	n/a	n/a	2.8	2.8	2.8	2.8	1.9	1.9
Suspended solids*	mg L ⁻¹	5.0	15.0	2.0	2.0	2.0	2.0	0.7	0.7
Turbidity	NTU	10.0 ^{QLD}	6.0 ^{QLD}	1.5**	1.5**	1.5**	1.5**	<1 ^{QLD}	<1 ^{QLD}
Secchi depth	m	1.0	1.5	10.0	10.0	10.0	10.0	17.0	17.0
NO _x	µg L ⁻¹	10.0 ^{QLD}	3.0 ^{QLD}	0.35***	0.35***	0.35***	0.35***	2.0 ^{QLD}	2.0 ^{QLD}
PO ₄	µg L ⁻¹	5.0 ^{QLD}	6.0 ^{QLD}	4.0 ^{QLD}	6.0 ^{QLD}	4.0 ^{QLD}	6.0 ^{QLD}	4.0 ^{QLD}	5.0 ^{QLD}

^{QLD} Indicates these values are Queensland Water Quality Guidelines (Department of Environment and Resource Management [DERM], 2009). Please note these are 80th percentile guidelines.

* Seasonal adjustments to these parameters are used to produce seasonal (wet and dry) guidelines for producing satellite exposure maps (Table B-3).

** The turbidity trigger value for open coastal and mid-shelf water bodies (1.5 NTU) was derived for the MMP reporting by transforming the suspended solids GV (2 mg L⁻¹) using an equation based on a comparison between direct water samples and instrumental turbidity readings (see QA/QC Report and Schaffelke *et al.*, 2009).

*** NO_x GV for open coastal and mid-shelf sites are provided by the Authority.

B-2 Calculation of the Water Quality Index

In the Great Barrier Reef Report Cards published prior to 2016, water quality assessments were based on the MMP broad-scale monitoring using ocean colour remote sensing imagery that covers a larger area than the fixed sampling locations reported here (Brando *et al.*, 2011).

However, the current design of the MMP focuses on interpreting trends in site-specific water quality within key focus regions.

The Water Quality Index (WQ Index) is an interpretation tool developed by AIMS to visualise trends in the suite of water quality variables measured and to compare monitored water quality to existing Water Quality Guidelines (Department of Environment and Resource Management, 2009; Great Barrier Reef Marine Park Authority, 2010). The WQ Index uses a set of five key indicators:

- Water clarity (TSS concentrations, Secchi depth, and turbidity measurements by FLNTUSB instruments, where available),
- Chl-*a* concentrations,
- PN concentrations,
- PP concentrations, and
- NO_x concentrations.

These five indicators are a subset of the comprehensive suite of water quality variables measured in the MMP inshore water quality program. They have been selected because GVs are available for these measures, and they can be considered as relatively robust indicators that integrate a number of bio-physical processes in the coastal ocean.

TSS concentration, turbidity, and Secchi depth are indicators of the clarity of the water, which is influenced by a number of factors, including wind, waves, tides, and river inputs of particulate material. Chl-*a* concentration is widely used as a proxy for phytoplankton biomass as a measure of the productivity of a system or its eutrophication status and is used to indicate nutrient availability (Brodie *et al.*, 2007). Particulate nutrients (PN, PP) are an indicator of nutrient stocks in the water column (predominantly bound in phytoplankton and other organic particles as well as adsorbed to fine sediment particles) but are less affected by small-scale variability in space and time than dissolved nutrients (Furnas *et al.*, 2005, 2011). Nitrate is included as an indicator of dissolved nutrient concentrations in the coastal zone, which tend to be rapidly used by phytoplankton. Guideline values for NO_x were provided by the Authority as available NO_x GVs from the Queensland Water Quality Guidelines (Department of Environment and Resource Management [DERM], 2009) are the 80th percentiles, which are considered to be high and not representative of values normally found in the Reef lagoon.

The WQ Index is calculated using two different methods due to changes in the MMP design that occurred in 2015, as well as concerns that the Index was not responsive to changes in environmental pressures of each year. The changes in design included increased number of sites, increased sampling frequency and a higher sampling frequency during December to April to better represent wet season variability. Thus, statistical comparisons between MMP data from 2005–15 to 2015–onwards must account for these changes. The two versions of the WQ Index have different purposes.

Long-term trend: This version of the WQ Index is based on the pre-2015 MMP sampling design and uses only the original sites (located in the open coastal water body) and three sampling dates per year. This sampling design had low temporal and spatial resolution and was aimed at detecting long-term trends in inshore water quality. To compensate for less frequent sampling, four-year running means are used to reduce the effect of sampling date on the Index. Monitoring data are compared against broad water body GVs that do not include wet and dry season GVs (Table B-1). Steps in the calculation of this version of the WQ Index are:

1. Calculate four-year mean values for each of the seven indicators (i.e., all values from 2005–08, 2006–09, 2007–10, *et cetera*).

2. Calculate the proportional deviations (ratios) of these running mean values (V) from the associated guideline value (GV) (Table B-1) as the difference of binary logarithms of values and guidelines:

$$\text{Ratio} = \log_2(V) - \log_2(GV)$$

Binary logarithm transformations are useful for exploring data on powers of 2 scales, and thus are ideal for generating ratios of two numbers in a manner that will be symmetrical around 0. Ratios of 1 and -1 signify a doubling and a halving, respectively, compared to the guideline. Hence, a ratio of 0 indicates a running mean that is the same as its GV, ratios <0 signify running means that exceeded the GV and ratios >0 signify running means that complied with the GV.

3. Ratios exceeding 1 or -1 (more than twice or half the GV) are capped at 1 to bind the WQ Index scales to the region -1 to 1.

4. A combined water clarity ratio is generated by averaging the ratios of Secchi depth, TSS and turbidity (where available).

5. The WQ Index for each site per four-year period is calculated by averaging the ratios of PP, PN, NO_x, Chl-*a*, and water clarity.

6. In accordance with other Great Barrier Reef Report Card indicators, the WQ Index scores (ranging from -1 to 1) are converted to a 'traffic light' colour scheme for reporting whereby:

- < -2/3 to -1 equates to 'very poor' and is coloured red
- < -1/3 to -2/3 equates to 'poor' and is coloured orange
- < 0 to -1/3 equates to 'moderate' and is coloured yellow
- > 0 to 0.5 equates to 'good' and is coloured light green
- > 0.5 to 1 equates to 'very good' and is coloured dark green.

7. For the focus region summaries, the Index scores of all sampling locations within a focus region (for example, all sites in the Tully focus region) are averaged and converted into the colour scheme as above. For regional summaries, the Index scores of all sampling locations within a region (for example, all sites in the Wet Tropics region) are averaged and converted as above.

Annual condition: This version of the WQ Index is based on the post-2015 MMP sampling design and uses all samples from open coastal and mid-shelf water bodies each year. (Note that the WQ Index in reports prior to the 2018–19 report included enclosed coastal sites, see below). Due to high spatial and temporal sampling, a running mean is not used. Monitoring data are compared against site-specific GVs that include wet and dry season GVs (Table C-8). Steps in the calculation of this version of the WQ Index are:

1. For each of the seven indicators, the annual, wet and dry season (aggregations) means and medians (statistic) are calculated per year.
2. Guidelines from the Authority are consulted to select the appropriate aggregation (annual, wet, or dry season) and statistic (mean or median) for each site and indicator (Table C-8).
3. Calculate the proportional deviations (ratios) of these aggregation statistics from the associated GVs as the difference of base 2 logarithms of values and GVs:

$$\text{Ratio} = \log_2(V) - \log_2(GV)$$

4. Ratios exceeding 1 or -1 (more than twice or half the GV) are capped at 1 to bind the WQ Index scales to the region -1 to 1.
5. Ratios of several indicators are combined to create a hierarchical structure. Three groups were created by averaging ratios as follows:
 - water clarity (average of Secchi depth, TSS concentration, and turbidity ratios),
 - productivity (average of Chl-*a* and NO_x ratios), and
 - particulate nutrients (average of PN and PP ratios).
6. The WQ Index for each site is calculated by averaging the ratios of water clarity, productivity, and particulate nutrients.
7. In accordance with other Reef Report Card indicators, the WQ Index scores (ranging from -1 to 1) are converted to a 'traffic light' colour scheme for reporting whereby:
 - < -2/3 to -1 equates to 'very poor' and is coloured red
 - < -1/3 to -2/3 equates to 'poor' and is coloured orange
 - < 0 to -1/3 equates to 'moderate' and is coloured yellow
 - > 0 to 0.5 equates to 'good' and is coloured light green
 - > 0.5 to 1 equates to 'very good' and is coloured dark green.
8. For the focus region summaries, the Index scores of all sampling locations within a focus region (for example, all sites in the Tully focus region) are averaged and converted into the colour scheme as above. For regional summaries, the Index scores of all sampling locations within a region (for example, all sites in the Wet Tropics region) are averaged and converted as above.
9. As of the 2018–19 report, this version of the Index now includes error bars, which propagate error in the Index via bootstrapping. Aggregation uncertainty is propagated through the spatial (site → focus region → region) and measure (measure → sub-indicator → indicator) hierarchies by repeatedly re-sampling (100 times with replacement) and aggregating bootstrapping. Each aggregation yields 100 estimates of each mean, and thus error bars represent the 95% quantile confidence intervals.

The annual condition version of the WQ Index has only been calculated since 2016 and is subject to future revision and refinement.

B-3 Monitoring of Reef water quality trends using remote sensing data

Remote sensing imagery is a useful assessment tool in the monitoring of turbid water masses and river flood plumes (hereafter river plumes) in the Reef lagoon. Ocean colour imagery provides synoptic-scale information regarding the movement, frequency of occurrence and composition of turbid waters in the Reef lagoon. Combined with *in situ* water quality sampling, the use of remote sensing is a valid and practical way to estimate wet season marine conditions as well as the extent and frequency of wet season water types exposure on Reef ecosystems, including river plumes and resuspension events.

Following recommendations from the 2012–13 MMP report, marine areas exposed to wet season water types have been mapped using MODIS true colour images and a surface water colour classification method extensively presented in Álvarez-Romero *et al.* (2013) and used in, for example, Devlin *et al.* (2013) and Petus *et al.* (2014b, 2016, 2018 and 2019). The true colour method is based on a semi-automated classification of spectrally enhanced quasi-true colour MODIS images. It exploits the differences in water colour existing between the turbid

coastal waters (including river plumes) and the marine ambient water, as well differences in water colour existing across coastal waters of the Reef during the wet season.

The wet season water types are produced using MODIS true colour imagery reclassified to six distinct colour classes defined by their colour properties. The wet season colour classes are regrouped into three wet season water types (primary, secondary and tertiary) characterised by different concentrations of optically active components (TSS, colour dissolved organic matter and Chl-*a*), which control the colour of the water and influence the light attenuation (Petus *et al.*, 2018), and different pollutant concentrations (Petus *et al.* 2019).

The brownish to brownish-green turbid waters (colour classes 1 to 4 or primary water type) are typical for inshore regions experiencing river plumes or nearshore marine areas with high concentrations of resuspended sediments found during the wet season.

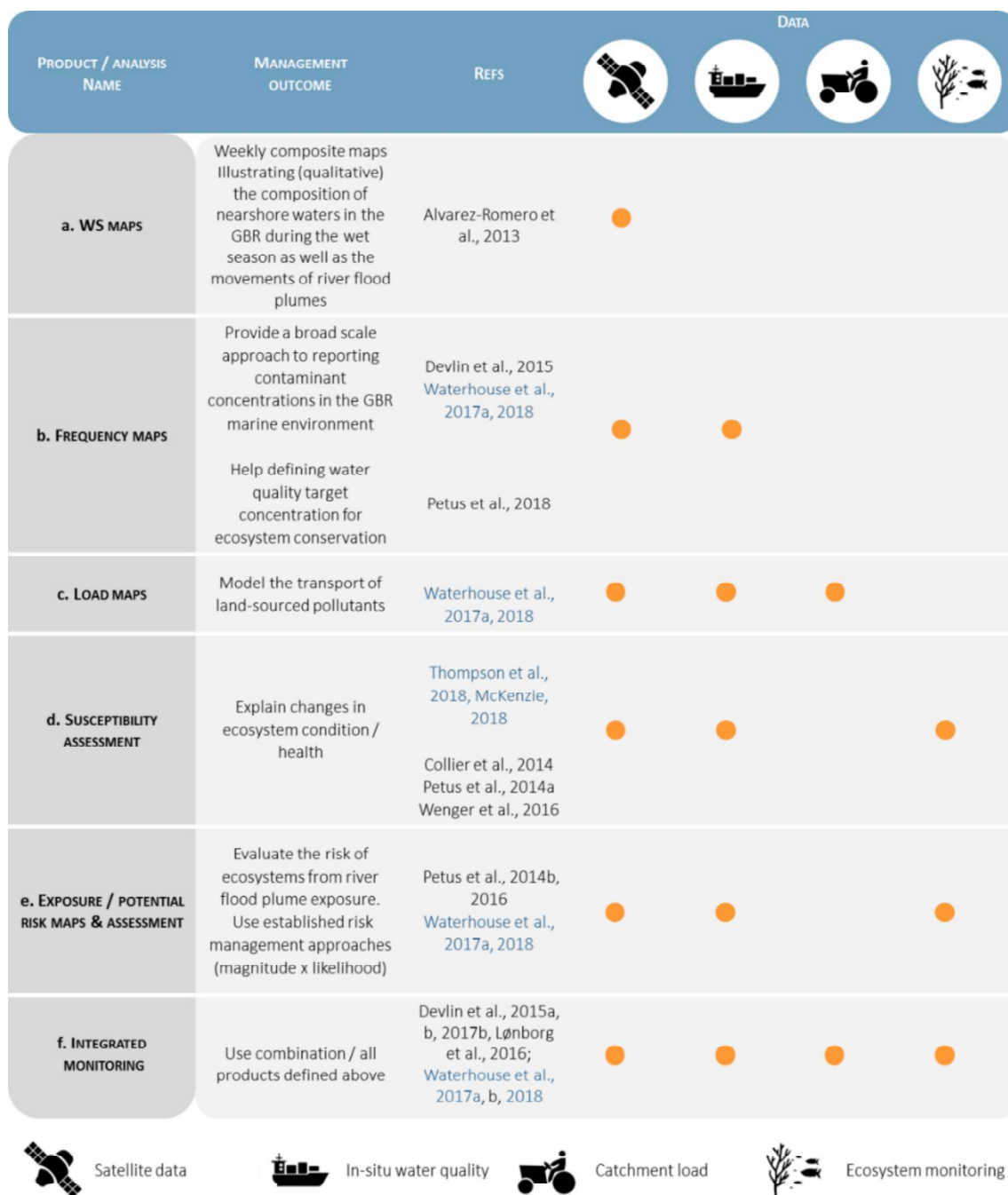


Figure B-1: Operational monitoring products and assessment methods used to monitor the inshore water quality of the Great Barrier Reef through the MMP (blue references) and examples of regional studies using the MMP satellite monitoring products (black references) (Petus et al., 2019). WS: wet season.

These water bodies in flood waters typically contain high nutrient and phytoplankton concentrations but are also enriched in sediment and dissolved organic matter resulting in reduced light levels. The greenish-to-greenish-blue turbid waters (colour class 5 or secondary water type) is typical of coastal waters rich in algae (Chl-a) and contain dissolved matter and fine sediment. This water body is found in open coastal waters as well as in the mid-water plumes where relatively high nutrient availability and increased light levels due to sedimentation (Bainbridge *et al.*, 2012) favour coastal productivity. Finally, the greenish-blue

waters (colour class 6 or tertiary water type) correspond to waters with above ambient water quality concentrations. This water body is typical for areas towards the open sea or offshore regions of river flood plumes.

Several operational monitoring products and frameworks have been developed using MODIS satellite imagery and the water colour classification method (Figure B-1). They are used within the annual MMP reports (Gruber *et al.*, 2019). Classification methods and monitoring products are quickly described below (Great Barrier Reef Marine Park Authority 2019). All products focus on the Austral wet season, i.e., the December to April period.

However, MODIS sensors are ageing (MODIS-Aqua was launched in 2002) and the quality of the MODIS imagery is declining. The use of Sentinel-3 Ocean Land Colour Instrument (OLCI) satellite imagery and another colour scale (the Forel-Ule (FU) colour scale) was proposed for the continuous mapping of Reef waters (Petus *et al.*, 2019). The FU colour scale is an historical colour scale standard to determine the colour and classifies worldwide bodies of water (Novoa *et al.*, 2013). It is composed of 22 colours; going from indigo blue to cola brown, and is applicable for all natural waters (inland, estuarine, inshore and offshore) and all environmental conditions, including wet and dry season conditions (Wernand *et al.*, 2012, 2013; Van der Woerd *et al.*, 2016; Van der Woerd and Wernand, 2018). MODIS-Aqua WS and Sentinel-3 FU colour class maps showed very similar patterns over the 2017–18 wet season in a case study focusing on Wet Tropics and Burdekin regions of the Reef (Petus *et al.*, 2019 and Figure 2-2b and Table 2-2). Further comparisons are presented in the case study (Appendix E).

For this report, Sentinel-3 images of the reef and the FU colour scale were used to produce map Reef water types instead of the MODIS imagery. FU equivalent water types were defined by grouping the FU colour classes 1–3 (equivalent to marine waters in the WS scale), FU colour classes 4–5 (equivalent to WS Tertiary water type), FU colour classes 6–9 (equivalent to WS Secondary water type) and $FU \geq 10$ (equivalent to wet season primary water type), as defined in Petus *et al.* (2019) (Table 2-2).

Supervised classification using spectral signatures

Previous methods used Daily MODIS Level-0 data acquired from the NASA Ocean Colour website, spectrally enhanced (from red-green-blue to hue-saturation-intensity colour system) and classified to six colour categories through a supervised classification using spectral signatures from typical wet season water mass types (including river plumes) in the Reef lagoon.

For this report, wet season water type maps were produced using daily Sentinel-3 OLCI Level 2 (hereafter, Sentinel-3 or S3) imagery reclassified to 21 distinct colour classes defined by their colour properties and using the Forel-Ule colour classification scale. Sentinel-3 imagery of the study area was downloaded on the EUMETSAT Data centre (URL: <https://www.eumetsat.int/eumetsat-data-centre>). Sentinel-3 are atmospherically corrected and were processed with the FU Satellite Toolbox implemented in the Sentinel Application Platform (SNAP, URL: <https://step.esa.int/main/toolboxes/snap/>) and using automated tools (python scripts and ArcGIS toolboxes) developed through MMP funding.

The FU satellite algorithm converts satellite normalised multi-band reflectance information into a discrete set of FU numbers using uniform colourimetric functions (Van der Woerd *et al.*, 2016, Van der Woerd and Wernand, 2018). The derivation of the colour of natural waters is based on the calculation of Tristimulus values of the three primaries (X, Y, Z) that specify the colour stimulus of the human eye. The algorithm is validated by a set of hyperspectral measurements from inland, coastal and marine waters (Van der Woerd *et al.*, 2016, Van der Woerd and Wernand, 2018). Technical details about the FU scale algorithm are synthesised through the European citclops (URL: <http://www.citclops.eu/>) and Eye on Water project

webpages (<https://www.eyeeonwater.org/>). The methods are described in further detail in Appendix B.

Production of weekly wet season water type maps (Figure B-1, a)

Weekly wet season water type composites are then created to minimise the image area contaminated by dense cloud cover and intense sun glint (Álvarez-Romero *et al.*, 2013). The maximum FU value of each pixel/week was used to keep the colour class with the highest turbidity level for each wet season week. The weekly composite maps were cleaned to remove single or small clusters of cells sometimes misclassified by the FU satellite algorithm in the offshore regions of the Great Barrier Reef (including, for example, around coral reefs due to bottom interference and residual glint contamination). The aim of cleaning is to minimise the image area contaminated by dense cloud cover and intense sun glint, and to remove shallow water interference around reefs. In all cases the effect of these phenomena can be that offshore waters are misclassified as, for example, primary waters ($FU \geq 10$). To minimise these effects an automated process is applied to the rasters that has the effect of sequentially infilling contiguous water-type areas one colour class at a time from FU1 through to FU21 using Python 2.7.3 (Python Software Foundation, 2012) and ArcGIS 10.7 (ESRI, 2019). Infilling was achieved using the following steps: 1) Raster to Polygon conversion (not simplified), 2) Union (no gaps) then 3) removal, using Erase, of an external polygon, and 4) Polygon to Raster conversion. This process generates a separate raster mask (values 1 or 0) for each colour class, and the final cleaned raster is created by adding the component raster masks. Whilst this process is effective at removing noise offshore it can occasionally have the effect of removing areas of turbid coastal and plume water if they are not directly connected to the coast. To counter this, a final step is included in the cleaning process whereby waters classified as FU classes ≥ 10 i.e., in the cleaned raster are replaced with pixels of FU classes ≥ 10 in the original raster, using Con (Spatial Analyst). Thus, pixels adjacent to the coast that are classified as highly turbid water are kept and pixels within otherwise contiguous water types offshore are removed.

Production of annual, multi-annual and typical Wet and Dry wet season water type maps (Figure B-1b)

Weekly wet season water type composites are thus overlaid in ArcGIS (i.e., presence/absence of one wet season water type) and normalised, to compute each year a seasonal normalised frequency maps of occurrence of wet season water type. Pixel (or cell) values of these maps range from 1 to 22; with a value of 22 meaning that one pixel has been exposed 22 weeks out of 22 weeks of the wet season. Annual frequency maps are normalised (0–1) and overlaid in ArcGIS to create multi-annual normalised frequency composites of occurrence of wet season water types. Multi-annual composites are calculated over different time frames, including (i) the long-term (2002–03 to 2017–18: 16 wet seasons) and (ii) a typical recovery period for Reef corals (2012–2017).

Composite frequency maps are also produced to represent typical wet year and dry year conditions. To account for broad-scale spatial variability in wet season river flows, wet- and dry-year maps are first produced separately by averaging frequency maps from the wettest and driest years in each NRM region. Wet years are defined as those in the top quartile for total catchment discharge in the NRM region; dry years as those in the bottom quartile (Figure B-2). The wet-year maps for each NRM region are combined into a single, composite, Reef-wide map using the maximum value of the input rasters. This method captures wet-year plume conditions across the entire Reef even if the most significant plume events originate outside the NRM (for example, if Fitzroy plumes are dominant in the Mackay-Whitsunday region the top-quartile discharges from the Fitzroy are already included in the composite raster). Conversely, the dry-year maps are combined into a Reef-wide composite map using the

minimum value of the input rasters, which thus represents the least extensive plume from an average of the driest years in each NRM region.

Except for the coral recovery period, reference maps (long-term, Wet and Dry frequency maps) are updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure they remains valid as a representative period and to improve their accuracy as more satellite data are available. Last update was in 2019.

The daily, weekly and wet season frequency maps are used to illustrate the wet season conditions for every year, to assess the extent of river flood plumes and resuspension events in the Reef and to compare seasonal with long-term trends, as well as trend in water composition during typical dry and wet years. Results are presented in the main report and in Appendix C-6.

Table B-2: Wettest and driest years used to compute the Typical Wet and Typical Dry Composite frequency maps in each NRM region.

Region	Wet years				Dry years				
Cape York	2004	2006	2011	2019	2003	2005	2007	2012	2016
Wet Tropics	2009	2011	2018	2019	2003	2005	2015	2016	2017
Burdekin	2008	2009	2011	2019	2003	2004	2014	2015	2016
Mackay-Whitsunday	2008	2010	2011	2012	2003	2004	2006	2015	2018
Fitzroy	2008	2010	2011	2013	2004	2005	2006	2007	2019
Burnett-Mary	2010	2011	2012	2013	2005	2006	2007	2014	2019

Surface loading maps (Figure B-1c)

Surface loading maps that model the transport of land-sourced pollutants (DIN, TSS and PN) are created using the eReefs marine model tracers for each river plume and dispersion of end of catchment loads (Figure B-1).

Susceptibility assessment (Figure B-1d)

Frequency maps are also compared with ecological health information collected through the coral reef and seagrass components of the MMP (McKenzie *et al.*, 2019, Thompson *et al.*, 2019) to better understand the susceptibility of the seagrass meadow and coral reef ecosystems to water quality conditions (Figure B-1d).

Mean long-term water quality concentrations across water types and colour classes

Additional information on wet season conditions is reported by characterising the long-term water quality concentrations across water types and colour classes (Figure B-2).

Match-ups between sampled date and corresponding weekly wet season water type maps are performed at site location basis using the *extract tool* of the raster package (Hijmans *et al.*, 2015) with bilinear interpolation method in R 3.2.4. This tool interpolates from the values of the four nearest raster cells (R Core Team, 2019). Several land-sourced pollutants are investigated through match-ups between *in situ* data and the six colour class maps, including DIN, PO₄, PP, PN, TSS, Chl-*a*, CDOM and *K_D* or Secchi depth. Boxplots of water quality parameters across water types and colour classes (Figure 4-4) and the mean long-term water quality concentrations across the three wet season water types in all focus regions (Figure B-2) are presented.

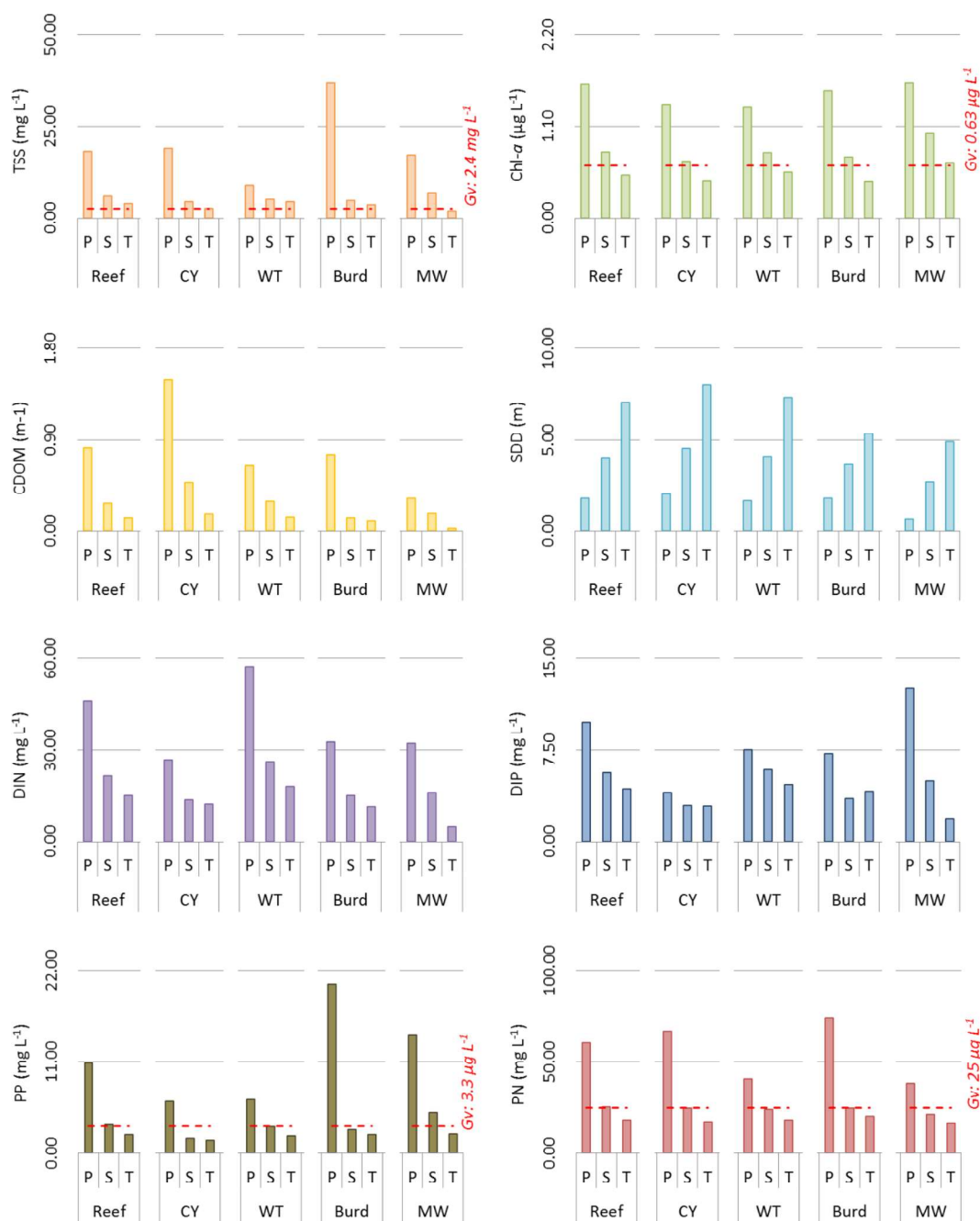


Figure B-2: Mean long-term (2004–2019) water quality concentrations across the three wet season water types in all focus regions. Red lines show the Reef-wide wet season GVs (Table B-3). The Burdekin region has the greatest average TSS, PP, and PN concentrations in the primary water type, which exceeded the long-term Reef-scale average. The greatest mean DIN and CDOM concentrations are measured in the primary water types of the Wet Tropics and Cape York regions, respectively. The greatest mean Chl-a concentrations are measured in the primary water types of the Mackay-Whitsunday and Burdekin regions. Except for CDOM and PN concentrations, the Cape York region shows the lowest concentrations of water quality parameters of all regions. Mean long-term water quality concentrations includes samples collected from the enclosed coastal water body (Table B-1), where high TSS, PN and PP concentrations are likely to contribute to exceedances of the Reef-wide GVs.

Detailed summaries of water quality parameters (mean, standard deviation, minimum, maximum and number of values for each pollutant across colour classes and water types) for the long-term and reporting year are provided in [Appendix C-4](#). Long-term water quality values are calculated using all surface data (<0.2 m) collected between December and April by JCU (since 2004), AIMS and the CYWMP (since 2016–17). Long-term water quality values are reviewed and updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure the water type characterisation remains valid as a representative period and to improve its accuracy as more field data are collected every wet seasons. Last update was in 2019, using field data collected from 2004 to 2019. Before 2016–17, the mean water quality concentrations were calculated using the JCU dataset only, assuming it was representative of high flow conditions. Long-term mean DIN, PP and PN concentrations were calculated as $DIN = NO_2 + NO_3 + NH_3$, $PP = TP - TDP$ and $PN = TN - DIN$, respectively.

Exposure maps and exposure assessment (Figure B-1e)

Information on the long-term pollutant concentrations measured in the WS colour classes are compared to published water quality guideline values and combined with frequency maps of occurrence of wet season colour classes, are used in a “*magnitude x likelihood*” risk management framework to develop surface exposure maps (also referred to as potential risk maps in some Reef studies). Different frameworks have been used to estimate the exposure and potential risk from exposure, and are described in Petus *et al.* (2014a, 2016), Waterhouse *et al.* (2017), Gruber (2019), and used in the MMP reports before 2015–16. In a collaborative effort between the MMP monitoring providers (JCU water quality and seagrass teams and the AIMS coral monitoring team), an updated exposure assessment framework was developed in 2015–16 (modified from Petus *et al.*, 2016), where the ‘potential risk’ corresponds to an exposure to above guideline concentrations of land-sourced pollutant during wet season conditions and focuses on the TSS, Chl-*a*, PP and PN concentrations.

The ‘*magnitude of the exposure*’ corresponds to the long-term concentration of pollutants (proportional exceedance of the guideline) mapped through the primary, secondary and tertiary water types. The ‘*likelihood of the exposure*’ is estimated by calculating the frequency of occurrence of each wet season water type. The exposure for each of the water quality parameters defined is as the proportional exceedance of the guideline multiplied by the likelihood of exposure in each of the wet season water type and calculated as below. For each cell (500 m x 500 m):

For each pollutant (Poll.) the exposure in each wet season water type (primary or secondary or tertiary, $Poll_expo_{water\ type}$) is calculated:

$$Poll_expo_{water\ type} = magnitude_{water\ type} \times likelihood_{water\ type}$$

$$magnitude_{water\ type} = ([Poll.]_{water\ type} - guideline) / guideline$$

$$likelihood_{water\ type} = frequency_{water\ type}$$

where *water type* is the primary, secondary or tertiary wet season water types, $[Poll.]_{water\ type}$ is the wet season or long-term mean TSS, Chl-*a*, PN, or PP concentration measured in each respective wet season water types and *guideline* is the Reef-wide wet season GV from De’ath and Fabricius (2008) for TSS, Chl-*a*, PP, and PN (Table B-3).

Table B-3: Reef-wide wet season guideline values used to calculate the exposure score for satellite exposure maps. These guidelines are based on seasonal adjustments to reef-wide annual guidelines (Great Barrier Reef Marine Park Authority, 2010), where wet season guidelines are +20% for TSS, PN, and PP, and +40% for Chl-*a* of annual guidelines (De’ath and Fabricius 2008).

Parameter	Unit	Reef-wide
Chlorophyll <i>a</i>	µg L ⁻¹	0.63

Parameter	Unit	Reef-wide
Particulate nitrogen	$\mu\text{g L}^{-1}$	25
Particulate phosphorus	$\mu\text{g L}^{-1}$	3.3
Suspended solids	mg L^{-1}	2.4

These GVs are compared against the mean long-term concentrations to calculate the exposure score in the satellite exposure maps (proportional exceedance of the guideline). Mean long-term water quality concentrations are calculated using all available surface water quality data in all Reef marine regions and water bodies (Table B-4). The variability in the number of samples between regions and water types is primarily driven by the sampling design which was reviewed in 2014. The small number of samples in the Burnett Mary region reflects the geographic extent of the MMP; with a majority of the samples collected by JCU in the 2011 and 2013 flood events when the design of the event monitoring was more opportunistic across the whole Reef. The relatively small number of samples in the Marine area reflects the geographic focus of the MMP design which is largely constrained to the inshore and mid-shelf waters. The last update in the mean long-term concentrations was in the 2018–19 reporting year (Gruber *et al.*, 2020), using field data collected from 2004 to 2019. Note also that the long-term and GBR wide water quality concentrations are used rather than the seasonal and/or regional mean concentrations in water type to avoid bias due to differential regional and seasonal sampling distribution.

Table B-4: Number of collected in situ samples used in exposure scoring by region and water type. Samples include all wet season (Dec–April) surface samples since 2004 (from JCU) and since the 2016–17 water year (AIMS and the CYWMP).

Region	Water type	Number of samples								
		Salinity	Secchi depth	TSS	Chl-a	CDOM	DIN	PO4	PP	PN
Cape York	Primary	125	109	125	136	101	138	137	91	135
	Secondary	124	120	124	132	51	131	132	98	131
	Tertiary	61	47	61	61	25	63	63	52	63
	Marine	9	4	9	9	3	9	9	8	9
Wet Tropics	Primary	224	164	375	368	357	321	324	301	309
	Secondary	244	289	482	495	438	475	476	446	447
	Tertiary	109	121	172	172	141	169	169	166	167
	Marine	17	22	29	29	27	28	28	20	20
Burdekin	Primary	100	81	132	131	86	129	131	126	127
	Secondary	104	146	188	187	132	187	187	177	176
	Tertiary	28	35	47	45	37	47	47	43	45
	Marine	14	16	18	21	15	22	22	19	19
Mackay - Whitsunday	Primary	12	9	26	23	25	26	26	24	24
	Secondary	44	34	86	81	53	86	86	77	78
	Tertiary	10	9	18	18	9	17	17	17	17
Fitzroy	Primary	15		76	77	56	77	78	75	76
	Secondary	13		34	48	43	52	54	53	53

	Tertiary	2		2	7	4	7	7	6	7
	Marine			6	6	1	6	6	6	6
Burnett-Mary	Primary	7	7	20	20	11	11	20	20	11
	Secondary	2	5	12	12	5	8	12	11	8
	Tertiary	1		1	1		1	1	1	1
	Marine			3	3	1	3	3	3	3
Reef-wide	Primary	483	370	754	755	636	702	716	637	682
	Secondary	531	594	926	955	722	939	947	862	893
	Tertiary	211	212	301	304	216	304	304	285	300
	Marine	40	42	65	68	47	68	68	56	57

For each pollutant, the total exposure ($Poll_expo$) is calculated at the exposure for each of the wet season water types:

$$Poll_expo = Poll_expo_{Primary} + Poll_expo_{Secondary} + Poll_expo_{Tertiary}$$

The overall exposure score ($Score_expo$) is calculated as the sum of the total exposure for each of the water quality parameters:

$$Score_expo = TSS.exp + Chla.exp + PP.exp + PN.exp$$

For example, using the long-term mean Chl-a values measured during high flow conditions in the primary, secondary and tertiary water type:

$$Chla_exp_{Primary} = \frac{1.61-0.63}{0.63} \times frequency_{water\ type\ (0-1,cell-specific)}$$

$$Chla_exp_{Secondary} = \frac{0.80-0.63}{0.63} \times frequency_{water\ type\ (0-1,cell-specific)}$$

$$Chla_exp_{Tertiary} = 0 \text{ as Chl-a levels are below the guideline for Chl-a;}$$

The total exposure for Chl-a:

$$Chla_expo = Chla_expo_{Primary} + Chla_expo_{Secondary} + Chla_expo_{Tertiary}$$

The overall exposure scores are then grouped into four potential classes (I to IV) based on a “Natural Break (or Jenks)” classification. Jenks is a statistical procedure, embedded in ArcGIS that analyses the distribution of values in the data and finds the most evident breaks in it (i.e., the steep or marked breaks; Jenks and Caspall, 1971). The Jenks classification determine the best arrangement of values into different classes by reducing the variance within classes and maximising the variance between classes.

The exposure classes are defined by applying the Jenks classification to the mean long-term exposure map, because this map presented the highest number of observations. Using the 2003–2018 mean exposure map, categories were defined as [$>0-0.9$] = cat. I, [$0.9-3.2$] = cat. II, [$3.2-7.5$] = cat III and [>7.5] = cat IV). Category I and areas mapped as “exposure = 0 (no exposure)”, are re-grouped into a unique category I (no or very low exposure). These categories are to all exposure composites created (seasonal, coral recovery period, typical wet and dry periods).

The methods presented above are slightly different than methods used in the two previous wet season’s reports (2016–17 and 2017–18 wet seasons) where (i) seasonal mean water quality concentrations across water types were used to produce the seasonal exposure map and (ii) exposure maps were reclassified using four equally-distributed colour classes.

Changes in 2019 (using only long-term mean water quality concentrations and a Jenk's classification of the exposure maps) were made in response to: (i) concerns that water quality concentrations collected in a specific wet season would likely get biased toward the sample size and the location and timing of sampling in this particular wet season conditions and (ii) that the equally distributed categories were not responsive enough to changes in environmental pressures of each year.

Exposure maps are produced for the whole of the Reef, for all focus regions and over different time frames: for the current reporting wet season, over the long-term (2002–03 to 2018–19: 16 wet seasons), over a documented recovery period for coral reefs (2012–2017 period) and representation of typical wet-year and dry-year conditions. Except for the coral recovery period, reference maps (long-term, Wet and Dry frequency maps) are updated every 4 years (and/or in the case of extremely wet year or specific event patterns) to ensure they remain valid as a representative period and to improve their accuracy as more satellite data are available. Last update was in 2019. Finally, assessments of ecosystem exposure are made through the calculation of the areas (km²) and percentages (%) of each region, coral reefs and seagrass meadows affected by different categories of exposure. The area and percentage are calculated as a relative measure between regions and waterbodies. The difference in percentages between 2019 and in the long-term is also calculated.

Figure B-3 presents the marine boundaries used for the Marine Park, each NRM region, the Reef waterbodies and the seagrass and coral reefs ecosystems. The area (km²) and percentages of seagrass and coral reefs in the Reef and regional waterbodies is indicated in Figure B-3. We assumed in this study that the seagrass shapefile can be used as a representation of the actual seagrass distribution. It is known, however, that absence on the composite map does not definitively equate to absence of seagrass and may also indicate un-surveyed areas.

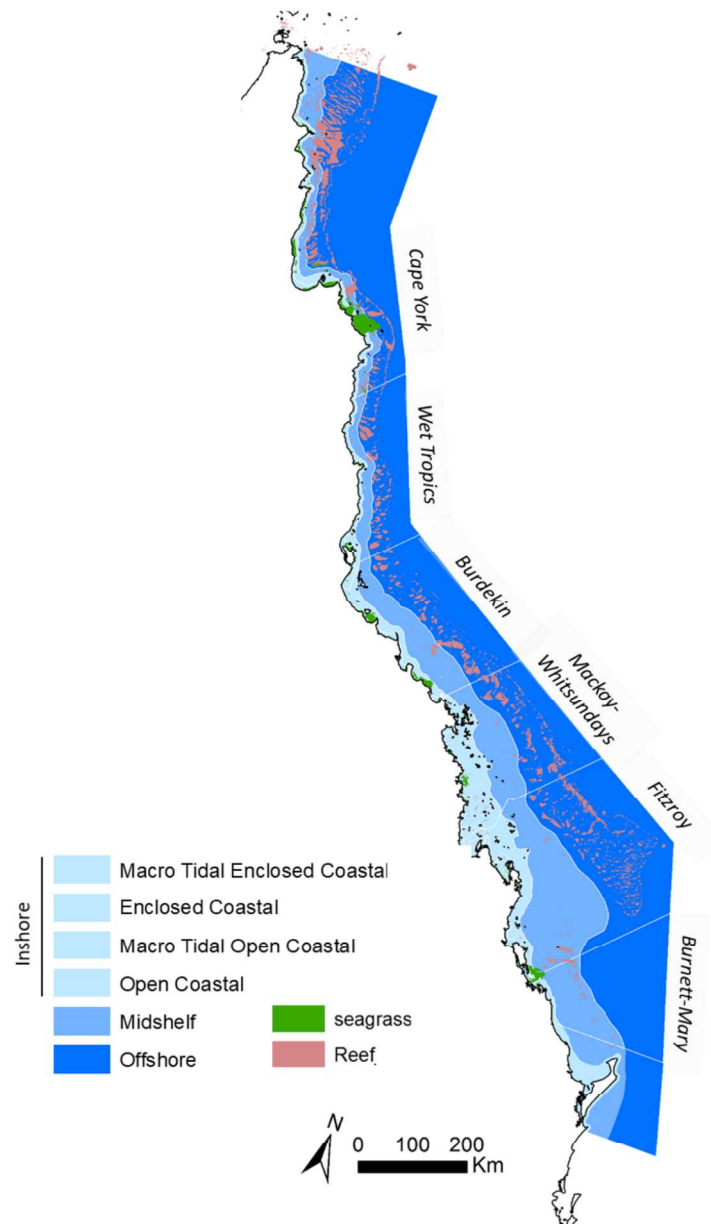


Figure B-3: Boundaries used for the Marine Park, each NRM region and the coral reefs and seagrass ecosystems. Coral reef and NRM layers derived from the Authority, supplied 2013. Seagrass layer is a composite of surveys conducted by Department of Agriculture and Fisheries, Qld.

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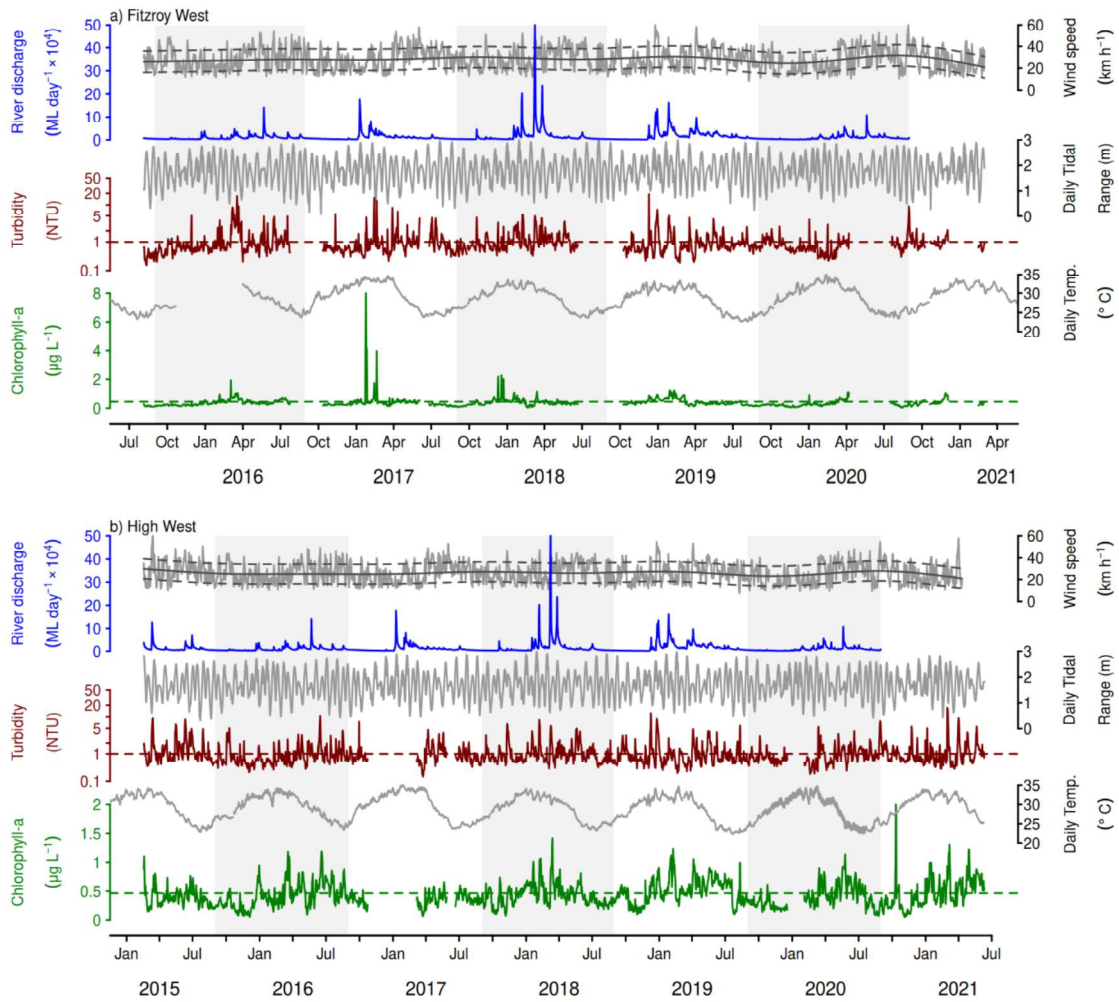
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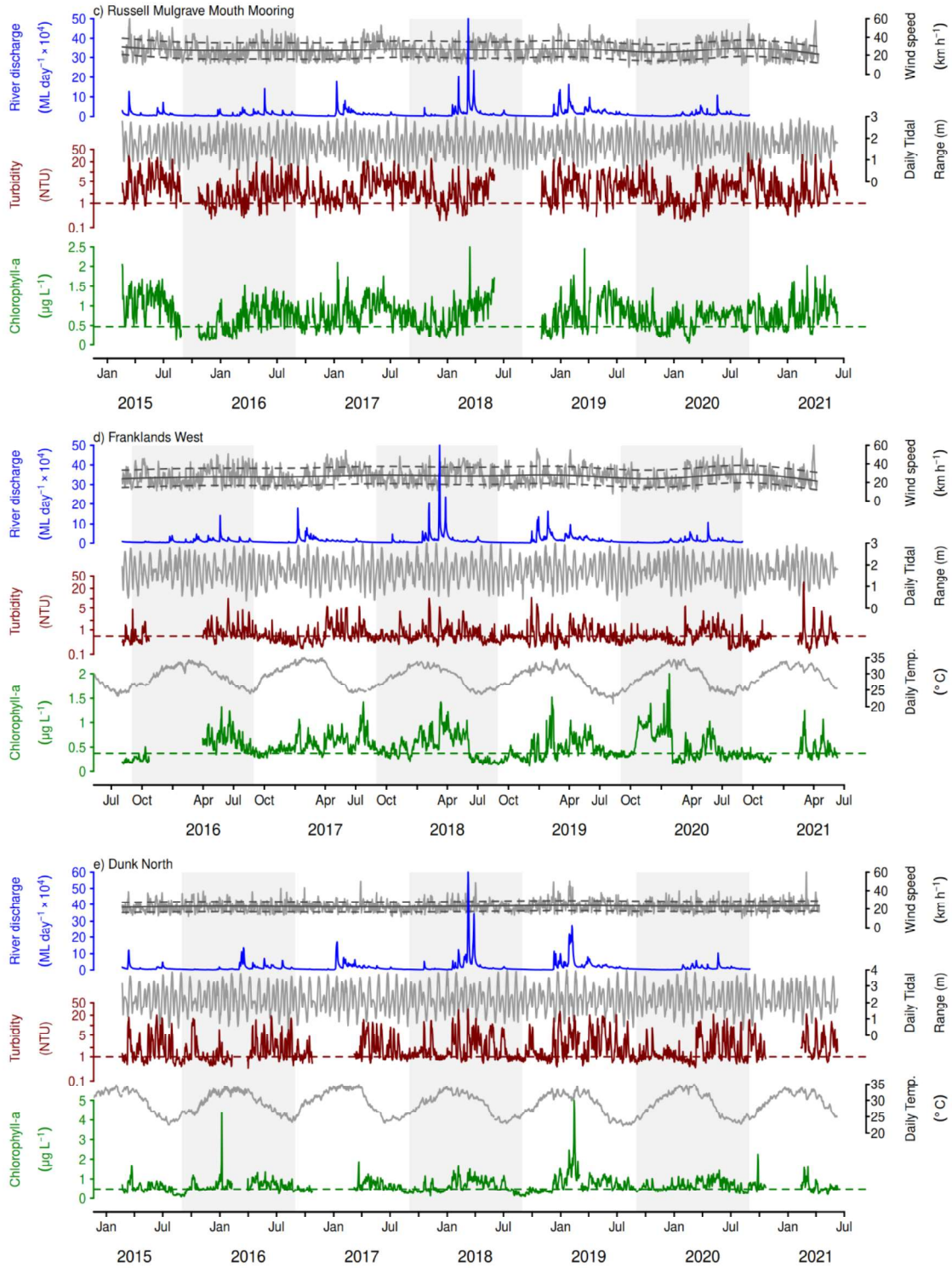
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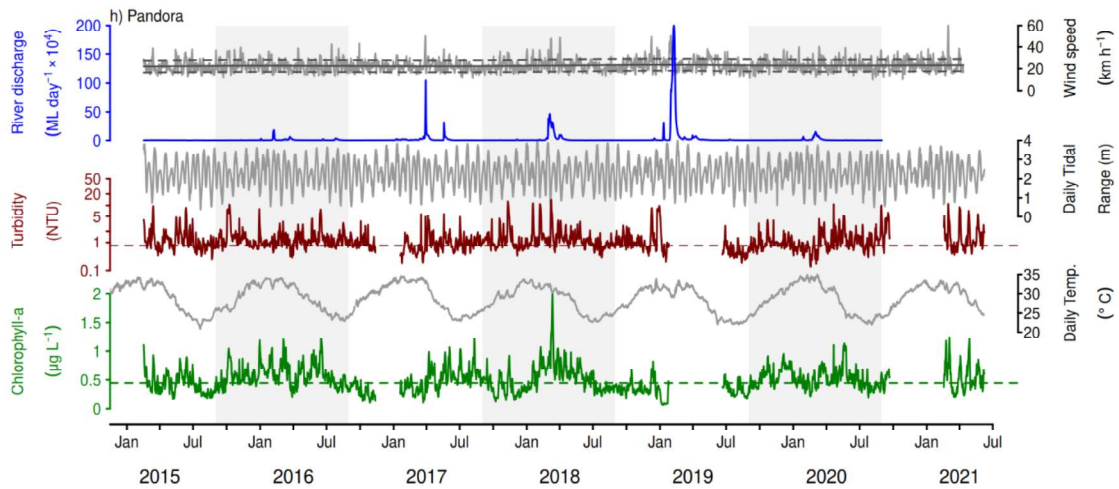
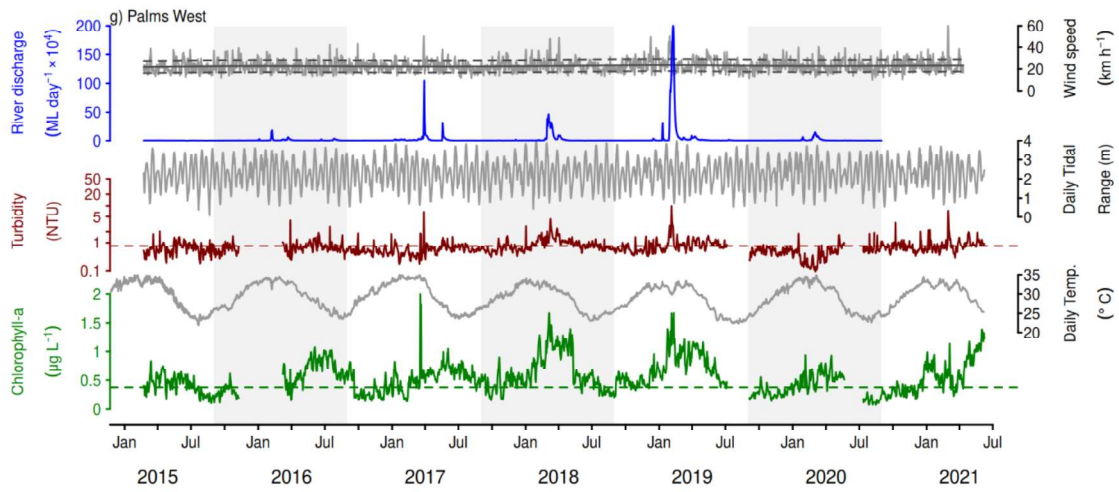
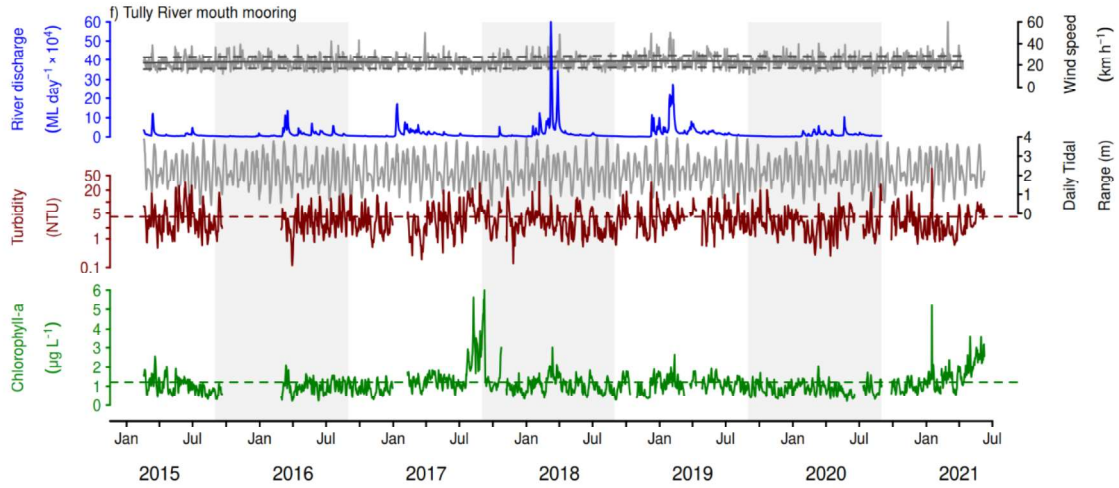
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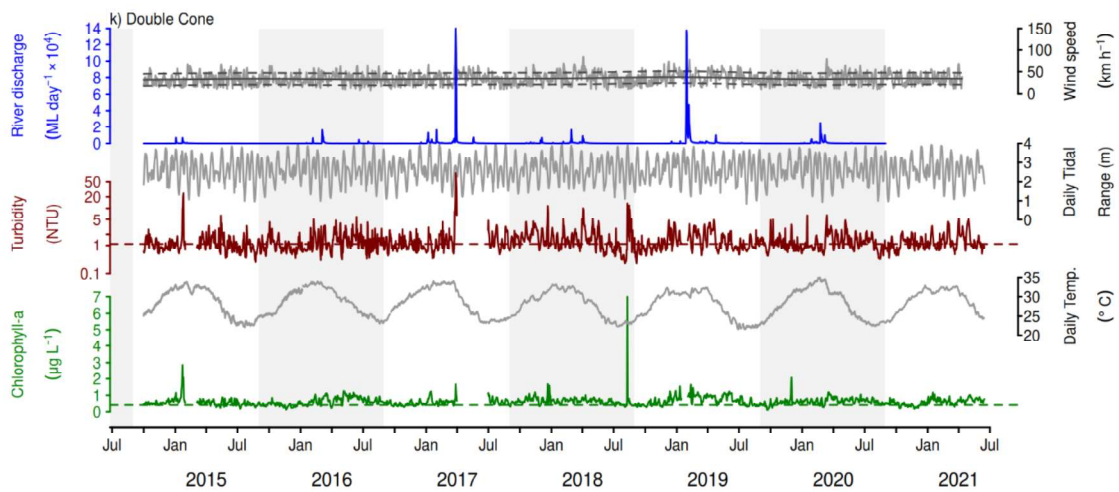
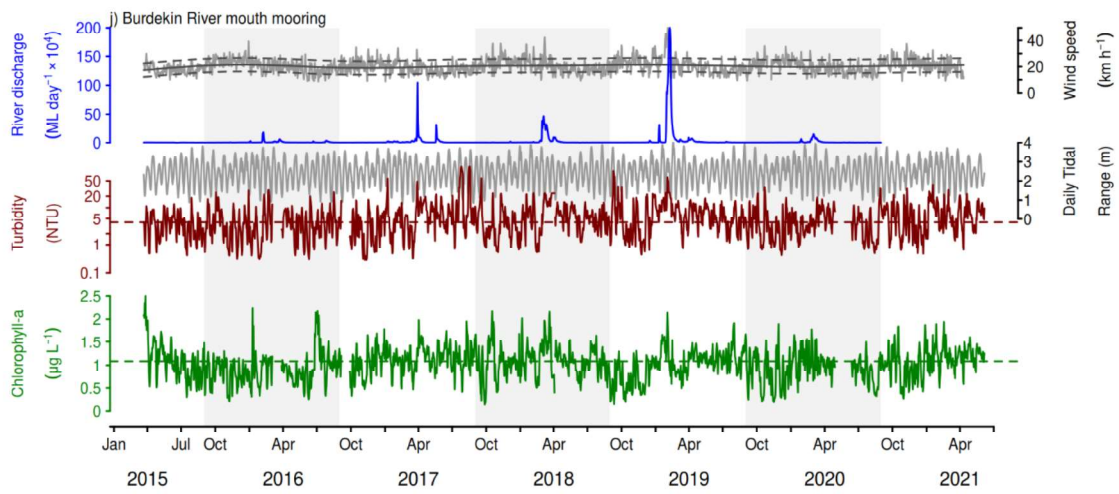
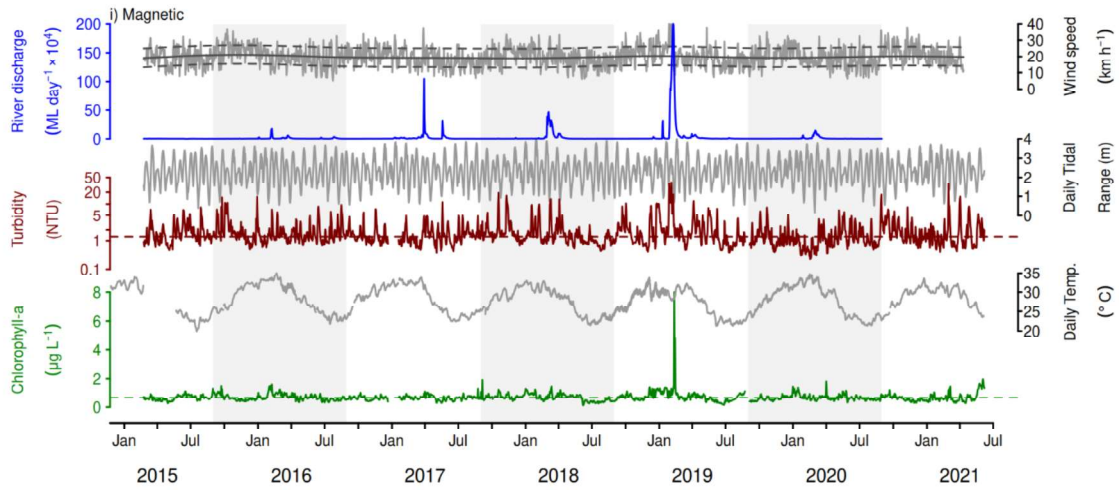
Appendix C: Additional information

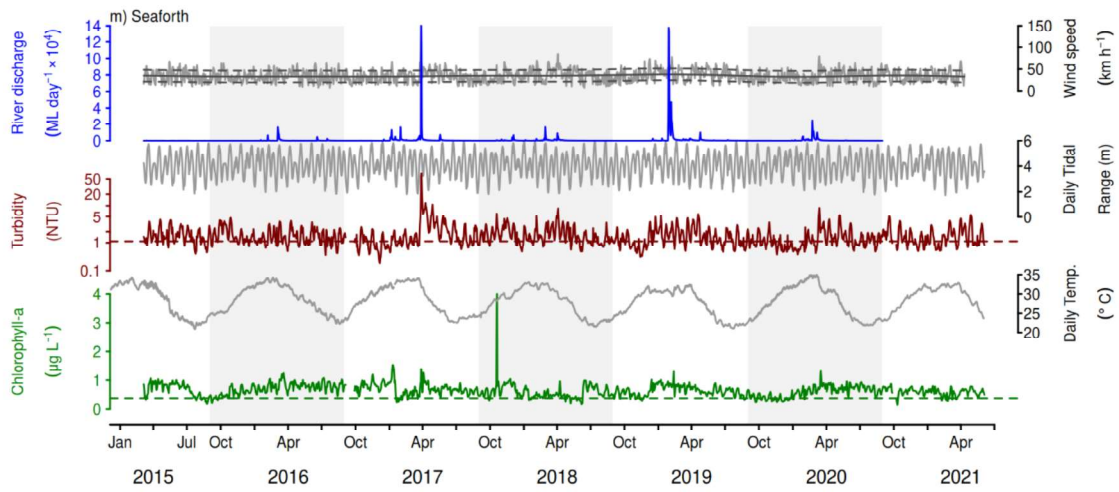
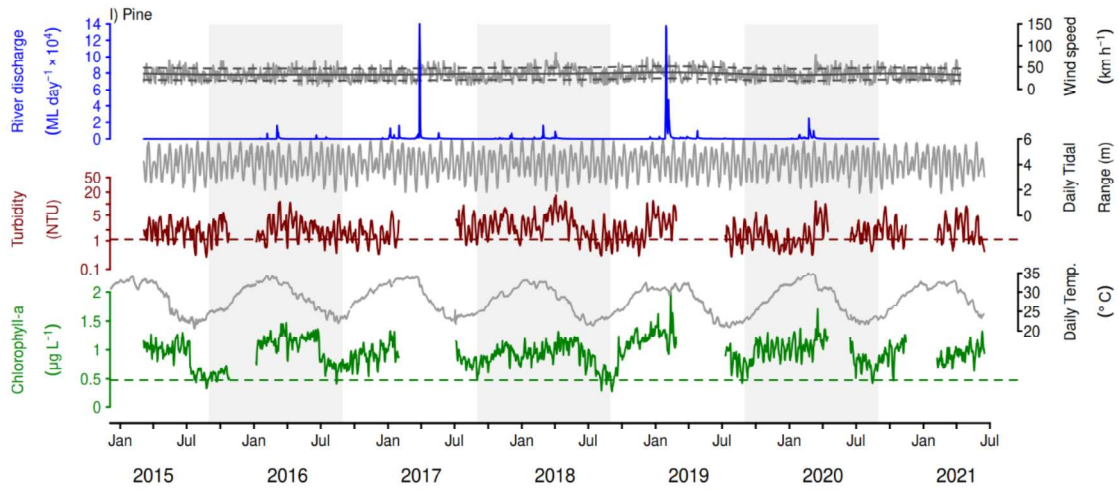
C-1 Continuous FLNTU data











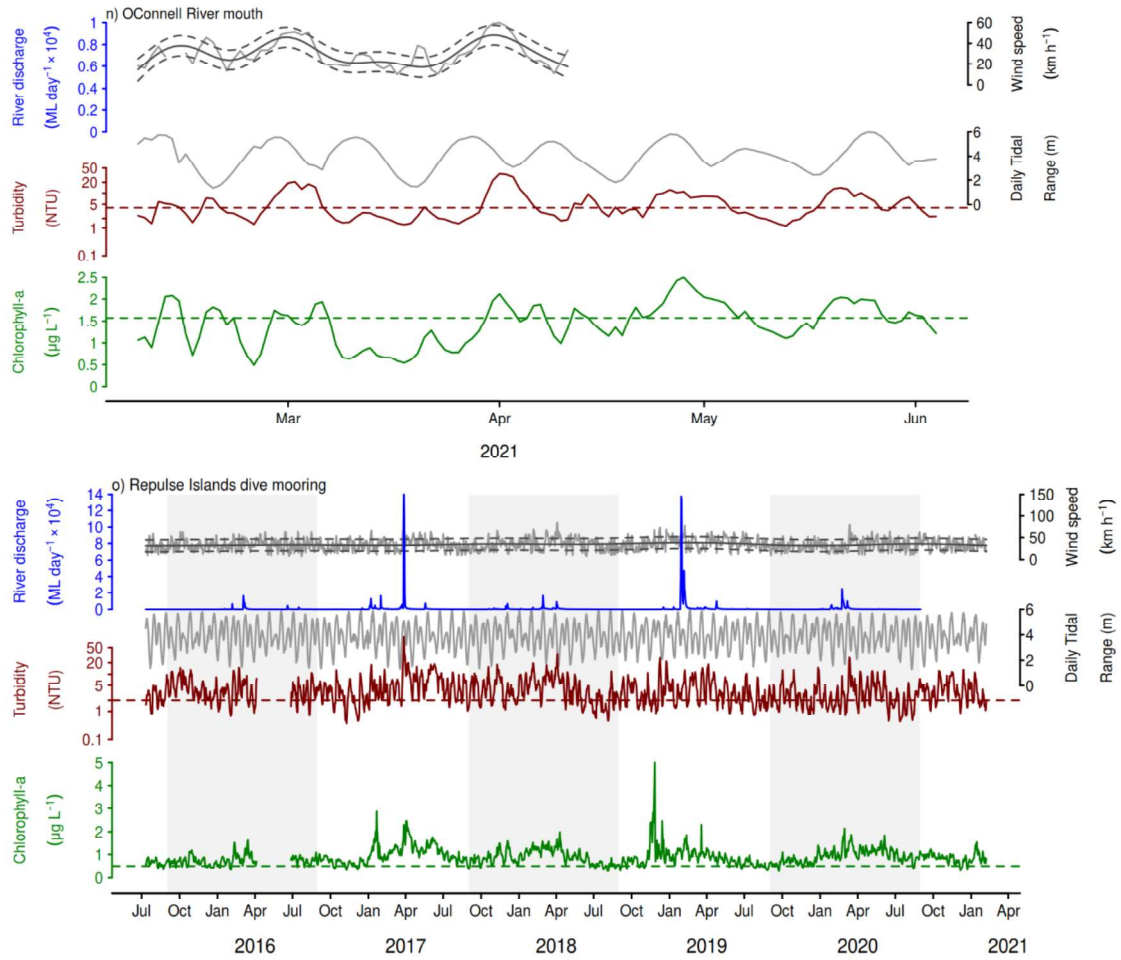


Figure C-1: Time-series of daily means of chlorophyll and turbidity collected by moored ECO FLNTUSB instruments; coloured dashed lines represent the Water Quality GV's. Daily river discharge from the nearest river, daily wind speeds from the nearest weather stations, daily tidal range from the nearest tidal gauge, and daily temperature are also shown. Locations of loggers are shown in Figure 2-1 and Section 5 and panels continue on additional pages below: a) Fitzroy West; b) High West; c) Russell-Mulgrave Mouth Mooring; d) Franklands West; e) Dunk North; f) Tully Mouth Mooring; g) Palms West; h) Pandora; i) Magnetic; j) Burdekin Mouth Mooring; k) Double Cone; l) Pine; m) Seaforth; n) O'Connell River, and o) Repulse Island.

C-2 Continuous temperature and salinity

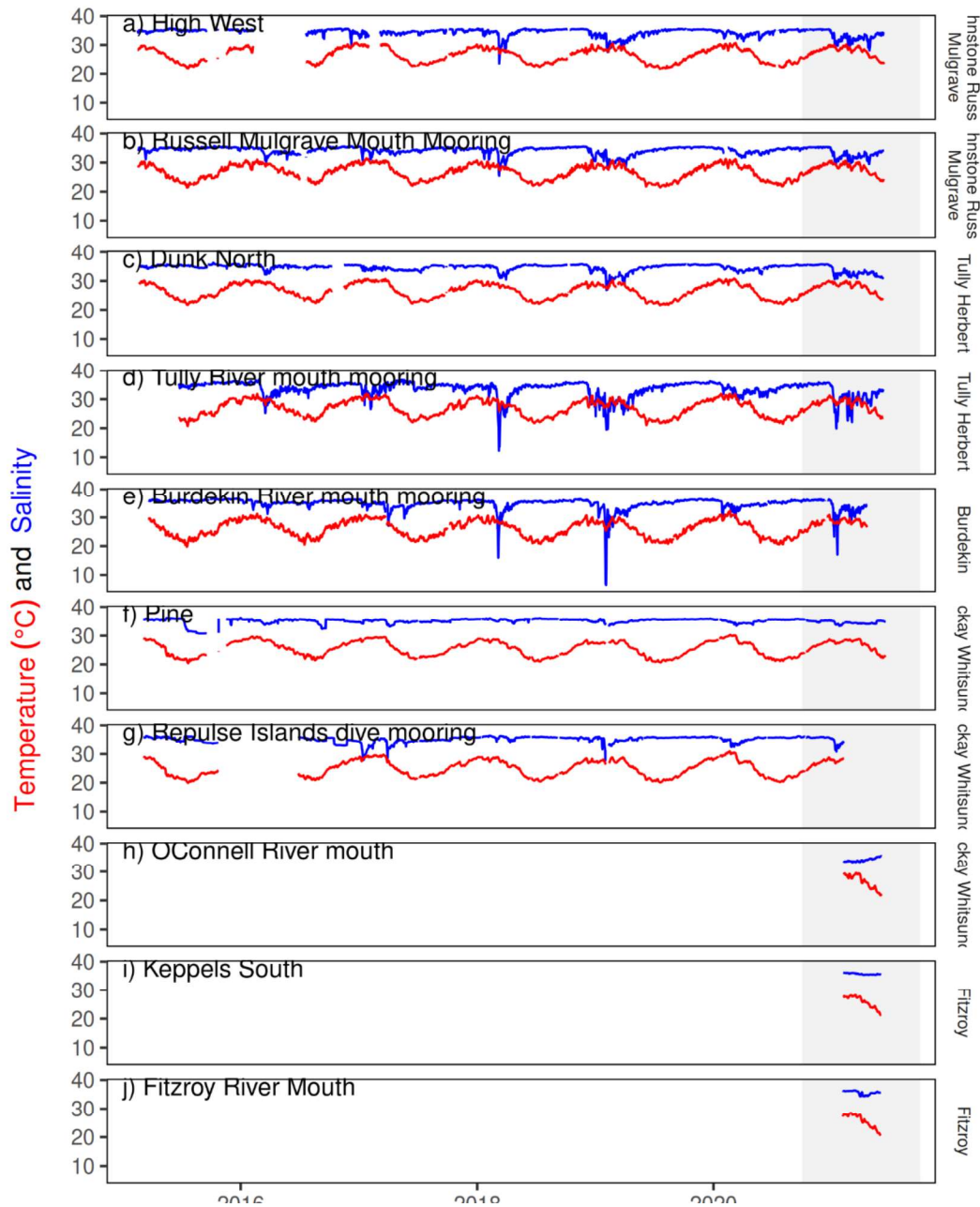


Figure C-2: Time-series of daily means of temperature and salinity derived from moored loggers (Sea-Bird Electronics SBE37s). Sub-figures represent instrument locations at: a) High West, b) Russel Mulgrave Mouth Mooring, c) Dunk North, d) Tully River Mouth Mooring, e) Burdekin Mouth Mooring, f) Pine, g) Repulse, h) O'Connell River mouth, i) Keppels South, and j) Fitzroy River mouth.

C-3 Summary statistics for all sites

Table C-1: Summary statistics for water quality parameters at individual monitoring sites from 1 September 2020 to 31 August 2021. N = number of sampling occasions. See Section 0 for descriptions of each analyte and its abbreviation. Mean and median values that exceed available Water Quality Guidelines (DERM, 2009; Great Barrier Reef Marine Park Authority, 2010; State of Queensland, 2020) are shaded in red. Averages that exceed wet season guidelines are shaded in yellow. DOF is direction of failure ('H' = high values fail, while 'L' = low values fail).

Region	Site	Measure	N	Mean	Median	Quantiles				Guidelines								
						Q05	Q20	Q80	Q95	DOF	Location	Annual	Dry	Wet				
Cape York	PRN04 (PRN04)	DIN ($\mu\text{g L}^{-1}$)	5															
		DOC ($\mu\text{g L}^{-1}$)	5	2395	2448	1940	2173	2620	2793									
		DON ($\mu\text{g L}^{-1}$)	5															
		DOP ($\mu\text{g L}^{-1}$)	5	6.35	6.66	4.52	4.85	7.23	8.49									
		Chl-a ($\mu\text{g L}^{-1}$)	5	0.33	0.28	0.21	0.22	0.46	0.49		H	Median	0.27					
		NO _x ($\mu\text{g L}^{-1}$)	5	1.9	0.7	0.43	0.55	2.55	5.26		H	Median	0.35					
		PN ($\mu\text{g L}^{-1}$)	5	26.48	23.14	20.59	21.49	32.6	34.58		H	Mean						
		PO ₄ ($\mu\text{g L}^{-1}$)	5	0.71	0.77	0.31	0.31	0.99	1.18		H	Median	0.62					
		POC (mg L ⁻¹)	5	133.08	114.39	91.09	103.01	176.08	180.83									
		PP ($\mu\text{g L}^{-1}$)	5	1.85	1.87	0.65	1.35	2.27	3.09		H	Mean						
		Secchi (m)	5	9.01	8.8	6.44	7.46	10.95	11.4		L	Mean	10					
		SiO ₄	5	204.37	131.11	81.14	109.45	223.25	476.9									
		TSS (mg L ⁻¹)	5	0.96	0.92	0.57	0.65	1.09	1.55		H	Mean						
			5	0.96	0.92	0.57	0.65	1.09	1.55		H	Median	1.5					

Chl-a (µg L ⁻¹)	5	0.29	0.26	0.14	0.16	0.45	0.47	H	Median			0.7
NO _x (µg L ⁻¹)	5	24.64	18.9	2.32	7.2	40.71	54.07	H	Median			1.5
PN (µg L ⁻¹)	5	91.57	65.84	41.44	43.12	111.01	196.42	H	Mean			
PO ₄ (µg L ⁻¹)	5	91.57	65.84	41.44	43.12	111.01	196.42	H	Median			
POC (mg L ⁻¹)	5	1.67	1.55	0.5	1.05	2.35	2.91	H	Median			3
PP (µg L ⁻¹)	5	889.92	445.45	333.43	336.55	1150.56	2183.64					
Secchi (m)	5	6.1	5.04	3.35	3.77	7.29	11.07	H	Mean			
SiO ₄	5	6.1	5.04	3.35	3.77	7.29	11.07	H	Median			
TSS (mg L ⁻¹)	5	1.45	1.45	1.45	1.45	1.45	1.45	L	Mean			
DIN (µg L ⁻¹)	5	1.45	1.45	1.45	1.45	1.45	1.45	L	Median			3
DOC (µg L ⁻¹)	5	3237.99	3691.59	1067.14	1973.88	4569.74	4887.6					
DON (µg L ⁻¹)	5	11.56	4.59	3.26	3.85	18.09	28.02	H	Median			4
DOP (µg L ⁻¹)	5											
Chl-a (µg L ⁻¹)	5	2651	2489	1859	2165	3045	3696					
NO _x (µg L ⁻¹)	5	6.13	5.57	4.74	5.02	6.69	8.64					
PN (µg L ⁻¹)	5	0.26	0.23	0.18	0.2	0.28	0.41	H	Median	0.27		
PO ₄ (µg L ⁻¹)	5	1.32	1.05	0.53	0.87	2.04	2.09	H	Median	0.35		
DOC (µg L ⁻¹)	5	24.5	24.44	20.06	21.32	27.92	28.76	H	Mean			
DON (µg L ⁻¹)	5	24.5	24.44	20.06	21.32	27.92	28.76	H	Median	18		
DOP (µg L ⁻¹)	5	1.08	0.77	0.37	0.56	1.86	1.86	H	Median	0.62		

PRS05
(PRS05)

	POC (mg L ⁻¹)	5	114.32	112.14	94.73	100.13	129.82	134.8					
	PP (µg L ⁻¹)	5	1.88	1.79	1.6	1.62	2.01	2.37	H	Mean			
		5	1.88	1.79	1.6	1.62	2.01	2.37	H	Median	2		
	Secchi (m)	5	10.53	10.2	8.1	9	11.88	13.47	L	Mean	10		
		5	10.53	10.2	8.1	9	11.88	13.47	L	Median			
	SiO ₄	5	111.66	115.03	65.53	76.74	148.09	152.89					
	TSS (mg L ⁻¹)	5	1.12	0.66	0.4	0.49	1.86	2.17	H	Mean			
		5	1.12	0.66	0.4	0.49	1.86	2.17	H	Median	1.5		
	DIN (µg L ⁻¹)	5											
	DOC (µg L ⁻¹)	5	2700	2552	2274	2380	3053	3242					
	DON (µg L ⁻¹)	5											
	DOP (µg L ⁻¹)	5	4.89	4.8	4.48	4.66	5.03	5.5					
	Chl-a (µg L ⁻¹)	5	0.32	0.25	0.17	0.22	0.43	0.51	H	Median	0.36	0.25	0.46
	NO _x (µg L ⁻¹)	5	0.82	0.49	0.29	0.34	1.35	1.62	H	Median	0.35	0.32	0.45
PRS2.5 (PRS2.5)	PN (µg L ⁻¹)	5	28.01	27.34	22.56	24.72	30.99	34.44	H	Mean	16		
		5	28.01	27.34	22.56	24.72	30.99	34.44	H	Median	18	20	
	PO ₄ (µg L ⁻¹)	5	0.46	0.39	0.31	0.31	0.54	0.77	H	Median	1.4	1.86	0.93
	POC (mg L ⁻¹)	5	133.86	123.2	103.74	110.64	162.28	169.46					
	PP (µg L ⁻¹)	5	2.61	2.62	2.12	2.35	2.93	3.05	H	Mean	2.3		
		5	2.61	2.62	2.12	2.35	2.93	3.05	H	Median	2.6		3
	Secchi (m)	5	6.31	6.25	4.07	5.03	7.26	8.94	L	Mean	10		
		5	6.31	6.25	4.07	5.03	7.26	8.94	L	Median			
	SiO ₄	5	208.17	239.89	100.97	159.71	256.67	283.64					

	TSS (mg L ⁻¹)	5	0.94	0.98	0.49	0.77	1.2	1.25	H	Mean	1.6	
	DIN (µg L ⁻¹)	5	0.94	0.98	0.49	0.77	1.2	1.25	H	Median	1.9	
	DOC (µg L ⁻¹)	5	2716	2726	1945	2321	3208	3378				
	DON (µg L ⁻¹)	5										
	DOP (µg L ⁻¹)	5	5.05	4.8	4.52	4.61	5.61	5.7				
	Chl-a (µg L ⁻¹)	5	0.28	0.31	0.19	0.19	0.35	0.38	H	Median	0.27	
	NO _x (µg L ⁻¹)	5	1.25	0.7	0.32	0.45	2.25	2.51	H	Median	0.35	
Middle Reef (PRBB)	PN (µg L ⁻¹)	5	28.6	28.44	23.12	26.06	31.7	33.68	H	Mean	18	
	PO ₄ (µg L ⁻¹)	5	28.6	28.44	23.12	26.06	31.7	33.68	H	Median	0.62	
	PO ₄ (µg L ⁻¹)	5	0.68	0.77	0.31	0.31	0.96	1.05	H	Median		
	POC (mg L ⁻¹)	5	154.56	161.29	110.52	124.57	183.11	193.32				
	PP (µg L ⁻¹)	5	2.73	2.41	1.99	2.29	2.9	2.9	4.03	H	Mean	
Secchi (m)		5	2.73	2.41	1.99	2.29	2.9	2.9	4.03	H	Median	2
		5	9.2	9.3	6.92	7.28	10.14	12.36	12.36	L	Mean	10
SiO ₄		5	9.2	9.3	6.92	7.28	10.14	12.36	L	Median		
		5	214.58	171.77	110.65	144.27	261.88	384.33				
	TSS (mg L ⁻¹)	5	1.7	1.58	0.53	0.66	2.22	3.51	H	Mean		
	DIN (µg L ⁻¹)	5	1.7	1.58	0.53	0.66	2.22	3.51	H	Median	1.5	
Hannah Island (SR05)	DIN (µg L ⁻¹)	4										
	DOC (µg L ⁻¹)	4	2193	2177	1941	2025	2354	2467				
	DON (µg L ⁻¹)	4										

	DOP (µg L ⁻¹)	4	5.26	5.38	4.61	4.96	5.62	5.76											
	Chl-a (µg L ⁻¹)	4	0.26	0.21	0.17	0.19	0.32	0.43		H	Median	0.27							
	NO _x (µg L ⁻¹)	4	1.23	0.91	0.84	0.84	1.48	2.05		H	Median	0.35							
	PN (µg L ⁻¹)	4	25.87	25.49	14.47	19.64	31.94	37.79		H	Mean								
	PO ₄ (µg L ⁻¹)	4	25.87	25.49	14.47	19.64	31.94	37.79		H	Median	18							
	PO ₄ (µg L ⁻¹)	4	1.2	1.35	0.44	0.82	1.64	1.75		H	Median	0.62							
	POC (mg L ⁻¹)	4	128.09	132.31	73.32	95.73	162.15	176.97											
	PP (µg L ⁻¹)	4	2.27	2.35	1.67	1.92	2.65	2.76		H	Mean								
	PP (µg L ⁻¹)	4	2.27	2.35	1.67	1.92	2.65	2.76		H	Median	2							
	Secchi (m)	4	7.7	8	6.01	6.96	8.56	8.97		L	Mean	10							
	Secchi (m)	4	7.7	8	6.01	6.96	8.56	8.97		L	Median								
	SiO ₄	4	194.33	184.06	89.59	94.17	290.38	313.45											
	TSS (mg L ⁻¹)	4	1.44	1.32	0.91	0.92	1.92	2.15		H	Mean								
	TSS (mg L ⁻¹)	4	1.44	1.32	0.91	0.92	1.92	2.15		H	Median	1.5							
	DIN (µg L ⁻¹)	3																	
	DOC (µg L ⁻¹)	3	2043	1986	1845	1892	2183	2281											
	DON (µg L ⁻¹)	3																	
	DOP (µg L ⁻¹)	3	5.42	5.57	5.02	5.2	5.67	5.71											
	Chl-a (µg L ⁻¹)	3	0.19	0.2	0.12	0.15	0.23	0.25		H	Median	0.36							
	NO _x (µg L ⁻¹)	3	0.47	0.42	0.29	0.34	0.59	0.67		H	Median	0.35							
	PN (µg L ⁻¹)	3	22.37	24.14	17.93	20	25.1	25.58		H	Mean	16							
	PN (µg L ⁻¹)	3	22.37	24.14	17.93	20	25.1	25.58		H	Median	18							

Burkitt Island (SR04)

		3	0.67	0.46	0.33	0.37	0.93	1.16	H	Median	1.4	1.86	0.93
PO ₄ (µg L ⁻¹)		3											
POC (mg L ⁻¹)		3	115.68	133.26	84.62	100.83	134.04	134.43					
PP (µg L ⁻¹)		3	2.04	2.14	1.55	1.75	2.35	2.46	H	Mean		2.3	
		3	2.04	2.14	1.55	1.75	2.35	2.46	H	Median	2.6		3
Secchi (m)		3	7.97	8.1	7.22	7.51	8.46	8.64	L	Mean	10		
		3	7.97	8.1	7.22	7.51	8.46	8.64	L	Median			
SiO ₄		3	171.68	96.49	88.9	91.43	236.88	307.08					
TSS (mg L ⁻¹)		3	2.38	0.88	0.68	0.75	3.71	5.12	H	Mean		1.6	
		3	2.38	0.88	0.68	0.75	3.71	5.12	H	Median	1.9		1.7
DIN (µg L ⁻¹)		4											
DOC (µg L ⁻¹)		4	2194	2200	1821	1941	2450	2560					
DON (µg L ⁻¹)		4											
DOP (µg L ⁻¹)		4	5.54	5.57	4.72	4.92	6.16	6.3					
Chl-a (µg L ⁻¹)		4	0.31	0.24	0.07	0.13	0.46	0.64	H	Median	0.36	0.25	0.46
NO _x (µg L ⁻¹)	SR03 (SR03)	4	0.81	0.84	0.46	0.59	1.04	1.1	H	Median	0.35	0.32	0.45
PN (µg L ⁻¹)		4	34.92	32.69	21.25	25.16	43.78	51.7	H	Mean		16	
		4	34.92	32.69	21.25	25.16	43.78	51.7	H	Median	18		20
PO ₄ (µg L ⁻¹)		4	0.66	0.62	0.36	0.5	0.81	1.01	H	Median	1.4	1.86	0.93
POC (mg L ⁻¹)		4	171.32	183.91	90.49	131.84	215.84	234.53					
PP (µg L ⁻¹)		4	2.6	2.61	2.04	2.19	3.02	3.15	H	Mean		2.3	
		4	2.6	2.61	2.04	2.19	3.02	3.15	H	Median	2.6		3
Secchi (m)		4	4.71	5	2.71	3.56	5.98	6.29	L	Mean	10		

	4	4.71	5	2.71	3.56	5.98	6.29	L	Median		
SiO ₄	4	196.63	184.06	106.61	112.11	276.12	304.25				
TSS (mg L ⁻¹)	4	2.1	1.7	0.77	1.19	2.85	4	H	Mean	1.6	
DIN (µg L ⁻¹)	4	2.1	1.7	0.77	1.19	2.85	4	H	Median	1.9	1.7
DOC (µg L ⁻¹)	4	2471	2512	1943	2061	2896	2942				
DON (µg L ⁻¹)	4										
DOP (µg L ⁻¹)	4	5.05	5.07	4.64	4.85	5.26	5.44				
Chl-a (µg L ⁻¹)	4	0.4	0.4	0.19	0.2	0.61	0.62	H	Median		0.4
NO _x (µg L ⁻¹)	4	1.35	1.58	0.47	1.04	1.75	1.91	H	Median		1.5
PN (µg L ⁻¹)	4	45.8	45.34	24.71	29.12	62.29	67.52	H	Mean		
PO ₄ (µg L ⁻¹)	4	45.8	45.34	24.71	29.12	62.29	67.52	H	Median		
POC (mg L ⁻¹)	4	1.22	1.32	0.65	0.96	1.52	1.66	H	Median		2
PP (µg L ⁻¹)	4	248.11	247.39	100.46	148.3	347.64	396.76				
Secchi (m)	4	4.51	4.17	2.45	2.52	6.36	7.05	H	Mean		
	4	4.51	4.17	2.45	2.52	6.36	7.05	H	Median		
	4	2.98	3.42	0.94	1.83	4.3	4.41	L	Mean		
	4	2.98	3.42	0.94	1.83	4.3	4.41	L	Median		3.1
SiO ₄	4	588.13	432.48	171.12	275.97	838.04	1223.07				
TSS (mg L ⁻¹)	4	5.34	4.12	2.28	3.05	7.15	10.13	H	Mean		
DIN (µg L ⁻¹)	4	5.34	4.12	2.28	3.05	7.15	10.13	H	Median		5

Corbett Reef (NR06)	DOC (µg L ⁻¹)	4	2131	1918	1879	1888	2289	2682													
	DON (µg L ⁻¹)	4																			
	DOP (µg L ⁻¹)	4	5.5	5.19	4.82	4.89	5.98	6.6													
	Chl-a (µg L ⁻¹)	4	0.2	0.16	0.14	0.15	0.23	0.3	0.3	H	Median	0.26									
	NO _x (µg L ⁻¹)	4	2.98	1.98	0.31	0.39	5.18	7.07			Median	0.42									
	PN (µg L ⁻¹)	4	21.85	21.78	16.54	18.8	24.86	27.25			Median	16									
	PO ₄ (µg L ⁻¹)	4	0.89	0.81	0.38	0.59	1.16	1.51			Median	0.39									
	POC (mg L ⁻¹)	4	107.82	94.68	74.01	74.59	135.78	160.02													
	PP (µg L ⁻¹)	4	1.66	1.65	1.09	1.23	2.1	2.26			Mean										
		4	1.66	1.65	1.09	1.23	2.1	2.26			Median	1.9									
	Secchi (m)	4	9.23	10.55	6.4	7.78	10.94	11.13			Mean	17									
		4	9.23	10.55	6.4	7.78	10.94	11.13			Median										
	SiO ₄	4	180.65	90.7	49.76	69.48	255.84	437.49													
	TSS (mg L ⁻¹)	4	1.26	1.29	0.83	1.03	1.5	1.65			Mean										
		4	1.26	1.29	0.83	1.03	1.5	1.65			Median	0.5									
	DIN (µg L ⁻¹)	4																			
DOC (µg L ⁻¹)	4	2355	2061	1947	1962	2630	3173														
DON (µg L ⁻¹)	4																				
DOP (µg L ⁻¹)	4	5.23	5.19	4.56	4.77	5.67	5.95														
Chl-a (µg L ⁻¹)	4	0.24	0.24	0.2	0.21	0.27	0.28			H	Median	0.27									
NO _x (µg L ⁻¹)	4	2.01	1.93	0.39	0.52	3.47	3.76			H	Median	0.35									

NR04 (NR04)	PN (µg L ⁻¹)	4	25.32	25.29	18.57	21.04	29.58	32.1	H	Mean			
		4	25.32	25.29	18.57	21.04	29.58	32.1	H	Median	18		
	PO ₄ (µg L ⁻¹)	4	0.81	0.77	0.38	0.59	1.02	1.3	H	Median	0.62		
	POC (mg L ⁻¹)	4	127.66	124.55	85.17	90.12	163.95	174.49					
	PP (µg L ⁻¹)	4	2.12	1.96	1.56	1.64	2.53	2.91	2.91	H	Mean		
		4	2.12	1.96	1.56	1.64	2.53	2.91	2.91	H	Median	2	
	Secchi (m)	4	8.77	8.88	6.97	7.49	10.1	10.43	10.43	L	Mean	10	
		4	8.77	8.88	6.97	7.49	10.1	10.43	10.43	L	Median		
	SiO ₄	4	242.56	92.84	44.45	68.65	356.57	650.28					
	TSS (mg L ⁻¹)	4	1.77	1.98	0.65	1.35	2.28	2.61	2.61	H	Mean		
		4	1.77	1.98	0.65	1.35	2.28	2.61	2.61	H	Median	1.5	
	DIN (µg L ⁻¹)	4											
	DOC (µg L ⁻¹)	4	2389	2046	1979	2003	2638	3279					
	DON (µg L ⁻¹)	4											
	DOP (µg L ⁻¹)	4	5.03	5.26	4.19	4.68	5.48	5.55					
	Chl-a (µg L ⁻¹)	4	0.26	0.25	0.22	0.23	0.28	0.3	0.3	H	Median	0.36	0.46
	NO _x (µg L ⁻¹)	4	1.45	1.12	0.8	0.9	1.88	2.57	2.57	H	Median	0.35	0.45
	PN (µg L ⁻¹)	4	23.34	19.89	16.51	17.32	27.98	35	35	H	Mean	16	
		4	23.34	19.89	16.51	17.32	27.98	35	35	H	Median	18	20
	PO ₄ (µg L ⁻¹)	4	0.85	0.85	0.64	0.71	0.99	1.06	1.06	H	Median	1.4	0.93
POC (mg L ⁻¹)	4	114.7	102.83	81.56	91.6	133.04	164.44						
	4	2.4	2.08	1.07	1.33	3.33	4.18	4.18	H	Mean		2.3	

PP (µg L ⁻¹)	4	2.4	2.08	1.07	1.33	3.33	4.18	H	Median	2.6	3
Secchi (m)	4	7.38	7.82	4.34	5.66	9.28	9.82	L	Mean	10	
	4	7.38	7.82	4.34	5.66	9.28	9.82	L	Median		
SiO ₄	4	274.79	97.61	68.13	81.66	397.05	729.5				
TSS (mg L ⁻¹)	4	2.12	2.58	0.59	1.46	2.96	3	H	Mean	1.6	
	4	2.12	2.58	0.59	1.46	2.96	3	H	Median	1.9	1.7
DIN (µg L ⁻¹)	4										
DOC (µg L ⁻¹)	4	2301	2353	2015	2138	2484	2513				
DON (µg L ⁻¹)	4										
DOP (µg L ⁻¹)	4	4.92	4.96	4.27	4.55	5.3	5.5				
Chl-a (µg L ⁻¹)	4	0.32	0.31	0.24	0.24	0.39	0.41	H	Median	0.36	0.46
NO _x (µg L ⁻¹)	4	0.6	0.63	0.32	0.45	0.76	0.82	H	Median	0.35	0.45
PN (µg L ⁻¹)	4	34.52	33.44	23.87	24.86	43.74	46.67	H	Mean	16	
	4	34.52	33.44	23.87	24.86	43.74	46.67	H	Median	18	20
PO ₄ (µg L ⁻¹)	4	0.81	0.85	0.64	0.71	0.93	0.93	H	Median	1.4	0.93
POC (mg L ⁻¹)	4	174.52	155.58	100.57	109.98	231.49	275				
PP (µg L ⁻¹)	4	2.48	2.43	2.17	2.21	2.72	2.85	H	Mean	2.3	
	4	2.48	2.43	2.17	2.21	2.72	2.85	H	Median	2.6	3
Secchi (m)	4	4.09	3.77	3.29	3.4	4.66	5.36	L	Mean	10	
	4	4.09	3.77	3.29	3.4	4.66	5.36	L	Median		
SiO ₄	4	273.53	211.8	196.43	201.74	320.62	437.04				
TSS (mg L ⁻¹)	4	2	1.99	0.9	1.33	2.66	3.11	H	Mean	1.6	
	4	2	1.99	0.9	1.33	2.66	3.11	H	Median	1.9	1.7

Chl-a (µg L ⁻¹)	4	0.78	0.73	0.38	0.45	1.08	1.23	H	Median			0.7
NO _x (µg L ⁻¹)	4	1.21	1.37	0.41	0.78	1.69	1.79	H	Median			1
PN (µg L ⁻¹)	4	57.65	50.89	39.92	40.04	72.57	84.85	H	Mean			
PO ₄ (µg L ⁻¹)	4	57.65	50.89	39.92	40.04	72.57	84.85	H	Median			
POC (mg L ⁻¹)	4	0.81	0.85	0.38	0.59	1.05	1.19	H	Median			2
PP (µg L ⁻¹)	4	258.06	231.02	173.77	185.67	319.63	380.21					
Secchi (m)	4	6.18	5.7	4.02	4.59	7.58	9	H	Mean			
SiO ₄	4	6.18	5.7	4.02	4.59	7.58	9	H	Median			
TSS (mg L ⁻¹)	4	2.16	2.05	1.53	1.78	2.5	2.95	L	Mean			
DIN (µg L ⁻¹)	4	2.16	2.05	1.53	1.78	2.5	2.95	L	Median			1.5
DOC (µg L ⁻¹)	4	500.7	366.15	305.75	326.35	621.24	884.03					
DON (µg L ⁻¹)	4	5.49	4.55	3.37	3.52	7.08	8.92	H	Mean			
DOP (µg L ⁻¹)	4	5.49	4.55	3.37	3.52	7.08	8.92	H	Median			6
Chl-a (µg L ⁻¹)	5											
NO _x (µg L ⁻¹)	5											
PN (µg L ⁻¹)	5	2105	1920	1639	1842	2374	2748					
PO ₄ (µg L ⁻¹)	5											
DOP (µg L ⁻¹)	5	4.71	4.8	4.12	4.4	5.02	5.2					
Chl-a (µg L ⁻¹)	5	0.27	0.25	0.22	0.24	0.29	0.35	H	Median	0.36	0.25	0.46
NO _x (µg L ⁻¹)	5	0.31	0.28	0.28	0.28	0.31	0.39	H	Median	0.35	0.32	0.45
PN (µg L ⁻¹)	5	21.34	21.54	16.24	20.14	24.06	24.72	H	Mean		16	
PO ₄ (µg L ⁻¹)	5	21.34	21.54	16.24	20.14	24.06	24.72	H	Median	18		20
PO ₄ (µg L ⁻¹)	5	1.18	1.08	0.34	0.43	1.73	2.29	H	Median	1.4	1.86	0.93

Endeavour offshore (ER03)

Endeavour north shore (ER02b)	POC (mg L ⁻¹)	5	99.03	98.53	80.77	87.86	109.46	118.53													
	PP (µg L ⁻¹)	5	2.08	1.97	1.72	1.77	2.23	2.69	2.69	2.6	2.3										
	Secchi (m)	5	7.81	9.1	5.11	5.14	5.14	9.46	10.24	10											
		5	7.81	9.1	5.11	5.14	5.14	9.46	10.24	10											
	SiO ₄	5	158.71	149.58	103.76	115.9	184.72	239.58													
		5	2.51	2.76	1.3	1.85	3.16	3.45	3.45	1.9	1.6										
	TSS (mg L ⁻¹)	5	2.51	2.76	1.3	1.85	3.16	3.45	3.45	1.9	1.6										
		5	2.51	2.76	1.3	1.85	3.16	3.45	3.45	1.9	1.6										
	DIN (µg L ⁻¹)	5																			
	DOC (µg L ⁻¹)	5	2250	2392	1798	1924	2522	2614													
	DON (µg L ⁻¹)	5																			
	DOP (µg L ⁻¹)	5	4.66	4.88	3.62	4.27	5.26														
	Chl-a (µg L ⁻¹)	5	0.27	0.2	0.15	0.15	0.35	0.47	0.47	0.36	0.25	0.46									
		5	0.86	0.32	0.28	0.28	0.94	2.49	2.49	0.35	0.32	0.45									
	PN (µg L ⁻¹)	5	24.64	21.74	17.22	20.16	31.92	32.16	32.16	18	16										
		5	24.64	21.74	17.22	20.16	31.92	32.16	32.16	18	16										
	PO ₄ (µg L ⁻¹)	5	0.91	0.85	0.31	0.31	1.27	1.83	1.83	1.4	1.86	0.93									
	POC (mg L ⁻¹)	5	120.47	112.44	82.84	88	156.02	163.05													
	PP (µg L ⁻¹)	5	2.3	2.03	1.62	1.84	2.87	3.15	3.15	2.6	2.3										
		5	2.3	2.03	1.62	1.84	2.87	3.15	3.15	2.6	2.3										
	Secchi (m)	5	5.56	4.6	4.1	4.1	7.02	7.98	7.98	10											
5		5.56	4.6	4.1	4.1	7.02	7.98	7.98	10												
SiO ₄	5	252.43	217.56	107.95	123.37	321.55	491.73														

Egret and Boulder Reef (AE04)	TSS (mg L ⁻¹)	5	2.38	2.58	0.82	1.28	3.21	4	H	Mean	1.6	
	DIN (µg L ⁻¹)	5	2.38	2.58	0.82	1.28	3.21	4	H	Median	1.9	
	DOC (µg L ⁻¹)	5										
	DON (µg L ⁻¹)	5	2040	2071	1773	1847	2218	2291				
	DOP (µg L ⁻¹)	5	4.92	5.11	4.43	4.48	5.28	5.33				
	Chl-a (µg L ⁻¹)	5	0.25	0.22	0.13	0.16	0.34	0.42	H	Median	0.27	
	NO _x (µg L ⁻¹)	5	0.5	0.42	0.28	0.28	0.64	0.87	H	Median	0.35	
	PN (µg L ⁻¹)	5	17.77	20.34	12.54	13.44	20.98	21.55	H	Mean		
	PO ₄ (µg L ⁻¹)	5	17.77	20.34	12.54	13.44	20.98	21.55	H	Median	18	
	POC (mg L ⁻¹)	5	0.84	0.77	0.31	0.31	1.11	1.67	H	Median	0.62	
	PP (µg L ⁻¹)	5	84.51	91.82	59.09	76.66	96.07	98.89				
	Secchi (m)		5	1.5	1.5	1.04	1.24	1.85	1.88	H	Mean	
			5	1.5	1.5	1.04	1.24	1.85	1.88	H	Median	2
	SiO ₄		5	12.25	11.1	7.07	7.58	15.92	19.58	L	Mean	10
	TSS (mg L ⁻¹)		5	12.25	11.1	7.07	7.58	15.92	19.58	L	Median	
	DIN (µg L ⁻¹)		5	87.08	87.92	56.64	67.72	108.41	114.69			
	DOC (µg L ⁻¹)		5	1.74	1.4	0.47	0.6	2.48	3.74	H	Mean	
	DON (µg L ⁻¹)		5	1.74	1.4	0.47	0.6	2.48	3.74	H	Median	1.5
	Dawson Reef (AR03b)	DIN (µg L ⁻¹)	5									
		DOC (µg L ⁻¹)	5	2014	2092	1677	1848	2193	2261			
DON (µg L ⁻¹)		5										

	DOP (µg L ⁻¹)	5	4.58	4.8	3.69	4.06	4.96	5.42												
	Chl-a (µg L ⁻¹)	5	0.19	0.2	0.12	0.18	0.21	0.22	H	Median	0.36	0.25	0.46							
	NO _x (µg L ⁻¹)	5	0.41	0.28	0.28	0.28	0.41	0.78	H	Median	0.35	0.32	0.45							
	PN (µg L ⁻¹)	5	17.72	16.04	11.78	14.3	22.22	24.26	H	Mean		16								
	PO ₄ (µg L ⁻¹)	5	17.72	16.04	11.78	14.3	22.22	24.26	H	Median	18		20							
	PO ₄ (µg L ⁻¹)	5	1.11	1.08	0.31	0.31	1.7	2.17	H	Median	1.4	1.86	0.93							
	POC (mg L ⁻¹)	5	81.85	74.31	59.91	70.18	98.47	106.4												
	PP (µg L ⁻¹)	5	1.68	1.65	1.32	1.52	1.9	2.01	H	Mean		2.3								
	PP (µg L ⁻¹)	5	1.68	1.65	1.32	1.52	1.9	2.01	H	Median	2.6		3							
	Secchi (m)	5	8.2	7.1	4.86	6.24	10.14	12.66	L	Mean	10									
	Secchi (m)	5	8.2	7.1	4.86	6.24	10.14	12.66	L	Median										
	SiO ₄	5	148.54	142.28	67.22	94.02	200.51	238.68												
	TSS (mg L ⁻¹)	5	2.18	1.56	0.86	1.38	3.07	4.01	H	Mean		1.6								
	TSS (mg L ⁻¹)	5	2.18	1.56	0.86	1.38	3.07	4.01	H	Median	1.9		1.7							
	DIN (µg L ⁻¹)	5																		
	DIN (µg L ⁻¹)	5																		
	DOC (µg L ⁻¹)	5	2143	1988	1966	1981	2322	2459												
	DOC (µg L ⁻¹)	5																		
	DON (µg L ⁻¹)	5																		
	DON (µg L ⁻¹)	5																		
Walker Bay (AR02b)	DOP (µg L ⁻¹)	5	4.71	4.8	4.04	4.55	5.05	5.09												
	Chl-a (µg L ⁻¹)	5	0.25	0.25	0.2	0.21	0.26	0.31	H	Median	0.36	0.25	0.46							
	NO _x (µg L ⁻¹)	5	0.79	0.6	0.28	0.28	1	1.8	H	Median	0.35	0.32	0.45							
	NO _x (µg L ⁻¹)	5	24.68	22.34	18.55	19.63	27.48	35.4	H	Mean		16								
	PN (µg L ⁻¹)	5	24.68	22.34	18.55	19.63	27.48	35.4	H	Median	18		20							

		5	0.93	0.93	0.93	0.31	0.31	0.31	1.22	1.87	H	Median	1.4	1.86	0.93
	PO ₄ (µg L ⁻¹)	5	0.93	0.93	0.93	0.31	0.31	0.31	1.22	1.87	H	Median	1.4	1.86	0.93
	POC (mg L ⁻¹)	5	116.42	102.63	87.99	89.1	87.99	89.1	139.95	162.41					
	PP (µg L ⁻¹)	5	2.21	2.23	1.79	1.87	1.79	1.87	2.44	2.72	H	Mean	2.3	2.3	
		5	2.21	2.23	1.79	1.87	1.79	1.87	2.44	2.72	H	Median	2.6	2.6	3
	Secchi (m)	5	6.92	7	5.95	6.4	5.95	6.4	7.48	7.79	L	Mean	10		
		5	6.92	7	5.95	6.4	5.95	6.4	7.48	7.79	L	Median			
	SiO ₄	5	169.75	167.77	106.62	122.67	106.62	122.67	192.51	259.17					
	TSS (mg L ⁻¹)	5	2.6	1.95	1.4	1.74	1.4	1.74	3.28	4.64	H	Mean	1.6	1.6	
		5	2.6	1.95	1.4	1.74	1.4	1.74	3.28	4.64	H	Median	1.9	1.9	1.7
	DIN (µg L ⁻¹)	3													
	DOC (µg L ⁻¹)	3	982	993	944	960	944	960	1006	1012					
	DON (µg L ⁻¹)	3													
	DOP (µg L ⁻¹)	3	5.68	5.65	5.65	5.65	5.65	5.65	5.7	5.72					
	Chl-a (µg L ⁻¹)	3	0.25	0.24	0.17	0.19	0.17	0.19	0.31	0.35	H	Mean	0.45	0.45	
		3	0.25	0.24	0.17	0.19	0.17	0.19	0.31	0.35	H	Median		0.32	0.63
	NO _x (µg L ⁻¹)	3	1.37	1.26	0.76	0.92	0.76	0.92	1.79	2.05	H	Median	0.35	0.35	
		3	12.27	12.55	10.95	11.48	10.95	11.48	13.11	13.39	H	Mean	20		
	PN (µg L ⁻¹)	3	12.27	12.55	10.95	11.48	10.95	11.48	13.11	13.39	H	Median		16	25
	PO ₄ (µg L ⁻¹)	3	1.14	1.16	0.46	0.7	0.46	0.7	1.58	1.79	H	Median	2		
	POC (mg L ⁻¹)	3	79.65	87.42	59.94	69.1	59.94	69.1	91.74	93.91					
	PP (µg L ⁻¹)	3	2.51	2.54	2.13	2.27	2.13	2.27	2.76	2.87	H	Mean	2.8	2.8	
		3	2.51	2.54	2.13	2.27	2.13	2.27	2.76	2.87	H	Median		2.3	3.3
	Secchi (m)	3	8.5	10	4.15	6.1	4.15	6.1	11.2	11.8	L	Mean	10		

Wet Tropics
Cape Tribulation (CI)

		3	8.5	10	4.15	6.1	11.2	11.8	L	Median		
	SiO ₄	3	119.73	105.41	93.78	97.65	138.95	155.72				
	TSS (mg L ⁻¹)	3	0.96	0.97	0.53	0.67	1.25	1.4	H	Mean	2	
	DIN (µg L ⁻¹)	3	0.96	0.97	0.53	0.67	1.25	1.4	H	Median		2.4
	DOC (µg L ⁻¹)	3	1012	989	920	943	1076	1120				
	DON (µg L ⁻¹)	3										
	DOP (µg L ⁻¹)	3	5.01	5.26	4.15	4.52	5.54	5.68				
	Chl-a (µg L ⁻¹)	3	0.27	0.29	0.21	0.23	0.31	0.32	H	Median	0.3	0.63
	NO _x (µg L ⁻¹)	3	6.84	2.84	1.58	2	10.88	14.9	H	Median	0.31	
	PN (µg L ⁻¹)	3	12.06	12.34	11.49	11.77	12.4	12.43	H	Median	14	25
	PO ₄ (µg L ⁻¹)	3	1.83	1.7	1.7	1.7	1.94	2.05	H	Median	2	
	POC (mg L ⁻¹)	3	82.03	83.72	75.7	78.37	86.03	87.18				
	PP (µg L ⁻¹)	3	2.52	2.47	2.15	2.26	2.78	2.93	H	Median	2	3.3
	Secchi (m)	3	7.5	6	3.75	4.5	10.2	12.3	L	Median	13	
	SiO ₄	3	146.21	158.57	91	113.53	181.36	192.76				
	TSS (mg L ⁻¹)	3	1.1	1.29	0.52	0.78	1.47	1.56	H	Median	1.2	2.4
	DIN (µg L ⁻¹)	3										
	DOC (µg L ⁻¹)	3	972	925	895	905	1029	1081				
	DON (µg L ⁻¹)	3										

	3	1.56	1.7	1.16	1.34	1.81	1.86	H	Median	2	2.3	3.3
PP (µg L ⁻¹)	3	15.33	16	12.4	13.6	17.2	17.8	L	Median	13		
Secchi (m)	3	60.3	59.97	51.19	54.12	66.42	69.64					
SiO ₄	3	0.39	0.26	0.11	0.16	0.6	0.77	H	Median	1.2	1.6	2.4
TSS (mg L ⁻¹)	3											
DIN (µg L ⁻¹)	3											
DOC (µg L ⁻¹)	3	1036	1002	967	979	1086	1128					
DON (µg L ⁻¹)	3											
DOP (µg L ⁻¹)	3	5.52	5.42	4.86	5.05	5.98	6.26					
Chl-a (µg L ⁻¹)	3	0.39	0.4	0.28	0.32	0.47	0.51	H	Mean	0.45		
	3	0.39	0.4	0.28	0.32	0.47	0.51	H	Median		0.32	0.63
NO _x (µg L ⁻¹)	3	3.26	3.15	1.1	1.79	4.7	5.48	H	Median	0.35		
PN (µg L ⁻¹)	3	18.6	19.66	14.06	15.93	21.48	22.39	H	Mean	20		
	3	18.6	19.66	14.06	15.93	21.48	22.39	H	Median		16	25
PO ₄ (µg L ⁻¹)	3	1.29	1.32	0.41	0.71	1.87	2.15	H	Median	2		
POC (mg L ⁻¹)	3	142.45	133.6	115.87	121.78	161.35	175.22					
PP (µg L ⁻¹)	3	4.58	3.93	3.05	3.35	5.68	6.55	H	Mean	2.8		
	3	4.58	3.93	3.05	3.35	5.68	6.55	H	Median		2.3	3.3
Secchi (m)	3	3.67	3	2.1	2.4	4.8	5.7	L	Mean	10		
	3	3.67	3	2.1	2.4	4.8	5.7	L	Median			
SiO ₄	3	198.27	207.37	169.96	182.43	215.93	220.2					
TSS (mg L ⁻¹)	3	2.84	1.82	1.09	1.33	4.15	5.32	H	Mean	2		
	3	2.84	1.82	1.09	1.33	4.15	5.32	H	Median		1.6	2.4

Yorkey's Knob (C6)

RM3 (RM3)	Chl-a ($\mu\text{g L}^{-1}$)	5	0.19	0.18	0.12	0.14	0.25	0.27	H	Mean	0.45		
		5	0.19	0.18	0.12	0.14	0.25	0.27	H	Median		0.32	0.63
	NO _x ($\mu\text{g L}^{-1}$)	5	2.14	1.96	0.49	0.81	2.79	4.63	H	Median	0.35		
	PN ($\mu\text{g L}^{-1}$)	5	14.51	14.44	10.24	10.41	18.7	18.73	H	Mean	20		
		5	14.51	14.44	10.24	10.41	18.7	18.73	H	Median		16	25
	PO ₄ ($\mu\text{g L}^{-1}$)	5	1.29	1.55	0.42	0.74	1.86	1.86	H	Median	2		
	POC (mg L ⁻¹)	5	95.81	95.18	52.25	53.48	137.99	140.15					
	PP ($\mu\text{g L}^{-1}$)	5	1.89	1.9	1.36	1.75	2.12	2.3	H	Mean	2.8		
		5	1.89	1.9	1.36	1.75	2.12	2.3	H	Median		2.3	3.3
	Secchi (m)	5	9.3	10	4.5	6	11.8	14.2	L	Mean	10		
		5	9.3	10	4.5	6	11.8	14.2	L	Median			
	SiO ₄	5	109.09	102.74	70.07	73.4	142.05	157.18					
	TSS (mg L ⁻¹)	5	0.74	0.69	0.28	0.52	1.01	1.23	H	Mean	2		
		5	0.74	0.69	0.28	0.52	1.01	1.23	H	Median		1.6	2.4
	DIN ($\mu\text{g L}^{-1}$)	10											
	DOC ($\mu\text{g L}^{-1}$)	10	1232	1140	914	1034	1303	1797					
	DON ($\mu\text{g L}^{-1}$)	10											
	DOP ($\mu\text{g L}^{-1}$)	10	5.41	5.23	4.54	4.92	5.98	6.43					
	Chl-a ($\mu\text{g L}^{-1}$)	10	0.28	0.25	0.19	0.2	0.33	0.44	H	Median	0.3	0.32	0.63
	NO _x ($\mu\text{g L}^{-1}$)	10	3.5	2.28	0.35	0.41	5.55	10.31	H	Median	0.31		
PN ($\mu\text{g L}^{-1}$)	10	24.1	18.25	11.52	12.03	35.8	42.59	H	Median	14	16	25	
PO ₄ ($\mu\text{g L}^{-1}$)	10	1.15	1.12	0.42	0.59	1.72	1.78	H	Median	2			

	POC (mg L ⁻¹)	10	159.23	136.36	74.33	79.35	223.18	300.46											
	PP (µg L ⁻¹)	10	2.43	2.38	1.68	1.93	2.62	3.52	H	Median	2	2.3							3.3
	Secchi (m)	10	7.8	8.25	4.4	6.3	9.3	10.77	L	Median	13								
	SiO ₄	10	206.46	188.62	82.37	110.69	275.25	380.6											
	TSS (mg L ⁻¹)	10	0.96	0.84	0.61	0.65	1.25	1.55	H	Median	1.2	1.6							2.4
	DIN (µg L ⁻¹)	10																	
	DOC (µg L ⁻¹)	10	1231	1110	940	987	1274	1937											
	DON (µg L ⁻¹)	10																	
	DOP (µg L ⁻¹)	10	5.37	5.34	4.36	4.75	5.9	6.31											
	Chl-a (µg L ⁻¹)	10	0.36	0.36	0.21	0.32	0.43	0.49	H	Mean	0.45								
		10	0.36	0.36	0.21	0.32	0.43	0.49	H	Median		0.32							0.63
	NO _x (µg L ⁻¹)	10	5.07	1.37	0.56	0.99	5.08	19.67	H	Median	0.35								
High West (RM8)	PN (µg L ⁻¹)	10	26.31	20.76	14.78	16.19	39.23	45.96	H	Mean	20								
		10	26.31	20.76	14.78	16.19	39.23	45.96	H	Median		16							25
	PO ₄ (µg L ⁻¹)	10	1.48	1.28	0.77	0.84	1.87	2.83	H	Median	2								
	POC (mg L ⁻¹)	10	157.62	136.72	106.22	127.59	182.35	243.15											
	PP (µg L ⁻¹)	10	2.84	2.96	1.8	2.08	3.33	3.97	H	Mean	2.8								
		10	2.84	2.96	1.8	2.08	3.33	3.97	H	Median		2.3							3.3
	Secchi (m)	10	7.17	6	3.31	4.4	8.1	14.62	L	Mean	10								
		10	7.17	6	3.31	4.4	8.1	14.62	L	Median									
	SiO ₄	10	284.23	269.63	101.29	184.5	326.8	534.66											
		10	1.54	1.4	0.95	1.07	2.05	2.39	H	Mean	2								

		10	1.54	1.4	0.95	1.07	2.05	2.39	H	Median	1.6	2.4
	TSS (mg L ⁻¹)	10	1591	1441	968	1061	1772	2902				
	DIN (µg L ⁻¹)	10										
	DOC (µg L ⁻¹)	10	1591	1441	968	1061	1772	2902				
	DON (µg L ⁻¹)	10										
	DOP (µg L ⁻¹)	10	4.99	4.96	4.13	4.63	5.45	5.74				
	Chl-a (µg L ⁻¹)	10	0.44	0.4	0.33	0.35	0.48	0.65	H	Mean	0.45	
		10	0.44	0.4	0.33	0.35	0.48	0.65	H	Median		0.63
	NO _x (µg L ⁻¹)	10	21.01	8.96	0.36	1.06	31.88	68.68	H	Median	0.35	
Russell Mulgrave Mouth Mooring (RM10)	PN (µg L ⁻¹)	10	37.91	36.45	17.55	20.42	45.65	71.53	H	Mean	20	
		10	37.91	36.45	17.55	20.42	45.65	71.53	H	Median		25
	PO ₄ (µg L ⁻¹)	10	1.91	1.55	0.84	1.3	2.26	3.64	H	Median	2	
	POC (mg L ⁻¹)	10	279.65	269.8	138.25	177.9	322.32	486.78				
		10	5.99	5.18	3.72	4.41	7.34	10.06	H	Mean	2.8	
		10	5.99	5.18	3.72	4.41	7.34	10.06	H	Median		2.3
		10	3.38	3.5	2.11	2.85	3.7	4.77	L	Mean	10	
		10	3.38	3.5	2.11	2.85	3.7	4.77	L	Median		
		10	726.78	575.07	132.9	304.73	1102.28	1748.61				
		10	2.68	2.29	1.31	1.79	3.11	5.01	5.01	H	Mean	2
	10	2.68	2.29	1.31	1.79	3.11	5.01	5.01	H	Median		2.4
Franklands West (RM7)	DIN (µg L ⁻¹)	10										
	DOC (µg L ⁻¹)	10	1264	1199	946	986	1478	1768				
	DON (µg L ⁻¹)	10										

	10	2.05	1.85	1.15	1.53	2.39	3.56	H	Median	2	2.3	3.3
PP (µg L ⁻¹)	10	11.3	11.75	5.8	8.8	14.6	16.1	L	Median	13		
Secchi (m)	10	126.68	110.78	51.92	92.78	172.33	203.76					
SiO ₄	10	0.8	0.65	0.32	0.53	0.94	1.59	H	Median	1.2	1.6	2.4
TSS (mg L ⁻¹)	10											
DIN (µg L ⁻¹)	10											
DOC (µg L ⁻¹)	10	1241	1191	971	1001	1426	1624					
DON (µg L ⁻¹)	10											
DOP (µg L ⁻¹)	10	5.44	5.38	4.71	4.94	5.84	6.39					
Chl-a (µg L ⁻¹)	10	0.32	0.32	0.17	0.24	0.44	0.49	H	Mean	0.45		
	10	0.32	0.32	0.17	0.24	0.44	0.49	H	Median		0.32	0.63
NO _x (µg L ⁻¹)	10	4.48	4.43	0.55	0.69	5.89	10.63	H	Median	0.35		
PN (µg L ⁻¹)	10	27.99	22	12.52	13.15	43.71	51.82	H	Mean	20		
	10	27.99	22	12.52	13.15	43.71	51.82	H	Median		16	25
PO ₄ (µg L ⁻¹)	10	1.44	1.51	0.42	0.84	1.92	2.51	H	Median	2		
POC (mg L ⁻¹)	10	204.98	186.16	94.03	102.06	255.42	403.98					
PP (µg L ⁻¹)	10	3.16	2.77	2.22	2.41	3.66	5.15	H	Mean	2.8		
	10	3.16	2.77	2.22	2.41	3.66	5.15	H	Median		2.3	3.3
Secchi (m)	10	4.78	5.25	2.45	3.4	6	6.27	L	Mean	10		
	10	4.78	5.25	2.45	3.4	6	6.27	L	Median			
SiO ₄	10	345.28	301.41	115.62	193.36	589.34	617.4					
TSS (mg L ⁻¹)	10	2.05	1.67	1.01	1.13	2.66	4.14	H	Mean	2		
	10	2.05	1.67	1.01	1.13	2.66	4.14	H	Median		1.6	2.4

Bedarra (TUL8)	Chl-a (µg L ⁻¹)	10	0.4	0.33	0.24	0.27	0.55	0.72	H	Mean	0.45		
		10	0.4	0.33	0.24	0.27	0.55	0.72	H	Median		0.32	0.63
	NO _x (µg L ⁻¹)	10	4.59	3.1	0.33	0.43	5.25	15.58	H	Median	0.35		
	PN (µg L ⁻¹)	10	28.44	27.35	14.94	15.87	36.89	47.85	H	Mean	20		
		10	28.44	27.35	14.94	15.87	36.89	47.85	H	Median		16	25
	PO ₄ (µg L ⁻¹)	10	1.23	1.39	0.31	0.31	1.7	2.44	H	Median	2		
	POC (mg L ⁻¹)	10	211.8	184.18	116.77	135.33	299.41	336.95					
	PP (µg L ⁻¹)	10	3.69	3.21	2.55	2.9	4.54	5.58	H	Mean	2.8		
		10	3.69	3.21	2.55	2.9	4.54	5.58	H	Median		2.3	3.3
	Secchi (m)	10	3.85	3.75	2.23	2.5	4.6	6.1	L	Mean	10		
		10	3.85	3.75	2.23	2.5	4.6	6.1	L	Median			
	SiO ₄	10	495.02	395.79	127.58	270.51	625.82	1158.4					
	TSS (mg L ⁻¹)	10	2.33	1.97	1.04	1.2	3.58	4.59	H	Mean	2		
		10	2.33	1.97	1.04	1.2	3.58	4.59	H	Median		1.6	2.4
	DIN (µg L ⁻¹)	10											
	DOC (µg L ⁻¹)	10	1344	1331	920	975	1611	1798					
	DON (µg L ⁻¹)	10											
	DOP (µg L ⁻¹)	10	6.62	5.5	4.63	5.11	6.04	12.47					
	Chl-a (µg L ⁻¹)	10	0.4	0.37	0.24	0.26	0.47	0.65	H	Mean	0.45		
		10	0.4	0.37	0.24	0.26	0.47	0.65	H	Median		0.32	0.63
NO _x (µg L ⁻¹)	10	5.38	2.17	0.36	0.56	6.06	20.02	H	Median	0.35			
PN (µg L ⁻¹)	10	30.18	28.44	14.15	14.82	45.5	50.95	H	Mean	20			
	10	30.18	28.44	14.15	14.82	45.5	50.95	H	Median		16	25	

	10	1.38	1.39	0.31	0.43	1.89	2.86	H	Median	2	
PO ₄ (µg L ⁻¹)	10	1.38	1.39	0.31	0.43	1.89	2.86	H	Median	2	
POC (mg L ⁻¹)	10	220.56	231.75	99.32	108.36	322.82	340.05				
PP (µg L ⁻¹)	10	3.44	2.93	2.47	2.56	4.04	5.6	H	Mean	2.8	
	10	3.44	2.93	2.47	2.56	4.04	5.6	H	Median	2.3	3.3
Secchi (m)	10	5.25	5	1.68	2.9	7.4	9.82	L	Mean	10	
	10	5.25	5	1.68	2.9	7.4	9.82	L	Median		
SiO ₄	10	418.06	437.15	125.78	199.35	481.6	860.57				
TSS (mg L ⁻¹)	10	2.22	1.6	0.79	0.9	3.05	5.59	H	Mean	2	
	10	2.22	1.6	0.79	0.9	3.05	5.59	H	Median	1.6	2.4
DIN (µg L ⁻¹)	10										
DOC (µg L ⁻¹)	10	1524	1427	1066	1092	1884	2153				
DON (µg L ⁻¹)	10										
DOP (µg L ⁻¹)	10	5.21	5.15	4.24	4.68	5.9	6.22				
Chl-a (µg L ⁻¹)	10	0.56	0.52	0.27	0.36	0.72	0.99	H	Median	1.1	
NO _x (µg L ⁻¹)	10	18.33	6.51	0.45	1.11	34.37	55.38	H	Median	3	
PN (µg L ⁻¹)	10	55.84	39.35	20.23	24.89	82.15	131.56	H	Median		
PO ₄ (µg L ⁻¹)	10	3.15	2.01	0.59	1.18	5.2	8.01	H	Median	3	
POC (mg L ⁻¹)	10	442.56	304.29	164.86	221.12	633.66	1050.94				
PP (µg L ⁻¹)	10	8.31	5.79	4.05	4.77	9.51	18.98	H	Median		
Secchi (m)	10	2.52	2.5	0.81	1.7	3.5	4.32	L	Median	1.6	
SiO ₄	10	823.24	615.35	183.54	272.23	1463.5	1618.71				

Tully River mouth mooring (TULL10)

	TSS (mg L ⁻¹)	10	9.77	4.98	1.84	2.97	12.57	30.02	H	Median	5		
Burdekin	DIN (µg L ⁻¹)	9											
	DOC (µg L ⁻¹)	9	1248	1174	895	952	1547	1881					
	DON (µg L ⁻¹)	9											
	DOP (µg L ⁻¹)	9	5.26	5.42	4.1	4.71	5.81	6.04					
	Chl-a (µg L ⁻¹)	9	0.24	0.18	0.12	0.16	0.33	0.43	H	Median	0.35	0.32	0.63
	NO _x (µg L ⁻¹)	9	2.88	0.98	0.45	0.49	4.8	9.7	H	Median	0.28		
	PN (µg L ⁻¹)	9	21.83	18.44	10.44	11.76	30.88	35.41	H	Median	12	16	25
	PO ₄ (µg L ⁻¹)	9	1.3	1.01	0.4	0.63	1.92	2.85	H	Median	1		
	POC (mg L ⁻¹)	9	148	141.17	57.55	70.25	218.67	240.41					
	PP (µg L ⁻¹)	9	2.21	2.08	1.38	1.69	2.79	2.91	H	Median	2.2	2.3	3.3
	Secchi (m)		9	7.67	6.2	3.46	4.84	10.8	14.4	L	Mean	10	
			9	7.67	6.2	3.46	4.84	10.8	14.4	L	Median		
	SiO ₄		9	147.25	177.6	56.6	74.76	204.57	223.53				
	TSS (mg L ⁻¹)		9	1.24	1.21	0.54	0.62	1.59	2.38	H	Median	1.2	1.6
Pandora (BUR2)	DIN (µg L ⁻¹)	9											
	DOC (µg L ⁻¹)	9	1266	1184	1013	1079	1500	1599					
	DON (µg L ⁻¹)	9											
	DOP (µg L ⁻¹)	9	5.5	5.42	4.74	5.2	5.81	6.32					
	Chl-a (µg L ⁻¹)	9	0.24	0.21	0.12	0.18	0.35	0.37	H	Median	0.35	0.32	0.63

NO _x (µg L ⁻¹)	9	2.29	1.44	0.39	0.6	3.4	6.8	H	Median	0.28		
PN (µg L ⁻¹)	9	22.58	19.84	11.1	13.14	29.54	41.53	H	Median	12	16	25
PO ₄ (µg L ⁻¹)	9	1.24	0.77	0.34	0.43	1.89	2.96	H	Median	1		
POC (mg L ⁻¹)	9	162.06	127.16	76.74	97.7	208.61	308.59					
PP (µg L ⁻¹)	9	3.49	2.65	1.72	2.09	5.03	6.1	H	Median	2.2	2.3	3.3
Secchi (m)	9	6.4	4.6	4.2	4.5	7.3	13	L	Mean	10		
	9	6.4	4.6	4.2	4.5	7.3	13	L	Median			
SiO ₄	9	186.96	187.36	75.24	110.08	276.83	311.08					
TSS (mg L ⁻¹)	9	1.75	1.27	0.19	0.71	1.78	4.98	H	Median	1.2	1.6	2.4
DIN (µg L ⁻¹)	9											
DOC (µg L ⁻¹)	9	1270	1224	879	958	1587	1660					
DON (µg L ⁻¹)	9											
DOP (µg L ⁻¹)	9	5.38	5.73	4.27	5.11	5.84	5.98					
Chl-a (µg L ⁻¹)	9	0.35	0.34	0.12	0.18	0.44	0.64	H	Median	0.59	0.32	0.63
NO _x (µg L ⁻¹)	9	9.21	3.82	2.05	2.74	10.36	29.72	H	Median	0.28		
PN (µg L ⁻¹)	9	26.44	21.34	14.93	17.74	34.22	47.72	H	Median	17	16	25
PO ₄ (µg L ⁻¹)	9	1.66	1.55	0.43	0.67	2.51	3.21	H	Median	1		
POC (mg L ⁻¹)	9	174.28	140.42	112.57	116.39	230.81	286.54					
PP (µg L ⁻¹)	9	3.31	3.28	2.01	2.48	3.94	4.8	H	Mean	2.8		
	9	3.31	3.28	2.01	2.48	3.94	4.8	H	Median		2.3	3.3

	Secchi (m)	9	4.21	4	2.1	3.3	5.28	6.48	L	Median	4	
	SiO ₄	9	262.7	220.09	105.03	138.1	375.41	500.51				
	TSS (mg L ⁻¹)	9	2.38	2.82	1.02	1.19	3.36	3.69	H	Median	1.9	1.6
	DIN (µg L ⁻¹)	9										
	DOC (µg L ⁻¹)	9	1292	1200	849	930	1610	1764				
	DON (µg L ⁻¹)	9										
	DOP (µg L ⁻¹)	9	6.37	6.04	3.44	5.44	7.4	9.91				
	Chl-a (µg L ⁻¹)	9	0.25	0.25	0.14	0.17	0.32	0.36	H	Mean	0.45	
		9	0.25	0.25	0.14	0.17	0.32	0.36	H	Median		0.32
	NO _x (µg L ⁻¹)	9	5.32	3.05	0.36	0.66	5.85	18.29	H	Median	1	
	PN (µg L ⁻¹)	9	26.73	23.04	13.1	13.93	33.4	50.68	H	Median	13	16
	PO ₄ (µg L ⁻¹)	9	1.63	1.08	0.43	0.67	2.82	3.56	H	Median	2	
	POC (mg L ⁻¹)	9	186.04	196.62	96.38	113.58	239.3	302.66				
	PP (µg L ⁻¹)	9	2.92	2.99	1.59	2.04	3.56	4.31	H	Median	2.1	2.3
		9	5.67	4.8	3.24	3.84	7.9	10	L	Mean	10	
	Secchi (m)	9	5.67	4.8	3.24	3.84	7.9	10	L	Median		
	SiO ₄	9	160.64	144.03	75.25	96.19	223.37	272.16				
	TSS (mg L ⁻¹)	9	2.57	1.93	0.68	1.46	3.13	6.19	H	Median	1.2	1.6
	DIN (µg L ⁻¹)	4										
	DOC (µg L ⁻¹)	4	934	888	758	792	1057	1174				
	DON (µg L ⁻¹)	4										

Mackay Whitsunday Double Cone (W/H11) Pine (W/H14)	POC (mg L ⁻¹)	9	351.5	314.57	172.48	257.04	502.62	531.69															
	PP (µg L ⁻¹)	9	6.83	6.97	4.61	5.08	8.38	8.84	H	Median													
	Secchi (m)	9	2.23	2	0.62	1.04	2.74	4.84	L	Median	1.5												
	SiO ₄	9	519.07	263.41	126.25	228.55	878.12	1225.52															
	TSS (mg L ⁻¹)	9	7.89	6.01	2.14	2.83	9.21	20.37	H	Median	2												
	DIN (µg L ⁻¹)	5																					
	DOC (µg L ⁻¹)	5	1003	1034	846	875	1083	1178															
	DON (µg L ⁻¹)	5																					
	DOP (µg L ⁻¹)	5	5.25	5.42	4.06	4.61	5.96	6.19															
	Chl-a (µg L ⁻¹)	5	0.31	0.34	0.23	0.23	0.35	0.37	H	Median	0.36											0.63	
	NO _x (µg L ⁻¹)	5	3.72	2.21	0.97	1.03	4.64	9.74	H	Median	1												
	PN (µg L ⁻¹)	5	15.73	15.6	12.43	12.91	17.07	20.64	H	Mean	14												
	PO ₄ (µg L ⁻¹)	5	1.7	1.55	1.01	1.01	2.34	2.62	H	Median	1												
	POC (mg L ⁻¹)	5	151.32	133.01	81.82	82.16	225.84	233.76															
	PP (µg L ⁻¹)	5	2.75	2.54	2.34	2.47	3.13	3.25	H	Median	2.3											3.3	
	Secchi (m)	5	5.5	5	3.8	4.7	6.4	7.6	L	Mean	10												
	SiO ₄	5	72.14	78.3	56.56	63.17	79.76	82.88															
	TSS (mg L ⁻¹)	5	1.38	1.23	0.92	1.15	1.65	1.97	H	Median	1.4											2.4	
	DIN (µg L ⁻¹)	5																					

OConnell River mouth (WH16)	PN (µg L ⁻¹)	5	15.28	15.46	12.81	13.03	17.45	17.64	H	Mean	14		
		5	15.28	15.46	12.81	13.03	17.45	17.64	H	Median	16	25	
	PO ₄ (µg L ⁻¹)	5	1.83	1.7	0.94	0.99	2.45	3.05	H	Median	1		
	POC (mg L ⁻¹)	5	124.36	133.5	86.35	90.19	151.05	160.72					
	PP (µg L ⁻¹)	5	2.99	2.82	2.71	2.79	3.12	3.5	H	Median	2.3	2.3	
	Secchi (m)	5	5	4.5	3.2	3.8	6.3	7.2	L	Mean	10		
		5	5	4.5	3.2	3.8	6.3	7.2	L	Median			
	SiO ₄	5	79.3	81.25	63.83	74.58	85.17	91.66					
	TSS (mg L ⁻¹)	5	1.57	1.31	0.88	1.18	1.92	2.58	H	Median	1.4	1.6	2.4
	DIN (µg L ⁻¹)	5											
	DOC (µg L ⁻¹)	5	1243	1221	1109	1119	1377	1387					
	DON (µg L ⁻¹)	5											
	DOP (µg L ⁻¹)	5	5.61	5.81	4.46	5.3	6.07	6.4					
	Chl-a (µg L ⁻¹)	5	0.63	0.66	0.4	0.47	0.76	0.84	H	Median	1.3		
	NO _x (µg L ⁻¹)	5	4.22	4.24	0.45	0.74	6.69	9	H	Median	4		
	PN (µg L ⁻¹)	5	28.14	25.28	19.45	22.2	31.6	42.17	H	Mean			
		5	28.14	25.28	19.45	22.2	31.6	42.17	H	Median			
	PO ₄ (µg L ⁻¹)	5	3.1	3.1	1.11	1.67	4.71	4.89	H	Median	3		
	POC (mg L ⁻¹)	5	235.93	228.75	165.93	165.94	262.7	356.33					
	PP (µg L ⁻¹)	5	6.64	6.18	5.19	5.27	7.52	9.05	H	Median			
Secchi (m)	5	3.4	3	1.7	2.3	5	5	L	Median	1.6			

	SiO ₄	5	243.61	227.04	103.08	177.82	322.28	387.84										
	TSS (mg L ⁻¹)	5	3.82	2.72	1.65	2.15	4.47	8.12	H	Median	5							
	DIN (µg L ⁻¹)	5																
	DOC (µg L ⁻¹)	5	1078	1020	939	994	1191	1245										
	DON (µg L ⁻¹)	5																
	DOP (µg L ⁻¹)	5	5.02	5.11	3.96	4.71	5.56	5.74										
	Chl-a (µg L ⁻¹)	5	0.51	0.48	0.3	0.42	0.64	0.71	H	Mean	0.45							
		5	0.51	0.48	0.3	0.42	0.64	0.71	H	Median		0.32	0.63					
	NO _x (µg L ⁻¹)	5	5.03	4.34	0.74	2.13	7.2	10.72	H	Median	0.25							
	PN (µg L ⁻¹)	5	19.2	18.54	13.6	16.7	21.97	25.21	H	Median	18	16	25					
	PO ₄ (µg L ⁻¹)	5	2.31	2.32	1.47	1.94	2.6	3.21	H	Median	2							
	POC (mg L ⁻¹)	5	172.3	162.59	99.32	138.77	221.63	239.21										
	PP (µg L ⁻¹)	5	5.12	4.8	4.17	4.34	6.14	6.18	H	Median	2.1	2.3	3.3					
	Secchi (m)	5	3.8	3.5	2.6	2.9	4.7	5.3	L	Mean	10							
		5	3.8	3.5	2.6	2.9	4.7	5.3	L	Median								
	SiO ₄	5	112.57	109.55	89.58	102.14	124.49	137.09										
	TSS (mg L ⁻¹)	5	3.51	2.64	1.18	1.8	5.26	6.68	H	Median	1.6	1.6	2.4					
	DIN (µg L ⁻¹)	9																
	DOC (µg L ⁻¹)	9	1742	2020	904	1273	2085	2157										
	DON (µg L ⁻¹)	9																
Fitzroy																		

DOP ($\mu\text{g L}^{-1}$)	9	5.17	5.26	4.29	4.75	5.57	5.85												
Chl-a ($\mu\text{g L}^{-1}$)	9	0.28	0.26	0.17	0.19	0.34	0.43	H											
	9	0.28	0.26	0.17	0.19	0.34	0.43	H										0.32	0.63
NO _x ($\mu\text{g L}^{-1}$)	9	2.13	1.02	0.41	0.56	4.2	5.8	H											
PN ($\mu\text{g L}^{-1}$)	9	14.99	13.59	9.94	11.37	17.5	21.43	H										16	25
PO ₄ ($\mu\text{g L}^{-1}$)	9	0.8	0.39	0.31	0.31	1.42	1.89	H											
POC (mg L ⁻¹)	9	105.54	89.22	56.17	66.74	142.04	169.28												
PP ($\mu\text{g L}^{-1}$)	9	2.31	2.42	1.45	1.49	3.03	3.14	H										2.3	3.3
Secchi (m)	9	10.37	11	6.32	7.52	12.7	13.6	L											
SiO ₄	9	39.39	37.29	22.02	32.35	52.43	55.42												
TSS (mg L ⁻¹)	9	1.19	0.64	0.29	0.37	1.23	3.75	H										1.6	2.4
DIN ($\mu\text{g L}^{-1}$)	9																		
DOC ($\mu\text{g L}^{-1}$)	9	1804	2056	888	1217	2141	2407												
DON ($\mu\text{g L}^{-1}$)	9																		
DOP ($\mu\text{g L}^{-1}$)	9	5.65	5.5	4.35	5	6.38	7.22												
Chl-a ($\mu\text{g L}^{-1}$)	9	0.19	0.18	0.14	0.15	0.24	0.26	H										0.32	0.63
NO _x ($\mu\text{g L}^{-1}$)	9	0.87	0.81	0.34	0.6	0.95	1.53	H											
PN ($\mu\text{g L}^{-1}$)	9	12.25	11.59	9.43	9.89	14.76	16.13	H										16	25
PO ₄ ($\mu\text{g L}^{-1}$)	9	0.92	0.7	0.31	0.4	1.56	1.84	H											

Barren (FTZ1)

		9	1.1	0.96	0.44	0.49	1.25	2.53	H	Mean	2		
	TSS (mg L ⁻¹)	9	1.1	0.96	0.44	0.49	1.25	2.53	H	Mean	2		2.5
	DIN (µg L ⁻¹)	9											
	DOC (µg L ⁻¹)	9	1899	2152	950	1288	2269	2530					
	DON (µg L ⁻¹)	9											
	DOP (µg L ⁻¹)	9	5.02	5.19	3.9	4.18	5.79	5.93					
	Chl-a (µg L ⁻¹)	9	0.35	0.32	0.13	0.14	0.49	0.68	H	Mean	0.45		
		9	0.35	0.32	0.13	0.14	0.49	0.68	H	Median		0.32	0.63
	NO _x (µg L ⁻¹)	9	1.88	0.91	0.46	0.62	3.12	5.22	H	Median	0.5		
	PN (µg L ⁻¹)	9	16.23	17.03	10.09	10.32	18.87	25.07	H	Mean	20		
		9	16.23	17.03	10.09	10.32	18.87	25.07	H	Median		16	25
Pelican (FTZ3)	PO ₄ (µg L ⁻¹)	9	1.74	1.63	0.85	1.36	2.31	2.59	H	Mean	2		
		9	1.74	1.63	0.85	1.36	2.31	2.59	H	Median			
	POC (mg L ⁻¹)	9	128.43	123.15	55.33	59.38	171.48	243.25					
		9	3.52	3.46	1.43	1.63	4.27	7.3	H	Mean	2.8		
		9	3.52	3.46	1.43	1.63	4.27	7.3	H	Median		2.4	3.4
	Secchi (m)	9	5.11	4	1.49	2.64	8.4	9.65	L	Mean	10		
		9	5.11	4	1.49	2.64	8.4	9.65	L	Median			
	SiO ₄	9	68.78	69.31	31.7	35.66	89.48	118.6					
		9	3.15	2.03	0.54	0.71	4.1	8.88	H	Mean	2		
		9	3.15	2.03	0.54	0.71	4.1	8.88	H	Median		1.7	2.5
Peak West (FTZ5)	DIN (µg L ⁻¹)	9											

	DOC (µg L ⁻¹)	9	1923	2254	924	1231	2340	2552												
	DON (µg L ⁻¹)	9																		
	DOP (µg L ⁻¹)	9	5.39	4.96	3.93	4.35	5.68	8.01												
	Chl-a (µg L ⁻¹)	9	0.46	0.4	0.25	0.33	0.6	0.82												
		9	0.46	0.4	0.25	0.33	0.6	0.82												0.32
	NO _x (µg L ⁻¹)	9	3.61	0.74	0.28	0.3	5.3	13.97												
		9	3.61	0.74	0.28	0.3	5.3	13.97												0.5
	PN (µg L ⁻¹)	9	18.96	16.28	12.39	13.74	23.67	30.74												
		9	18.96	16.28	12.39	13.74	23.67	30.74												20
	PO ₄ (µg L ⁻¹)	9	2.18	2.01	1.02	1.63	2.83	3.39												
		9	2.18	2.01	1.02	1.63	2.83	3.39												2
	POC (mg L ⁻¹)	9	162.26	146.01	85.69	97.57	202	293.71												
		9	162.26	146.01	85.69	97.57	202	293.71												
	PP (µg L ⁻¹)	9	4.4	3.43	2.21	2.68	5.55	8.52												
		9	4.4	3.43	2.21	2.68	5.55	8.52												2.4
		9	4.4	3.43	2.21	2.68	5.55	8.52												3.4
	Secchi (m)	9	2.7	2.75	1.34	2.3	3.16	3.76												
		9	2.7	2.75	1.34	2.3	3.16	3.76												10
		9	2.7	2.75	1.34	2.3	3.16	3.76												
	SiO ₄	9	84	85.67	55.07	59.16	106.11	121.24												
		9	84	85.67	55.07	59.16	106.11	121.24												
	TSS (mg L ⁻¹)	9	5.12	3.34	1.58	2.19	6.78	12.33												
		9	5.12	3.34	1.58	2.19	6.78	12.33												2
		9	5.12	3.34	1.58	2.19	6.78	12.33												1.7
	DIN (µg L ⁻¹)	9																		
		9																		
		9																		
	DOC (µg L ⁻¹)	9	2303	2488	1006	1302	2746	3678												
		9	2303	2488	1006	1302	2746	3678												
	DON (µg L ⁻¹)	9																		
		9																		
		9																		
	DOP (µg L ⁻¹)	9	4.89	5.19	3.45	4.24	5.62	5.81												
		9	4.89	5.19	3.45	4.24	5.62	5.81												
		9	4.89	5.19	3.45	4.24	5.62	5.81												

Fitzroy River Mouth (FTZ6)

	Chl-a (µg L ⁻¹)	9	0.86	0.78	0.68	0.73	1.05	1.13	H	Median	1
	NO _x (µg L ⁻¹)	9	9.37	9.8	2	5.91	11.78	16.61	H	Median	3
	PN (µg L ⁻¹)	9	35.68	35.53	24.55	27.58	42.75	47.86	H	Median	
	PO ₄ (µg L ⁻¹)	9	5.63	5.57	3.38	4.49	6.89	7.68	H	Median	3
	POC (mg L ⁻¹)	9	394.76	400.96	215.36	270.13	505.29	581.85			
	PP (µg L ⁻¹)	9	14.08	13.18	7.82	9.16	19.69	19.82	H	Median	
	Secchi (m)	9	0.69	0.5	0.38	0.5	0.93	1.26	L	Median	
	SiO ₄	9	135.01	139.4	110.04	122.39	141.98	162			
	TSS (mg L ⁻¹)	9	20.46	20.75	5.99	8.77	31.99	35.3	H	Median	

Table C-2: Summary of turbidity measurements from moored loggers in all regions except Cape York (site locations in Section 5) for the past three water years. N = number of daily means in the time-series; SE = standard error; %d> Trigger refers to the percentage of days each year with mean or median values above the site-specific water quality guideline values (Table C-8). Red shading indicates the annual means or medians that exceeded guideline values. %d> 5 NTU refers to the percentage of days above 5 NTU, a threshold suggested by Cooper et al. (2007, 2008) above which hard corals are likely to experience photo-physiological stress.

Subregion	Site	Oct 2018 - Sept 2019					Oct 2019 - Sept 2020					Oct 2020 - Sept 2021							
		N	Annual Mean	SE	Annual Median	%d > Trigger	%d > 5 NTU	N	Annual Mean	SE	Annual Median	%d > Trigger	%d > 5 NTU	N	Annual Mean	SE	Annual Median	%d > Trigger	%d > 5 NTU
Cape York	Dawson	150	1.63	0.11	1.07	65.33	3.33	128	1.00	0.06	0.68	38.28	0.00	225	1.39	0.15	0.64	41.78	3.56
	Forrester	N/A	N/A	N/A	N/A	N/A	N/A	215	0.46	0.45	0.01	38.14	0.00	222	0.31	0.01	0.25	3.60	0.00
Johnstone Russell Mulgrave	Fitzroy West	357	1.14	0.07	0.87	33.33	1.40	263	0.97	0.05	0.79	28.52	0.76	69	1.04	0.04	1.00	49.28	0.00
	Franklands West	365	0.92	0.05	0.66	60.82	1.10	366	0.82	0.03	0.65	59.84	0.55	174	1.20	0.24	0.61	52.30	2.87
	High West	365	1.23	0.07	0.87	37.81	1.92	320	1.16	0.05	0.89	39.06	1.25	254	1.43	0.12	0.90	42.52	3.94
	Russell Mulgrave Mouth Mooring	317	4.92	0.24	3.46	89.59	35.65	366	3.81	0.24	2.12	77.60	22.95	254	4.16	0.32	2.34	87.40	23.23

Subregion	Site	Oct 2018 - Sept 2019						Oct 2019 - Sept 2020						Oct 2020 - Sept 2021					
		N	Annual Mean	SE	Annual Median	%d > Trigger	%d > 5 NTU	N	Annual Mean	SE	Annual Median	%d > Trigger	%d > 5 NTU	N	Annual Mean	SE	Annual Median	%d > Trigger	%d > 5 NTU
Tully Herbert	Dunk North	361	3.63	0.24	1.50	74.52	21.61	366	2.81	0.17	1.25	70.22	17.21	139	3.70	0.33	2.05	89.93	23.02
	Tully River mouth mooring	318	4.63	0.20	3.84	46.86	30.50	318	3.82	0.21	2.79	29.25	20.13	251	3.96	0.34	2.67	31.87	22.71
Burdekin	Burdekin River mouth mooring	365	7.72	0.38	5.67	65.48	56.99	322	5.39	0.29	3.72	46.58	38.82	249	7.55	0.40	5.60	60.64	54.22
	Magnetic	353	2.72	0.22	1.51	58.07	12.46	366	1.77	0.09	1.21	43.99	4.64	250	2.14	0.18	1.36	53.20	6.40
	Palms West	304	0.99	0.04	0.85	55.59	0.33	313	0.66	0.02	0.64	23.96	0.00	251	0.99	0.04	0.88	62.55	0.40
Mackay-Whitsunday	Pandora	219	1.34	0.12	0.84	55.71	5.02	357	1.43	0.07	1.04	73.95	1.96	112	1.93	0.19	1.15	77.68	8.93
	Double Cone	347	1.54	0.05	1.21	57.06	0.00	366	1.42	0.04	1.14	54.64	0.82						
	Pine	232	2.68	0.15	1.89	78.45	13.36	306	2.17	0.11	1.50	67.97	8.50	258	1.55	0.05	1.26	62.79	1.16
	Repulse Islands dive mooring	365	4.20	0.20	2.90	67.40	27.40	366	3.59	0.17	2.72	62.84	19.13	118	6.04	0.56	3.51	46.61	38.14
	Seaforth	365	1.68	0.05	1.37	66.30	1.37	363	1.54	0.05	1.21	57.58	2.20	175	2.49	0.14	1.78	77.71	11.43

C-4 Data used to generate remote sensing maps

Table C-3: Summary of water quality data collected across the wet season colour classes (CC1–6) and water types (primary, secondary, tertiary) as part of the wet season event sampling of the MMP. Multi-years samples were collected between December–April by AIMS and CYWMP since 2016–17 and by JCU since 2003–04 and up to 2018–19. No Data = nd

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)	
Reef region	CC1	mean	54.63	2.20	1.90	0.95	62.52	16.87	29.83	119.32
		SD	101.36	3.41	1.24	1.05	48.38	22.09	40.53	115.83
		min	0.50	0.20	0.00	0.00	2.00	1.00	0.00	1.00
		max	590.00	26.70	6.03	5.00	325.00	98.00	167.00	573.00
		count	117	125	91	66	112	116	93	113
	CC1	mean	27.11	0.56	2.73	0.20		4.18	15.10	106.76
		SD	20.06	0.21	0.83	0.34		2.63	8.78	51.29
		min	2.91	0.24	1.91	0.00	Nd.	1.55	4.35	44.44
		max	54.14	0.89	3.56	0.92		6.81	24.39	173.71
		count	6	6	6	6		6	6	6
CC2	mean	18.30	1.48	0.94	1.35	50.36	9.50	10.66	53.80	
	SD	23.91	1.12	0.69	1.68	50.71	13.89	11.77	60.96	
	min	0.43	0.20	0.03	0.00	2.00	0.21	0.00	1.00	
	max	150.00	5.41	4.40	12.00	237.00	80.00	73.00	282.00	
	count	104	101	85	57	93	94	86	91	
CC2	mean	9.01	0.55	1.99	1.15		2.43	8.51	80.20	
	SD	5.48	0.37	2.05	0.96		1.40	4.58	43.82	
	min	2.95	0.12	0.04	0.00	Nd.	0.31	1.85	21.24	
	max	17.58	1.08	5.68	2.50		4.03	15.69	159.60	
	count	7	7	7	7		7	7	7	
CC3	mean	15.11	2.28	0.84	1.37	51.75	13.59	12.25	61.79	
	SD	14.14	2.98	0.83	0.74	47.76	13.86	13.68	61.82	

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
	min	0.80	0.20	0.05	0.50	2.00	1.55	0.00	1.00
	max	67.00	22.43	4.19	3.00	218.00	75.00	75.00	296.00
	count	78	78	63	21	68	71	62	66
2020-21	mean	2.64	0.65	0.94	1.42		1.16	6.11	49.43
	SD	2.57	0.32	0.59	0.99		1.48	3.56	35.62
	min	0.47	0.29	0.10	0.00	Nd.	0.31	3.58	21.44
	max	7.03	1.12	1.39	2.79		3.72	11.14	110.60
	count	4	4	4	4		4	4	4
multi-annual	mean	8.30	1.41	0.56	2.20	38.38	7.47	6.25	43.96
	SD	8.95	2.09	0.57	1.66	45.59	6.56	7.66	54.93
	min	0.00	0.10	0.00	0.00	0.14	0.00	0.00	0.00
	max	73.00	30.90	3.71	11.50	357.00	55.00	63.00	374.00
	count	424	420	366	197	398	404	365	381
2020-21	mean	3.68	0.40	0.35	2.58		1.32	4.32	40.66
	SD	3.08	0.26	0.48	2.42		1.73	2.31	15.67
	min	0.30	0.09	0.02	0.00	Nd.	0.31	0.48	11.04
	max	14.44	1.19	1.72	10.54		10.53	9.23	75.68
	count	37	37	37	37		37	37	37
multi-annual	mean	18.27	1.61	0.82	1.78	46.05	9.77	10.87	60.55
	SD	45.70	2.37	0.88	1.75	49.86	12.73	19.44	76.73
	min	0.00	0.10	0.00	0.00	0.14	0.00	0.00	0.00
	max	590.00	30.90	6.03	16.00	357.00	98.00	167.00	573.00
	count	754	755	636	370	702	716	637	682
2020-21	mean	6.70	0.46	0.70	2.04		1.57	5.94	52.42
	SD	10.22	0.29	1.11	2.22	Nd.	1.85	4.88	34.80
	min	0.30	0.09	0.02	0.00		0.31	0.48	11.04

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
	max	54.14	1.19	5.68	10.54		10.53	24.39	173.71
	count	54	54	54	54		54	54	54
S (or CC5)	mean	5.92	0.80	0.27	4.00	21.51	5.62	3.45	25.49
	SD	7.99	0.84	0.41	2.33	28.51	5.75	4.36	33.62
	min	0.00	0.02	0.00	0.20	0.00	0.00	0.00	0.00
	max	130.00	12.50	3.25	16.00	369.00	63.00	47.90	456.00
	count	926	955	722	594	939	947	862	893
	mean	2.94	0.34	0.31	5.90		0.99	3.06	35.35
SD	4.10	0.32	0.60	3.12		0.88	2.30	26.60	
min	0.13	0.07	0.01	0.00		Nd.	0.31	0.07	9.64
max	31.34	2.95	4.06	14.70			6.19	15.29	224.88
count	149	149	149	149			149	149	149
T (or CC6)	mean	3.92	0.51	0.13	7.05	15.22	4.27	2.27	18.17
	SD	5.10	0.51	0.23	3.76	15.04	3.84	2.82	21.44
	min	0.00	0.02	0.00	0.50	0.04	0.02	0.00	0.00
	max	31.00	5.34	2.00	19.00	104.00	21.00	18.00	174.00
	count	301	304	216	212	304	304	285	300
	mean	2.17	0.29	0.14	8.35		0.94	2.76	30.40
SD	2.34	0.20	0.32	3.57		1.01	2.65	18.04	
min	0.14	0.04	0.01	0.00		Nd.	0.31	0.10	12.44
max	12.77	1.33	2.27	20.80			8.05	23.73	142.48
count	101	101	101	101			101	101	101

Table C-4: Summary of water quality data collected in the Cape York region across the wet season colour classes (CC1–6) and water types (primary, secondary, tertiary) as part of the wet season event sampling of the MMP. Multi-years samples were collected between December and April by CYWMP since 2016–17 and up to 2018–19. No Data = nd.

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
multi-annual	mean	28.73	1.56	2.82	1.11	34.38	4.74	11.83	97.63
	SD	49.00	1.23	1.50	1.01	17.24	2.95	10.63	93.58
	min	0.50	0.20	0.00	0.10	4.00	1.00	1.00	14.00
	max	250.00	5.34	6.03	4.15	83.18	12.00	35.00	532.25
	count	32	37	27	31	37	37	18	36
2020-21	mean	25.98	0.62	1.91	0.18		1.55	12.01	84.44
	SD	22.29	0.17	0.00	0.37		0.00	8.02	38.93
	min	2.91	0.42	1.91	0.00	Nd.	1.55	4.35	44.44
	max	54.14	0.89	1.91	0.92		1.55	23.08	137.20
	count	5	5	5	5		5	5	5
multi-annual	mean	24.69	1.32	1.38	2.40	32.26	3.99	8.21	49.91
	SD	36.59	0.97	1.20	2.84	22.69	25.33	56.19	
	min	0.35	1.00	0.31	1.40	0.03	3.67	1.60	0.00
	max	150.00	3.90	4.40	12.00	80.00	10.00	35.00	244.00
	count	20	19	12	14	21	20	14	21
2020-21	mean	11.25	0.54	2.86	0.70		1.14	8.96	91.81
	SD	5.96	0.37	2.82	0.55		0.64	5.34	51.78
	min	3.25	0.12	0.04	0.00	Nd.	0.31	1.85	21.24
	max	17.58	1.06	5.68	1.53		1.86	15.69	159.60
	count	4	4	4	4		4	4	4
multi-annual	mean	11.50	3.41	2.15	1.55	27.99	4.90	7.00	77.75
	SD	17.09	2.48	1.27	0.74	25.78	2.16	2.55	79.27
	min	0.80	0.79	0.47	0.75	4.33	2.71	3.00	2.00
	max	53.00	8.82	4.19	2.80	89.00	9.00	10.00	253.00

		TSS (mg L ⁻¹)		Chl- <i>a</i> (µg L ⁻¹)		CDOM (m ⁻¹)		SDD (m)		DIN (µg L ⁻¹)		DIP (µg L ⁻¹)		PP (µg L ⁻¹)		PN (µg L ⁻¹)	
	count	7	9	9	9	6	9	9	9	9	9	4	8				
2020-21	mean	2.64	0.65	0.94	1.42	1.16	6.11	1.16	49.43								
	SD	2.57	0.32	0.59	0.99	1.48	3.56	1.48	35.62								
	min	0.47	0.29	0.10	0.00	0.31	3.58	0.31	21.44								
	max	7.03	1.12	1.39	2.79	3.72	11.14	3.72	110.60								
	count	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00								
multi-annual	mean	5.44	1.14	1.21	3.02	3.26	2.94	3.26	50.61								
	SD	5.54	1.00	1.20	2.14	1.79	1.94	1.79	58.97								
	min	0.10	0.10	0.00	0.25	1.00	0.00	1.00	2.00								
	max	34.00	5.18	3.71	9.50	11.00	7.00	11.00	318.00								
	count	44	49	31	36	49	33	49	48								
2020-21	mean	3.40	0.37	0.37	2.52	0.87	3.86	0.87	36.84								
	SD	3.60	0.25	0.57	2.89	0.53	2.63	0.53	16.35								
	min	0.30	0.10	0.02	0.00	0.31	0.48	0.31	11.04								
	max	14.44	1.19	1.72	10.54	1.86	9.23	1.86	67.04								
	count	22	22	22	22	22	22	22	22								
multi-annual	mean	19.13	1.36	1.49	2.03	3.98	6.22	3.98	66.59								
	SD	38.36	1.30	1.53	1.94	2.34	7.56	2.34	77.80								
	min	0.10	0.10	0.00	0.10	1.00	0.00	1.00	0.00								
	max	250.00	8.82	6.03	12.00	12.00	35.00	12.00	532.25								
	count	125	136	101	109	137	91	137	135								
2020-21	mean	6.98	0.46	0.70	1.85	0.96	5.52	0.96	49.75								
	SD	11.65	0.29	1.21	2.50	0.75	4.83	0.75	35.42								
	min	0.30	0.10	0.02	0.00	0.31	0.48	0.31	11.04								
	max	54.14	1.19	5.68	10.54	3.72	23.08	3.72	159.60								
	count	35	35	35	35	35	35	35	35								

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
S (or CC5)	multi-annual	mean	4.47	0.68	4.51	13.71	2.99	1.79	24.80
		SD	7.06	0.60	2.63	15.36	1.40	2.31	29.75
		min	0.10	0.07	0.20	2.32	1.00	0.00	0.00
		max	60.00	3.26	16.00	131.25	8.00	13.00	179.00
		count	124	132	51	120	132	98	131
S (or CC5)	2020-21	mean	2.96	0.30	6.22		0.82	2.77	32.70
		SD	4.36	0.23	3.34		0.63	2.06	26.41
		min	0.13	0.07	0.00	Nd.	0.31	0.07	9.64
		max	31.34	1.37	14.70		3.10	12.33	224.88
		count	109	109	109		109	109	109
T (or CC6)	multi-annual	mean	2.48	0.45	8.01	12.27	2.93	1.60	17.22
		SD	2.37	0.46	4.08	13.99	1.47	1.51	19.40
		min	0.10	0.02	0.80	2.94	1.00	0.00	0.00
		max	14.00	1.95	17.40	104.00	7.14	5.00	84.00
		count	61	61	47	63	63	52	63
T (or CC6)	2020-21	mean	2.28	0.28	8.96		0.80	2.42	25.79
		SD	2.15	0.21	3.49		0.66	1.39	9.22
		min	0.14	0.04	0.00	Nd.	0.31	0.10	12.44
		max	12.43	1.33	20.80		3.41	7.65	50.48
		count	70	70	70	70	70	70	70

Table C-5: Summary of water quality data collected in the Wet Tropics region across the wet season colour classes (CC1–6) and water types (primary, secondary, tertiary) as part of the wet season event sampling of the MMP. Samples were collected between December and April by AIMS since 2016–17 and JCU since 2003–04 and up to and up to 2018–19. No Data = nd.

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
multi-annual	mean	0.90	11.52	1.09	1.10	68.89	4.23	10.04	40.09
	SD	0.59	8.04	1.40	0.46	45.18	1.91	9.51	43.24
	min	0.00	2.10	0.20	0.26	18.00	1.78	0.00	1.00
	max	2.00	38.00	6.14	1.82	140.00	8.00	32.00	167.00
	count	13	18	18	18	10	11	10	11
2020-21	mean	Nd.							
	SD	Nd.							
	min	Nd.							
	max	Nd.							
	count	Nd.							
multi-annual	mean	0.89	14.02	1.43	1.00	72.87	6.82	9.83	50.26
	SD	0.71	15.65	1.08	0.43	62.16	4.43	9.85	53.41
	min	0.00	2.30	0.20	0.33	11.16	1.97	0.00	2.00
	max	2.25	92.00	5.34	2.37	237.00	18.00	52.00	263.00
	count	27	50	48	49	40	40	39	39
2020-21	mean	Nd.							
	SD	Nd.							
	min	Nd.							
	max	Nd.							
	count	Nd.							
multi-annual	mean	1.13	11.20	1.53	0.55	64.15	10.89	6.85	46.71
	SD	0.69	8.29	1.53	0.31	57.72	6.02	5.16	35.57
	min	0.50	1.40	0.20	0.10	6.00	1.55	0.00	2.00
	max	2.50	34.00	7.48	1.43	218.00	21.00	21.00	134.00

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
	count	7	38	37	34	30	30	26	28
2020-21	mean	Nd.							
	SD								
	min								
	max								
	count								
multi-annual	mean	2.01	7.10	1.31	0.54	49.08	7.30	5.53	36.73
	SD	1.55	7.53	2.08	0.44	54.86	4.95	7.72	52.39
	min	0.00	0.00	0.20	0.00	0.14	0.00	0.00	0.00
	max	11.50	70.00	30.90	3.11	357.00	21.00	63.00	374.00
	count	112	262	258	249	234	236	219	224
2020-21	mean	Nd.							
	SD								
	min								
	max								
	count								
multi-annual	mean	1.65	8.86	1.33	0.65	57.28	7.54	6.48	40.87
	SD	1.44	9.60	1.88	0.48	60.16	5.12	8.06	53.78
	min	0.00	0.00	0.20	0.00	0.14	0.00	0.00	0.00
	max	11.50	92.00	30.90	3.11	357.00	21.00	63.00	374.00
	count	164	375	368	357	321	324	301	309
2020-21	mean	Nd.							
	SD								
	min								
	max								
	count								

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
S (or CC5)	multi-annual	mean	4.09	0.79	0.29	26.12	5.89	3.25	23.92
		SD	2.34	0.70	0.40	34.99	4.74	3.63	30.47
		min	0.50	0.02	0.00	0.08	0.00	0.00	0.00
		max	13.00	11.24	2.74	369.00	22.00	29.00	372.00
		count	289	482	438	475	476	446	447
S (or CC5)	2020-21	mean	Nd.						
		SD	Nd.						
		min	Nd.						
		max	Nd.						
		count	Nd.						
T (or CC6)	multi-annual	mean	7.33	0.55	0.14	18.03	4.68	2.14	18.32
		SD	3.85	0.60	0.19	16.56	4.18	2.56	23.40
		min	0.50	0.02	0.00	0.04	0.03	0.00	0.00
		max	19.00	5.34	1.38	82.00	21.00	17.00	174.00
		count	121	172	141	169	169	166	167
T (or CC6)	2020-21	mean	10.62	2.27	2.25	8.05	8.05	23.73	142.48
		SD	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		min	10.62	0.16	2.27	2.25	8.05	23.73	142.48
		max	10.62	0.16	2.27	2.25	8.05	23.73	142.48
		count	1	1	1	1	1	1	1

Table C-6: Summary of water quality data collected in the Burdekin region across the wet season colour classes (CC1–6) and water types (primary, secondary, tertiary) as part of the wet season event sampling of the MMP. Multi-years samples were collected between December and April by AIMS since 2016–17 and JCU since 2003–04 and up to 2018–19. No Data = nd.

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
multi-annual	mean	105.00	1.45	1.68	0.90	75.14	11.58	45.48	141.23
	SD	146.58	1.13	1.02	1.41	58.07	7.48	52.84	132.97
	min	1.35	0.20	0.07	0.00	2.00	1.00	0.00	14.00
	max	590.00	5.48	3.48	5.00	325.00	29.00	167.00	573.00
	count	37	40	25	17	37	39	37	38
2020-21	mean	Nd.							
	SD	Nd.							
	min	Nd.							
	max	Nd.							
	count	Nd.							
multi-annual	mean	17.74	1.71	0.39	1.23	21.09	7.13	12.87	50.59
	SD	25.48	1.21	0.37	0.88	21.70	9.12	16.89	52.99
	min	0.43	0.20	0.04	0.20	2.00	0.21	0.00	1.00
	max	120.00	5.41	1.34	3.50	90.00	46.00	73.00	255.00
	count	22	23	16	16	22	22	21	21
2020-21	mean	Nd.							
	SD	Nd.							
	min	Nd.							
	max	Nd.							
	count	Nd.							
multi-annual	mean	11.85	2.09	0.59	1.08	27.78	6.74	15.87	64.50
	SD	15.72	2.33	0.54	0.36	29.41	5.62	20.09	74.71
	min	2.70	0.53	0.05	0.50	2.00	2.00	0.00	3.00
	max	66.00	9.25	1.66	1.50	96.00	20.00	75.00	289.00

		TSS (mg L ⁻¹)		Chl- <i>a</i> (µg L ⁻¹)		CDOM (m ⁻¹)		SDD (m)		DIN (µg L ⁻¹)		DIP (µg L ⁻¹)		PP (µg L ⁻¹)		PN (µg L ⁻¹)			
		14	13	7	6	7	6	12	12	12	12	12	12	12	12	12	12		
		count	count	count	count	count	count	count	count	count	count	count	count	count	count	count	count		
2020-21	CC3	mean																	
		SD																	
		min																	
		max																	
		count																	
multi-annual	CC4	mean	7.52	1.42	0.34	2.10	11.07	4.48	7.72	39.86									
		SD	10.55	2.15	0.40	1.17	8.57	4.32	8.32	40.14									
		min	0.05	0.20	0.02	0.30	0.26	0.09	0.00	2.00									
		max	73.00	13.78	1.81	4.50	62.00	30.00	37.90	239.00									
		count	57	53	36	40	56	56	54	54									
2020-21	CC4	mean	5.01	0.58	0.32	2.74	2.52	4.90	49.44										
		SD	2.09	0.30	0.33	1.89	3.33	1.64	14.81										
		min	2.63	0.25	0.05	1.20	0.31	2.62	26.24										
		max	8.69	1.08	0.99	7.00	10.53	8.26	75.68										
		count	7	7	7	7	7	7	7	7									
multi-annual	P	mean	36.91	1.53	0.75	1.79	32.63	7.21	20.33	73.85									
		SD	89.58	1.77	0.88	2.02	43.77	7.13	34.74	94.74									
		min	0.05	0.14	0.00	0.00	0.26	0.09	0.00	1.00									
		max	590.00	13.78	3.48	16.00	325.00	46.00	167.00	573.00									
		count	132	131	86	81	129	131	126	127									
2020-21	P	mean	5.01	0.58	0.32	2.74	2.52	4.90	49.44										
		SD	2.09	0.30	0.33	1.89	3.33	1.64	14.81										
		min	2.63	0.25	0.05	1.20	0.31	2.62	26.24										
		max	8.69	1.08	0.99	7.00	10.53	8.26	75.68										
		count	7	7	7	7	7	7	7	7									

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)
S (or CC5)	multi-annual	mean	4.86	0.13	3.68	15.15	3.55	2.90	24.65
		SD	9.64	0.24	2.08	21.61	3.51	4.20	23.98
		min	0.20	-0.02	0.20	0.00	0.01	0.00	0.00
		max	130.00	8.69	14.00	245.68	27.90	47.90	146.00
		count	188	187	146	187	187	177	176
S (or CC5)	2020-21	mean	3.47	0.13	4.97		1.37	3.40	39.98
		SD	3.57	0.26	1.77		0.97	2.28	33.88
		min	0.73	0.07	1.90	Nd.	0.31	0.97	16.24
		max	13.55	2.95	7.90		4.03	9.63	172.88
		count	20	20	20		20	20	20
T (or CC6)	multi-annual	mean	3.60	0.10	5.34	11.49	4.09	2.30	20.34
		SD	2.55	0.20	2.50	8.93	3.15	2.49	20.54
		min	0.15	0.00	1.40	0.11	0.02	0.00	0.00
		max	12.00	1.14	13.00	40.00	12.00	11.00	80.96
		count	47	45	35	47	47	43	45
T (or CC6)	2020-21	mean	2.34	0.03	5.51		1.02	2.55	36.18
		SD	3.57	0.26	1.77		0.97	2.28	33.88
		min	0.73	0.07	1.90	Nd.	0.31	0.97	16.24
		max	13.55	2.95	7.90		4.03	9.63	172.88
		count	20	20	20		20	20	20

Table C-7: Summary of water quality data collected in the Mackay-Whitsunday region across the wet season colour classes (CC1–CC6) and water types (primary, secondary, tertiary) as part of the wet season event sampling of the MMP. Multi-year samples were collected between December and April by AIMS since 2016–17 and JCU since 2003–04 and up to 2018–19. No Data = nd.

		TSS (mg L ⁻¹)	Chl- <i>a</i> (µg L ⁻¹)	CDOM (m ⁻¹)	SDD (m)	DIN (µg L ⁻¹)	DIP (µg L ⁻¹)	PP (µg L ⁻¹)	PN (µg L ⁻¹)	
multi-annual	CC1	mean	73.00	1.13	0.35	44.00	13.67	25.67	73.67	
		SD	36.12	0.44	0.12	26.99	8.38	7.72	40.20	
		min	24.00	1.42	0.20	15.00	5.00	15.00	32.00	
		max	110.00	6.78	0.50	80.00	25.00	33.00	128.00	
		count	3	3	3	3	3	3	3	
2020-21	CC1	mean	Nd.							
		SD	Nd.							
		min	Nd.							
		max	Nd.							
		count	Nd.							
multi-annual	CC2	mean	22.35	0.92	0.11	27.50	8.00	14.50	32.00	
		SD	16.65	0.65	0.03	5.50	2.00	9.50	27.00	
		min	5.70	0.27	0.07	Nd.	6.00	5.00	5.00	
		max	39.00	1.56	0.14	33.00	10.00	24.00	59.00	
		count	2	2	2	2	2	2	2	
2020-21	CC2	mean	Nd.							
		SD	Nd.							
		min	Nd.							
		max	Nd.							
		count	Nd.							
multi-annual	CC3	mean	14.00	1.35	0.14	58.50	8.00	12.50	15.00	
		SD	0.00	0.05	0.00	Nd.	6.00	3.50	5.00	
		min	14.00	1.30	0.14	33.00	2.00	9.00	10.00	

C-5 Site-specific Guideline Values for MMP sites

Table C-8: Site-specific Guideline Values (GVs) used for comparison with water quality monitoring data. These GV values are used to calculate the annual condition version of the WQ Index for each water quality sampling location and are derived from the Water Quality Guidelines for the Great Barrier Reef Marine Park (Great Barrier Reef Marine Park Authority, 2010, see Table B-1). Basin-level water quality objectives can be accessed online (Great Barrier Reef Marine Park Authority, Water quality guidelines for the Great Barrier Reef). Seasonal guideline values (i.e., wet vs. dry) are calculated as described in De'ath and Fabricius (2008). Guideline values for the Cape York region come from State of Queensland, (2020). See Appendix B for details on Index calculation. DOF is direction of failure ('H' = high values fail, while 'L' = low values fail). Annual mean GV values are applied to annual mean values of monitoring data (and median GV values are applied to median data, et cetera). Bold GV values are those applied to monitoring data.

GBRMMPA group	GBRMMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
30	ER01, AR01, PRN01, PRS01	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				0.70
		NO _x ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				1.50
		PN ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				
		PO ₄ ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				3.00
		PP ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				
		Secchi (m)	Enclosed Coastal waters	L				3.00
		TSS (mg L^{-1})	Enclosed Coastal waters	H				4.00
		Turbidity (NTU)	Enclosed Coastal waters	H		10.00		
40	KR01, KR02, BR01, NR01, NR02	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				0.70
		NO _x ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				1.00
		PN ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				
		PO ₄ ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				2.00
		PP ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				
		Secchi (m)	Enclosed Coastal waters	L				1.50
		TSS (mg L^{-1})	Enclosed Coastal waters	H				6.00
		Turbidity (NTU)	Enclosed Coastal waters	H		11.00		
50	ER02b, ER03, AR02b, AR03b, CI01, NR03, NR04, SR03, SR04, PRN02, PRN03, PRS02, PRS03, PRS2.5	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.36	0.25	0.46
		NO _x ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.35	0.32	0.45
		PN ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		18.00		20.00
		PO ₄ ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		1.40	1.86	0.93
		PP ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		2.60		3.00
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L^{-1})	Open Coastal waters	H		1.90		1.70
		Turbidity (NTU)	Open Coastal waters	H			0.90	0.80
		60	AE04, ER05, NR05, SR05, SR06, PRN04	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Midshelf waters	H		0.27
NO _x ($\mu\text{g L}^{-1}$)	Midshelf waters			H		0.35		

GBRMPA group	GBRMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
	PRN05, PRN06, PRBB, PRS05	PN ($\mu\text{g L}^{-1}$)	Midshelf waters	H		18.00		
		PO ₄ ($\mu\text{g L}^{-1}$)	Midshelf waters	H		0.62		
		PP ($\mu\text{g L}^{-1}$)	Midshelf waters	H		2.00		
		Secchi (m)	Midshelf waters	L	10.00			
		TSS (mg L^{-1})	Midshelf waters	H		1.50		
		Turbidity (NTU)	Midshelf waters	H		0.50		
70	NR06, ER06	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Offshore waters	H		0.26		
		NO _x ($\mu\text{g L}^{-1}$)	Offshore waters	H		0.42		
		PN ($\mu\text{g L}^{-1}$)	Offshore waters	H		16.00		
		PO ₄ ($\mu\text{g L}^{-1}$)	Offshore waters	H		0.39		
		PP ($\mu\text{g L}^{-1}$)	Offshore waters	H		1.90		
		Secchi (m)	Offshore waters	L	17.00			
		TSS (mg L^{-1})	Offshore waters	H		0.50		
		Turbidity (NTU)	Offshore waters	H		0.50		
1	C1, C6, C8, RM1, RM4, RM8, TUL1	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.35		
		PN ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	20.00		16.00	25.00
		PO ₄ ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		2.00		
		PP ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L^{-1})	Open Coastal waters	H	2.00		1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		1.00		
2	RM9, RM10, TUL3, TUL4, TUL5, TUL6, TUL8, TUL9	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.35		
		PN ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	20.00		16.00	25.00
		PO ₄ ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		2.00		
		PP ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L^{-1})	Open Coastal waters	H	2.00		1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		1.00		
3	C4, C5, C11, RM2, RM3, RM5, RM6, RM7, TUL2	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Midshelf waters	H		0.30	0.32	0.63
		NO _x ($\mu\text{g L}^{-1}$)	Midshelf waters	H		0.31		
		PN ($\mu\text{g L}^{-1}$)	Midshelf waters	H		14.00	16.00	25.00

GBRMMPA group	GBRMMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
		PO ₄ (µg L ⁻¹)	Midshelf waters	H		2.00		
		PP (µg L ⁻¹)	Midshelf waters	H		2.00	2.30	3.30
		Secchi (m)	Midshelf waters	L		13.00		
		TSS (mg L ⁻¹)	Midshelf waters	H		1.20	1.60	2.40
		Turbidity (NTU)	Midshelf waters	H		0.60		
4	RM12, TUL11	Chl- <i>a</i> (µg L ⁻¹)	Midestuarine waters	H		2.00		
		NO _x (µg L ⁻¹)	Midestuarine waters	H		15.00		
		PN (µg L ⁻¹)	Midestuarine waters	H				
		PO ₄ (µg L ⁻¹)	Midestuarine waters	H		3.00		
		PP (µg L ⁻¹)	Midestuarine waters	H				
		Secchi (m)	Midestuarine waters	L		1.50		
		TSS (mg L ⁻¹)	Midestuarine waters	H		7.00		
		Turbidity (NTU)	Midestuarine waters	H		5.00		
5	TUL7, TUL10	Chl- <i>a</i> (µg L ⁻¹)	Lower estuarine waters	H		1.10		
		NO _x (µg L ⁻¹)	Lower estuarine waters	H		3.00		
		PN (µg L ⁻¹)	Lower estuarine waters	H				
		PO ₄ (µg L ⁻¹)	Lower estuarine waters	H		3.00		
		PP (µg L ⁻¹)	Lower estuarine waters	H				
		Secchi (m)	Lower estuarine waters	L		1.60		
		TSS (mg L ⁻¹)	Lower estuarine waters	H		5.00		
		Turbidity (NTU)	Lower estuarine waters	H		4.00		
6	BUR1, BUR2	Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H		0.35	0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		0.28		
		PN (µg L ⁻¹)	Open Coastal waters	H		12.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		1.00		
		PP (µg L ⁻¹)	Open Coastal waters	H		2.20	2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L ⁻¹)	Open Coastal waters	H		1.20	1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		0.80		
7	BUR3	Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		0.28		
		PN (µg L ⁻¹)	Open Coastal waters	H	20.00		16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		1.00		

GBRMMPA group	GBRMMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
		PP ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L^{-1})	Open Coastal waters	H	2.00		1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		0.80		
8	BUR4	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.59	0.32	0.63
		NO _x ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.28		
		PN ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		17.00	16.00	25.00
		PO ₄ ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		1.00		
		PP ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L		4.00		
		TSS (mg L^{-1})	Open Coastal waters	H		1.90	1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		1.30		
9	BUR5	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.60	0.32	0.63
		NO _x ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		0.50		
		PN ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	20.00		16.00	25.00
		PO ₄ ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		2.00		
		PP ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L		3.00		
		TSS (mg L^{-1})	Open Coastal waters	H		5.00	1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		3.00		
10	BUR6, BUR7	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		1.00		
		PN ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		13.00	16.00	25.00
		PO ₄ ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		2.00		
		PP ($\mu\text{g L}^{-1}$)	Open Coastal waters	H		2.10	2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L^{-1})	Open Coastal waters	H		1.20	1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H	2.00			
11	BUR8, BUR9	Chl- <i>a</i> ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H		1.00		
		NO _x ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H		4.00		
		PN ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				
		PO ₄ ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H		1.00		
		PP ($\mu\text{g L}^{-1}$)	Enclosed Coastal waters	H				

GBRMMPA group	GBRMMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
		Secchi (m)	Enclosed Coastal waters	L		1.50		
		TSS (mg L ⁻¹)	Enclosed Coastal waters	H		2.00		
		Turbidity (NTU)	Enclosed Coastal waters	H		4.00		
12	BUR10	Chl- <i>a</i> (µg L ⁻¹)	Midshelf waters	H		0.33	0.32	0.63
		NO _x (µg L ⁻¹)	Midshelf waters	H		0.28		
		PN (µg L ⁻¹)	Midshelf waters	H		14.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	Midshelf waters	H		1.00		
		PP (µg L ⁻¹)	Midshelf waters	H		2.00	2.30	3.30
		Secchi (m)	Midshelf waters	L	10.00			
		TSS (mg L ⁻¹)	Midshelf waters	H		0.80	1.60	2.40
		Turbidity (NTU)	Midshelf waters	H		0.50		
13	BUR11, BUR12	Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		1.00		
		PN (µg L ⁻¹)	Open Coastal waters	H	20.00		16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		2.00		
		PP (µg L ⁻¹)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L ⁻¹)	Open Coastal waters	H	2.00		1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		2.00		
14	BUR13, BUR14, BUR15	Chl- <i>a</i> (µg L ⁻¹)	Enclosed Coastal waters	H		1.00		
		NO _x (µg L ⁻¹)	Enclosed Coastal waters	H		4.00		
		PN (µg L ⁻¹)	Enclosed Coastal waters	H				
		PO ₄ (µg L ⁻¹)	Enclosed Coastal waters	H		1.00		
		PP (µg L ⁻¹)	Enclosed Coastal waters	H				
		Secchi (m)	Enclosed Coastal waters	L		1.50		
		TSS (mg L ⁻¹)	Enclosed Coastal waters	H		2.00		
		Turbidity (NTU)	Enclosed Coastal waters	H		4.00		
15	WHI1, WHI2, WHI3, WHI4, WHI5	Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H		0.36	0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		1.00		
		PN (µg L ⁻¹)	Open Coastal waters	H	14.00		16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		1.00		
		PP (µg L ⁻¹)	Open Coastal waters	H		2.30	2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			

GBRMPA group	GBRMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
		TSS (mg L ⁻¹)	Open Coastal waters	H		1.40	1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H		1.10		
16	WHI6	Chl- <i>a</i> (µg L ⁻¹)	Enclosed Coastal waters	H		1.30		
		NO _x (µg L ⁻¹)	Enclosed Coastal waters	H		4.00		
		PN (µg L ⁻¹)	Enclosed Coastal waters	H				
		PO ₄ (µg L ⁻¹)	Enclosed Coastal waters	H		3.00		
		PP (µg L ⁻¹)	Enclosed Coastal waters	H				
		Secchi (m)	Enclosed Coastal waters	L		1.60		
		TSS (mg L ⁻¹)	Enclosed Coastal waters	H		5.00		
		Turbidity (NTU)	Enclosed Coastal waters	H		4.00		
17	WHI7, WHI10	Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		0.25		
		PN (µg L ⁻¹)	Open Coastal waters	H		18.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		2.00		
		PP (µg L ⁻¹)	Open Coastal waters	H		2.10	2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L ⁻¹)	Open Coastal waters	H		1.60	1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H	2.00			
18	WHI8, WHI11	Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		1.00		
		PN (µg L ⁻¹)	Open Coastal waters	H	20.00		16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		2.00		
		PP (µg L ⁻¹)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L ⁻¹)	Open Coastal waters	H	2.00		1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H	2.00			
19	WHI9	Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		0.25		
		PN (µg L ⁻¹)	Open Coastal waters	H		18.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		2.00		
		PP (µg L ⁻¹)	Open Coastal waters	H		2.10	2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L ⁻¹)	Open Coastal waters	H		1.60	1.60	2.40

GBRMPA group	GBRMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
20	WHI10.1, WHI10.2	Turbidity (NTU)	Open Coastal waters	H	1.00			
		Chl- <i>a</i> (µg L ⁻¹)	Open Coastal waters	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	Open Coastal waters	H		1.00		
		PN (µg L ⁻¹)	Open Coastal waters	H	20.00		16.00	25.00
		PO ₄ (µg L ⁻¹)	Open Coastal waters	H		2.00		
		PP (µg L ⁻¹)	Open Coastal waters	H	2.80		2.30	3.30
		Secchi (m)	Open Coastal waters	L	10.00			
		TSS (mg L ⁻¹)	Open Coastal waters	H	2.00		1.60	2.40
		Turbidity (NTU)	Open Coastal waters	H			2.00	12.00
	FTZ1	Chl- <i>a</i> (µg L ⁻¹)	Midshelf waters	H		0.27	0.32	0.63
	FTZ2, FTZ3, FTZ4, FTZ5		Open Coastal waters	H	0.45		0.32	0.63
	FTZ6		Enclosed Coastal waters	H		1.00		
	SR01, SR02		Enclosed Coastal waters	H				0.40
	FTZ1	NO _x (µg L ⁻¹)	Midshelf waters	H		0.50		
	FTZ2, FTZ3, FTZ4, FTZ5		Open Coastal waters	H		0.50		
	FTZ6		Enclosed Coastal waters	H		3.00		
	SR01, SR02		Enclosed Coastal waters	H				1.50
	FTZ1	PN (µg L ⁻¹)	Midshelf waters	H		12.00	16.00	25.00
	FTZ2, FTZ3, FTZ5		Open Coastal waters	H	20.00		16.00	25.00
	FTZ4		Open Coastal waters	H		15.00	16.00	25.00
	FTZ6		Enclosed Coastal waters	H				
	SR01, SR02		Enclosed Coastal waters	H				
	FTZ1		Midshelf waters	H		2.00		
	FTZ2, FTZ3	PO ₄ (µg L ⁻¹)	Open Coastal waters	H	2.00			
	FTZ4, FTZ5		Open Coastal waters	H		2.00		
	FTZ6	PP (µg L ⁻¹)	Enclosed Coastal waters	H		3.00		
	SR01, SR02		Enclosed Coastal waters	H				2.00
	FTZ1		Midshelf waters	H		1.90	2.40	3.40
	FTZ2, FTZ3, FTZ5		Open Coastal waters	H	2.80		2.40	3.40
	FTZ4	PP (µg L ⁻¹)	Open Coastal waters	H		2.50	2.30	3.30
	FTZ6		Secchi (m)	Enclosed Coastal waters	H			
	SR01, SR02		Secchi (m)	Enclosed Coastal waters	H			

GBRMPA group	GBRMPA sites	Measure	Water body	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
	ER01, AR01, SR01, SR02	TSS (mg L ⁻¹)	Enclosed Coastal waters	L				
	FTZ1		Midshelf waters	L		12.00		
	FTZ2, FTZ3, FTZ5		Open Coastal waters	L	10.00			
	FTZ4	Secchi (m)	Open Coastal waters	L		10.00		
	FTZ6	TSS (mg L ⁻¹)	Enclosed Coastal waters	L				
	SR01, SR02	TSS (mg L ⁻¹)	Enclosed Coastal waters	L				3.10
	FTZ1	Turbidity (NTU)	Midshelf waters	H		0.40	1.70	2.50
	FTZ2, FTZ3	TSS (mg L ⁻¹)	Open Coastal waters	H	2.00		1.70	2.50
	FTZ4	Turbidity (NTU)	Open Coastal waters	H		1.00	1.60	2.40
	FTZ5	TSS (mg L ⁻¹)	Open Coastal waters	H	2.00		1.70	2.50
	FTZ6	Turbidity (NTU)	Enclosed Coastal waters	H				
	SR01, SR02	Turbidity (NTU)	Enclosed Coastal waters	H				5.00
	FTZ1	Turbidity (NTU)	Midshelf waters	H		0.30		
	FTZ2, FTZ3		Open Coastal waters	H	1.50			
	FTZ4		Open Coastal waters	H		0.50		
	FTZ5	Turbidity (NTU)	Open Coastal waters	H	1.50			
	FTZ6		Enclosed Coastal waters	H			7.00	15.00
	SR01, SR02		Enclosed Coastal waters	H		10.00		

C-6 Regional exposure assessments for waterbodies

Regional results of the exposure assessment are shown for each waterbody in Appendix C-4.

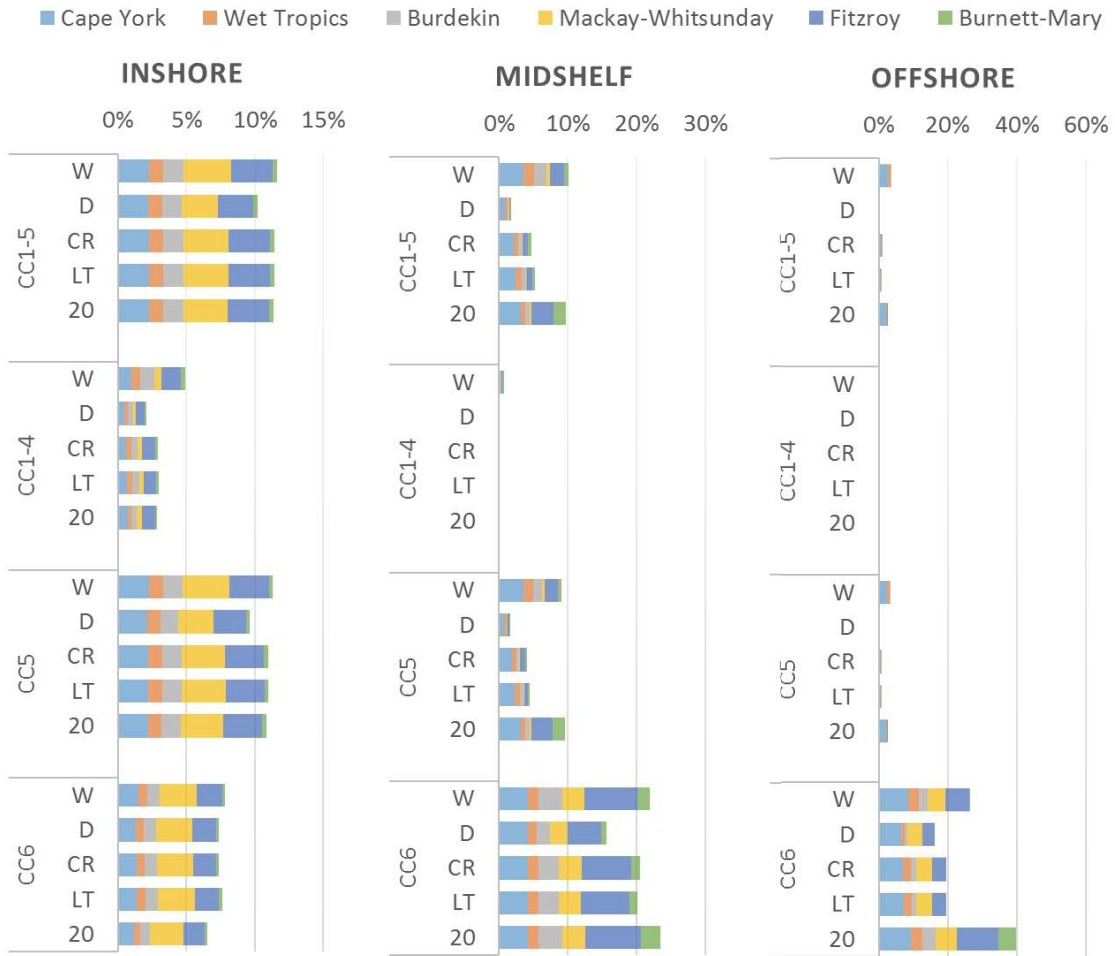


Figure C-3: Percentages (%) of the Reef lagoon (total 348,839 km²) and division by regional waterbodies affected by the primary and secondary wet season water types combined, and the three wet season water types individually during the current wet season and for a range of reference periods (long-term (LT), typical wet (W), typical dry (D) and coral recovery (CR) period composites) (and/or in the case of extremely wet year or specific event patterns). Areas and percentage are only calculated for frequencies > 0.1. Inshore waters include the macro-tidal enclosed coastal, enclosed coastal, macro-tidal open coastal and open coastal waterbodies combined.

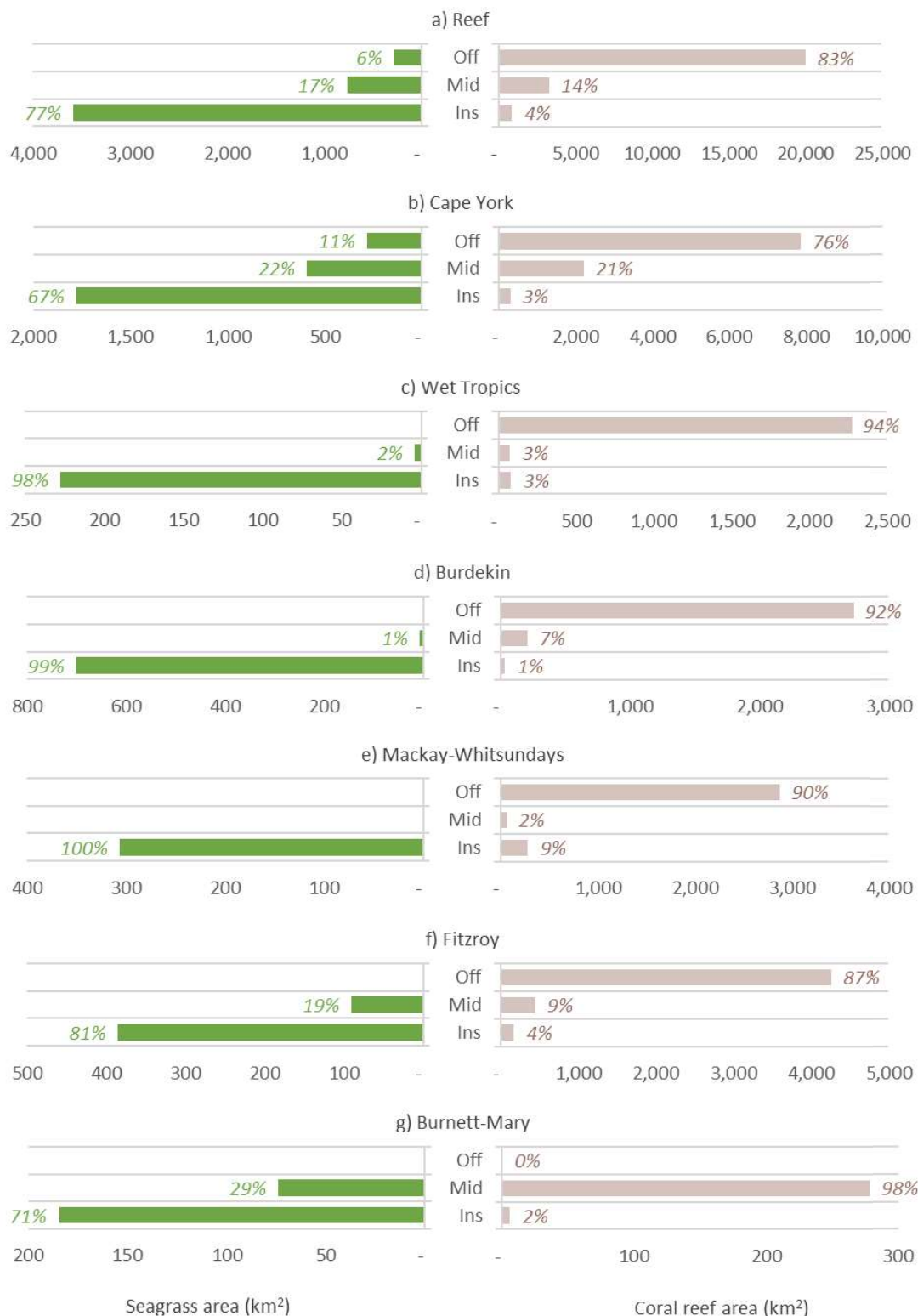


Figure C-4: Areas (in km² and represented as horizontal bars) of seagrass (left) and coral reefs (right) in the a) Reef and regional waterbodies; b) Cape York, c) Wet Tropics, d) Burdekin, e) Mackay-Whitsunday, f) Fitzroy, g) Burnett-Mary. Percentages of total Reef habitats or total regional habitats are indicated in italics.

C-7 Pesticide monitoring results

Table C-9: Concentration of PSII herbicides and other pesticides measured in the Mackay-Whitsunday region in 2020–21. Note that pesticides highlighted in yellow are not used to calculate the Pesticide Risk Metric. Risk categories colour coding: Dark green - Very Low ($\geq 99\%$ species protected); Green- Low (95 to $< 99\%$ species protected); Yellow – Moderate (90 to $< 95\%$ species protected); Orange – High (80 to $< 90\%$ species protected); Red – Very high ($< 80\%$ species protected).

Site Name	Deployment Dates		Sample Type	Days Deployed	Flow Rate (m/s)	Sample Name	Concentration of PSII herbicides (ng/L)													Concentration of other pesticides (ng/L)													% species affected	% species protected
	Deployment	Retrieval					Ametryn*	Atrazine*	Diuron*	Hexazinone*	Tebuthiuron*	Bromacil*	Fluometuron*	Metrbuzin*	Prometryn*	Propazine*	Simazine*	Terbuthylazine*	Terbutryn*	Atrazine desethyl*	Atrazine desisopropyl*	Metolachlor (S+R)	2,4-D*	Haloxyp*	MCPA*	Fluazip*	Furoxypr*	Imazpic*	Imidacloprid*	Metsulfuron methyl*	Tebucnazole			
Flat Top Island S-21.15593 E-149.23747	31/10/2020	29/11/2020	ED	29	0.33	GBR1120_ED_FLT	<1.08	0.310	1.97	0.710	<0.160	<0.170	<0.150	<0.160	<0.220	<0.370	<0.180	<0.210	<1.44	<0.270	<0.220	<0.220	<0.680	<0.020	<0.220	<0.220	<0.220	<0.220	<0.220	<0.220	0.0	100		
	29/11/2020	06/01/2021	ED	38	0.64	GBR1220_ED_FLT	<1.38	12.9	20.4	8.72	<0.140	<0.130	<0.160	<0.180	<0.300	<0.180	<0.120	0.540	<1.18	1.34	0.470	0.890	<0.090	<0.550	<0.020	<0.180	<0.180	<0.180	<0.180	<0.180	0.5	99.5		
	06/01/2021	07/02/2021	ED	32	0.31	GBR0121_ED_FLT	<1.55	13.1	31.5	12.7	<0.160	<0.150	<0.140	0.210	<0.340	0.210	<0.140	1.21	<1.33	1.09	<0.210	2.24	<0.880	<0.020	<0.210	<0.210	0.93	4.59	<0.210	1.5	98.5			
	07/02/2021	13/03/2021	ED	34	0.24	GBR0221_ED_FLT	<1.48	0.840	3.05	1.54	<0.150	<0.130	<0.140	<0.200	<0.320	<0.200	<0.130	<0.180	<1.27	<0.240	<0.200	<0.190	<0.820	<0.000	<0.200	<0.200	<0.200	1.60	<0.200	0.1	99.9			
Repsise Bay S-20.58823 E-148.69754	13/03/2021	09/05/2021	ED	57	0.78	GBR0321_ED_FLT	<1.09	0.400	4.51	1.91	<0.110	<0.100	<0.100	<0.140	<0.240	<0.100	<0.130	<0.140	<0.930	<0.170	<0.140	<0.140	<0.440	<0.010	<0.140	<0.140	0.280	<0.140	0.0	100				
	09/05/2021	08/06/2021	ED	30	0.265	GBR0421_ED_FLT	<1.70	0.300	0.800	0.320	<0.170	<0.150	<0.160	<0.220	<0.370	<0.150	<0.210	<0.150	<1.45	<0.270	<0.220	<0.220	<0.680	<0.020	<0.220	<0.220	<0.220	<0.220	<0.220	0.0	100			
	17/01/2021	17/01/2021	ED	49	0.207	GBR1220_ED_REB	<1.18	6.77	25.6	15.7	0.400	<0.110	<0.160	<0.160	<0.260	<0.160	<0.110	1.13	<1.01	1.09	0.170	1.58	<0.650	<0.470	<0.020	<0.160	0.190	12.2	<0.160	0.7	99.3			
	05/02/2021	18/03/2021	ED	41	0.252	GBR0121_ED_REB	<2.42	8.13	37.9	27.0	0.280	6.66	<0.220	<0.320	<0.530	<0.320	<0.220	1.72	<2.06	0.470	<0.320	3.44	<1.34	<0.170	<0.970	<0.030	<0.320	11.6	0.430	<0.320	1.0	99		
Sandy Creek S-21.20713 E-149.23914	31/10/2020	29/11/2020	ED	29	0.861	GBR1120_ED_SCK_DUP	<1.14	1.59	9.76	4.53	<0.170	<0.150	<0.160	<0.220	<0.360	<0.150	<0.200	<1.40	<0.260	<0.220	0.400	<0.910	<0.110	<0.660	<0.020	<0.220	0.290	<0.220	<0.220	0.3	99.7			
	29/11/2020	06/01/2021	ED	38	0.274	GBR1220_ED_SCK	<1.36	12.0	64.4	23.8	<0.140	<0.120	<0.130	<0.180	<0.300	0.200	<0.150	<0.200	<1.26	0.230	<0.180	2.29	1.12	<0.090	<0.950	<0.020	<0.180	2.19	<0.180	1.4	98.6			
	07/02/2021	13/03/2021	ED	34	0.297	GBR0221_ED_SCK	<1.48	0.830	4.26	1.89	<0.150	<0.130	<0.140	<0.200	<0.320	<0.200	<0.130	<0.180	<1.26	<0.220	<0.200	0.190	<0.820	<0.100	<0.600	<0.020	<0.200	0.600	<0.200	0.0	100			
	13/03/2021	09/05/2021	ED	57	0.715	GBR0321_ED_SCK	<1.09	0.390	4.93	1.89	<0.110	<0.100	<0.100	<0.140	<0.240	<0.100	<0.130	<0.140	<0.930	<0.170	<0.140	0.150	<0.610	<0.080	<0.440	<0.010	<0.140	0.190	0.150	<0.140	0.2	99.8		
09/05/2021	08/06/2021	ED	30	0.331	GBR0421_ED_SCK	<1.62	0.250	0.560	0.340	<0.160	<0.150	<0.160	<0.210	<0.360	<0.160	<0.210	<0.150	<0.200	<1.39	<0.260	<0.210	<0.210	<0.660	<0.020	<0.210	<0.210	0.950	<0.210	<0.210	0.1	99.9			

C-8 References

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Appendix D: Water Quality Monitoring in the Fitzroy NRM region 2020–21

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D-2 Introduction and Background

The Fitzroy National Resource Management (NRM) Region extends from Carnarvon Gorge National Park to Rockhampton and out to the mouth of the Fitzroy River. Covering 15.7 million hectares, it has the largest catchment area draining into the Great Barrier Reef (the Reef) (Lewis *et al.*, 2021), equating to ~33% of all suspended sediment load from all the Great Barrier Reef Catchment Area (GBRCA) (Packett *et al.*, 2009). The region has a sub-tropical, semi-arid climate with high inter-annual variability in rainfall, high evaporation rates, and prolonged dry periods followed by infrequent major floods. The most consistent rain usually occurs during the wet season (November-March), while rain in Winter and Autumn months is unreliable. Annual rainfall varies substantially across the region, from ~530mm in the west to ~850mm in the central and ~2000mm in the north-east coastal area (Packett *et al.*, 2009). The region's rainfall has been decreasing by ~30mm annually for the past 30 years (Yu *et al.*, 2013). The total rainfall for 2020 was 464mm, well below the total area average (BOM, 2020).

From 2005 to 2014, water quality monitoring by the Australian Institute of Marine Science (AIMS) occurred three times per year at three sites in the Fitzroy region under the Marine Monitoring Program (MMP) and results were published annually (Thompson *et al.*, 2014, previous reports cited therein). A program re-design of the MMP occurred in 2014 to increase the number of sites and the sampling frequency across the focus regions being monitored at that time. Due to funding constraints, this new program design was not able to be extended to the Fitzroy region and monitoring there by AIMS ceased at the end of 2014.

A partnership between the Great Barrier Reef Foundation and AIMS began in 2020 to re-establish marine water quality monitoring in the Fitzroy region. The program design for this monitoring follows the same design principles as the MMP in other NRM regions (see [Appendix A](#)) and is funded to continue until 2024.

The primary land use in The Fitzroy Region is cattle grazing (75%), followed by nature conservation (8.7%) and forestry (6.6%). This extensive grazing area supports 55% of the cattle in the GBRCA (Lewis *et al.*, 2021). Mining is another prominent industry in the area, accounting for 102,389 hectares of the catchment. The region holds 75% of Queensland's active coal mines and 47% of its gas mines (QLUMP, 2019). Land-use change such as these, requires the clearing of vegetation, leaving sediment susceptible to erosion. Erosion of hillslope and streambank soil ends up in local waterways and is transported into the Great Barrier Reef lagoon (Marwick *et al.*, 2014). Much of this sediment is extremely fine and remains

suspended in the water, travelling onto coral reefs, seagrass beds and other sensitive marine ecosystems, reducing their light availability (Bainbridge *et al.*, 2018). Catchment-derived sediments contain fertilizer and pesticides from agricultural sources. This additional nutrient generates an increase in macroalgae and can cause algal blooms and eutrophication (Brodie *et al.*, 2011). Additionally, river discharge can initiate crown of thorns outbreaks (Brodie *et al.*, 2005; Woolridge and Brodie, 2015), increase susceptibility of coral to disease (Bruno *et al.*, 2003; Haapkylä *et al.*, 2011; Kline *et al.*, 2006; Kuntz *et al.*, 2005; Weber *et al.*, 2012; Vega Thurber *et al.*, 2013) and exacerbate coral bleaching (Woolridge, 2009). This discharge often contains pesticides. Pesticide exposure can inhibit photosynthesis (Gallen *et al.*, 2014) and affect corals, seagrass, fish, and other marine organisms.

Large-volume floods, which occur once every few decades, can deliver catchment sediment and pollution to the mid and outer reef (Devlin *et al.*, 2001). However, small-scale local flooding adversely affects the inshore reef zone at a much higher frequency. The coastal area of the Fitzroy region comprises many inshore reefs and islands. This includes the 19 Islands making up the Keppel group. Long-term monitoring of inshore coral reef sites in the Fitzroy region were consistently classed as 'very poor' to 'poor' and from 2005 to 2020 (Thompson *et al.*, 2021). Reefs closest to rivers had the lowest coral cover and improved with distance from the coast. Macroalgae was 'high' at almost all reefs in the region.

D-3 Methods

This Section provides a brief overview of the sampling methods and indicators that are monitored in the Fitzroy region. More details are presented in the Methods Section of the main report, Appendix A, B and C, and in a separate quality assurance/quality control (QA/QC) report published annually (Great Barrier Reef Marine Park Authority, 2021).

Sampling design

This monitoring program is designed to measure the annual condition and long-term trends in coastal water quality rather than short-term episodic changes in water quality associated with periods of high river discharge. This type of monitoring is considered 'ambient', which refers to routine sampling during the wet and dry seasons outside of major flood events. This program design is analogous to ambient monitoring conducted since 2005 under the MMP.

Monitoring site locations were selected along water quality gradients related to exposure to land-based runoff, with sites located with increasing distance from the Fitzroy River mouth and from the coast (Álvarez-Romero *et al.*, 2013). In order to maintain some continuity with the existing 10-year monitoring dataset (2005–2014), the three original sites (FTZ1–3) were re-instated in the current design (Table D-1, Figure D-1).

Table D-1: Description of the Fitzroy water quality sites monitored during 2020–21. Presence of data-logging instruments (turbidity/fluorescence or salinity loggers) is indicated by tick marks.

Site Name (Short Name)	Latitude	Longitude	Turbidity/fluorescence logger	Salinity logger	Number of times sampled (season)	Sampling
Barren Island (FTZ1)*	-23.152	151.069	√		10 times per year (7 wet season and 3 dry season)	Duplicate samples surface and bottom
Humpy Island (FTZ2)*	-23.217	150.960	√	√	10 times per year (7 wet season and 3 dry season)	Duplicate samples surface and bottom

Pelican Island (FTZ3)*	-23.233	150.873			10 times per year (7 wet season and 3 dry season)	Duplicate samples surface and bottom
North Keppel (FTZ4)	-23.092	150.913			10 times per year (7 wet season and 3 dry season)	Duplicate samples surface and bottom
Peak West (FTZ5)	-23.341	150.905			10 times per year (7 wet season and 3 dry season)	Duplicate samples surface and bottom
Fitzroy River Mouth (FTZ6)	-23.475	150.938	√	√	10 times per year (7 wet season and 3 dry season)	Duplicate samples surface and bottom

*Indicates sites that were monitored by AIMS from 2005–2014

From 2005 to 2014, monitoring occurred ~3 times per year at 3 sites in the various MMP monitoring regions including in the Fitzroy region (discontinued in 2015). An independent statistical review of the MMP in 2014 (Kuhnert *et al.*, 2015) showed that additional sites and higher sampling frequency would provide better statistical power. The current program design was implemented in February 2015 and includes most of the sampling sites in the pre-2015 design, allowing for the continuation of the long-term time-series, and inclusion of additional sites.

The program currently includes nine other focus areas, each with 5 to 6 sites measured routinely: Pascoe, Normanby-Kennedy, Annan-Endeavour and Stewart Rivers in the Cape York NRM (all added in 2017); Barron-Daintree, Russell Mulgrave and Tully in the Wet Tropics NRM; Burdekin and Mackay-Whitsunday. The frequency of ambient water quality monitoring was increased in 2015, and sites are now visited 5–10 times annually, depending on the focus region.

Water quality sampling

At each of the sampling locations (Figure D-1, Table D-1), vertical profiles of water salinity and temperature were measured with a Conductivity Temperature Depth (CTD) profiler (Sea-Bird Electronics SBE19plus). CTD profiles are used to characterise the water column and to identify its state of vertical mixing. See the QA/QC report for a detailed description of CTD data processing (Great Barrier Reef Marine Park Authority, 2021).

Immediately following the CTD cast, discrete water samples were collected with Niskin bottles. Samples collected at ambient sites were from the surface (~0.5 m below water surface) and bottom (~1 m above the seabed) of the water column, whereas for some event-based sampling only surface water samples were collected. Samples from the Niskin bottles were taken in duplicate and were analysed for a broad suite of water quality parameters (Table 2-1). Detailed descriptions of analytical chemistry techniques can be found in the QA/QC report (Great Barrier Reef Marine Park Authority, 2021). Values of water quality variables presented in this report are depth-weighted means calculated using surface and bottom samples.

Below is a brief description of each of the main water quality variables measured. These definitions are not all-encompassing but are meant to provide a short description of what aspects of water quality they measure and what processes influence the variables:

- **Total Suspended Solids (TSS)** is a measure of the suspended particulate material in the water column. These solids include suspended sediments (sand, silt, and clay), living plankton, and detrital (non-living organic) material. TSS concentrations are affected by oceanographic processes including primary production and

resuspension, as well as inputs from other sources such as dredging and land-based run-off.

- **Secchi depth** is a visual measure of water clarity and proxy for light penetration, which is measured using a high-contrast black and white patterned disc called a Secchi disc. The Secchi depth is the average of the vertical disappearance and reappearance depths of the disc, where clarity increases with increasing Secchi depth. Secchi depth is a simple method that has been used for over 150 years, so is excellent for assessing long-term change and for cross-system comparisons.
- **Turbidity** is a measure of light scattering caused by fine suspended particles, such as sediment, detritus, and plankton. Turbidity is affected by a wide range of factors including oceanographic processes such as resuspension of bottom sediments by wind, waves and currents; river discharge; and anthropogenic factors such as dredging.
- **Chlorophyll a (Chl-a)** concentration is a measure of phytoplankton biomass in a water body. Phytoplankton grow quickly in response to nutrient availability, so elevated values of Chl-a can indicate increased nutrient loading.
- **Dissolved inorganic nutrients (NH₃, NO_x, PO₄ and Si)** measure the amount of readily available nutrients for plankton growth in water samples. Inorganic nitrogen (NH₃, NO_x) and phosphate (PO₄) represent around 1% of the nutrient pools in the Reef. The inorganic nutrient pools are affected by a complex range of biogeochemical processes including both natural (for example, plankton uptake, upwelling, nitrogen fixation, and remineralisation) and anthropogenic (for example, dredging and nutrient inputs from changed land use) processes.
- **Particulate nutrients (POC, PN and PP)** are a measure of the suspended material retained on a filter with a pore size of approximately 0.7 µm. This material consists of a minor fraction of living biomass (for example, bacteria, phytoplankton) and a major fraction of detritus (for example, dead cells, faecal pellets). Particulate nutrient concentrations are affected by oceanographic processes (primary production, bacterial production, resuspension, and remineralisation) as well as sources such as dredging and land-based run-off.
- **Dissolved organic carbon (DOC)** is a measure of organic carbon concentrations passing through a filter with a pore size of 0.45 µm. DOC has a complex chemical composition and is used by bacteria as a source of energy. The DOC pool is affected by a range of production and degradation pathways. The sources include primary production by phytoplankton, zooplankton grazing, resuspension events, river runoff, and abiotic breakdown of POC. DOC can be degraded by sunlight.

***In situ* loggers**

Continuous *in situ* Chl-a fluorescence and turbidity were measured using WET Labs ECO FLNTUSB Combination Fluorometer and Turbidity Sensors located at three sites (Table D-1), which were deployed at 5 m below the surface and sampled at 10 min intervals. Water samples for analyses of Chl-a and TSS were collected three times per year to calibrate logger fluorescence and turbidity to *in situ* conditions. Diver-operated Niskin bottles were used to sample close to the moored loggers and samples were preserved and analysed in the same manner as ship-based water samples.

Daily averages of the chlorophyll and turbidity time-series are presented in section D-7. Annual means and medians of turbidity were also calculated for each site based on the 'water year' (1 October to 30 September) and compared with the water quality guideline value (GV) (Table D-4).

Salinity and temperature loggers (Sea-Bird Electronics SBE37) were deployed at two locations, with one of these being placed on a fixed mooring near the Fitzroy River mouth (Figure D-1, Table D-1). See the QA/QC report (Great Barrier Reef Marine Park Authority, 2021) for detailed descriptions of logger pre- and post-deployment procedures. Site-specific time-series of salinity and temperature can be found in Figure C-2.

Data analyses – Summary statistics and trends

Concentrations of water quality parameters at each sampling occasion were calculated as depth-weighted means by trapezoidal integration of the data from all sampling depths. At most sites, only two vertical points are sampled (i.e., surface and bottom samples), and this method averages these values to derive the depth-weighted mean. Measurements falling below the instrumental detection limit were represented as half the detection limit. Summary statistics for all water quality variables are presented for all monitoring sites in Table D-3. Concentrations were compared to site-specific GVs (Table D-2), which are defined for Chl-*a*, PN, PP, TSS, Secchi depth, NO_x, and PO₄. Concentrations of water quality parameters are presented along the sampling transects for each focus region with distance from river mouths. Trends in water quality are represented with generalised additive models, fitted with a maximum of five knots and modelled with a gamma-distributed response and log-link function.

Temporal trends in key water quality variables (Chl-*a*, TSS, Secchi depth, turbidity, NO_x, PN, PP, DOC, and POC) since 2005 are reported using only open coastal and mid-shelf sites, as GVs for enclosed coastal waters are derived differently and are not available for all variables, creating statistical imbalance.

Generalised additive mixed effects models (GAMMs) were used to decompose each irregularly spaced time-series into its trend cycles (long-term) and periodic (seasonal) components (Wood, 2006). GAMMs are an extension of additive models. These models allow flexible modelling of non-linear relationships by incorporating penalised regression spline types of smoothing functions into the estimation process. They are useful where the degree of smoothing of each smooth term (and by extension, the estimated degrees of freedom of each smoother) is treated as a random effect and thus estimable via its variance as with other effects in a mixed modelling structure (Wood, 2006).

For each water quality variable within each focus region, the variable was modelled against a thin-plate smoother for date and a cyclical cubic regression spline (maximum of 5 knots) over months within the year. Spatial and temporal autocorrelation in the residuals was addressed by including sampling locations as a random effect and imposing a first-order continuous-time auto-regressive correlation structure (Pinheiro and Bates, 2000). All GAMMs were fitted using the *mgcv* (Wood, 2006, 2011) package in R 3.6.1 (R Core Team, 2019).

To provide a more quantitative assessment of trend, linear change in values of GAMMs was measured starting in 2015 to the present sampling year. This period was chosen as it covers the MMP re-design, which began in 2015; using earlier data would unbalance this analysis as the amount of sampling greatly changed in 2015. As GAMMs are de-trended to remove the effects of seasons, tides, and wind, this analysis aims to quantify trends occurring outside of these cycles. The outputs for the Fitzroy region are complicated in that they do not include data since the MMP re-design. GAMMs are presented with no data through this period and should be interpreted with caution, until more data becomes available.

Data analyses – Water Quality Index

The Water Quality Index (WQ Index) is an interpretation tool developed by AIMS to visualise trends in the suite of water quality variables measured, and to compare monitored water quality to existing Water Quality Guidelines (Department of Environment and Resource

Management, 2009; Great Barrier Reef Marine Park Authority, 2010). The WQ Index uses a set of five key indicators:

- Water clarity (TSS concentrations, Secchi depth, and turbidity measurements by FLNTUSB instruments, where available)
- Chl-*a* concentrations
- PN concentrations
- PP concentrations
- NO_x concentrations.

These five indicators are a subset of the comprehensive suite of water quality variables measured in the MMP inshore water quality program. They have been selected because GVs are available for these measures, and they can be considered as relatively robust indicators that integrate a number of bio-physical processes in the coastal ocean.

For each monitoring site, these indicators are compared to GVs, scored based on performance relative to guidelines, and averaged to give an overall site-specific score. Sites are then averaged over a region or focus region to give a regional score (see Appendix B for details of Index calculation).

The WQ Index is calculated using two different methods due to the objectives of the program needing to report both the long-term trend in water quality condition, and the annual condition that ecosystems are exposed to, which both affect the response of those ecosystems but in different ways. Changes in the MMP design that occurred in 2015 also needed to be accommodated. The changes in design included increased number of sites, increased sampling frequency and a higher sampling frequency during December to April to better represent wet season variability. Thus, statistical comparisons between MMP data from 2005–15 to 2015–onwards must account for these changes. The two versions of the WQ Index have different purposes:

- 5. Long-term trend:** This version is based on the pre-2015 MMP sampling design and uses only the original sites (open coastal water body) and three sampling dates per year. This sampling design had low temporal and spatial resolution and was aimed at detecting long-term trends in inshore water quality. Key aspects of this version are:
 - annual water quality GVs are used for scoring monitoring data (Appendix B 0)
 - only AIMS monitoring data are used
 - a four-year running mean is applied to data to reduce the effect of sampling time on the Index
 - the Index is an average of scores for five indicators (water clarity, Chl-*a*, NO_x, PN, and PP weighted equally).
- 6. Annual condition:** This version is based on the post-2015 MMP sampling design and uses all sites (except enclosed coastal sites) and sampling dates per year. Key aspects of this version are:
 - seasonal site-specific water quality GVs are used for scoring monitoring data (i.e., wet season data are compared to a wet season GV and dry season data are compared to a dry season GV) (Table D-2)
 - both AIMS and JCU monitoring data are used
 - a running mean is not applied
 - the Index is a hierarchical combination of scores for five indicators [water clarity, productivity (combined score of Chl-*a* and NO_x), and particulate nutrients (combined score of PN and PP) are weighted equally].

Details of Index calculation are in Appendix B.

D-4 Drivers and pressures influencing water quality in 2020–21

Coastal development including agriculture

The Fitzroy Region is home to ~235,000 people, just 5% of Queensland's population (FBA, 2018). By area, cattle grazing is the primary land use in the catchment (Brodie *et al.*, 2003) and the initial clearing of vegetation for this purpose marked a significant change in the source and quantity of sediment exported by the Fitzroy River (Hughes *et al.*, 2009). Intensive cultivation of food crops and livestock feed production also contributes to the sediment load in the Fitzroy River (Hughes *et al.*, 2009). The region has over 472,000 ha of grain crops, largely for feeding livestock, and 25,000 ha of cotton (Thornburn and Wilkinson, 2013). Fluctuations in climate, cattle numbers and farming can greatly affect the state and nature of vegetation cover, and therefore, the susceptibility of soils to erosion, in turn, leading to greater runoff of suspended sediments and nutrients. As Australia's cattle production has stayed relatively consistent since 2000 (MLA, 2021), the erosion of soil on cleared grazing and crop land will continue without the adoption of best practices. The contribution of this to river discharge and suspended sediment is highly dependent on the weather of the region.

Annual total suspended solids (TSS) export from The Fitzroy Basin into the Great Barrier Reef lagoon is between 3 and 4.5 million tonnes per year, accounting for ~33% of all annual TSS reaching the Reef (Dougall *et al.*, 2005). Best estimates for anthropogenic derived total suspended solids (TSS) from the Fitzroy Region is 2.9 million tonnes per year (Kroon *et al.* 2012). This is 3.4× higher than pre-European levels and is the region with the second highest anthropogenically derived TSS level in the GBRCA. TSS samples taken from the Fitzroy River during flood events were highest in areas with substantial intensive agriculture but were highly variable (Packett *et al.*, 2009). Inshore TSS and chlorophyll *a* annual mean values in the sector regularly exceed the water quality guideline values (Tracey *et al.*, 2017). Dissolved organic carbon (DOC) was the dominant component of the TOC load in these areas and particle size was small, with ~90% measuring <14 microns (Packett *et al.*, 2009). These small particles, once discharged and settled in the marine environment, are more easily resuspended during adverse weather events.

Fertilisers are lost from cropping systems and transported to nearby water systems, contributing to dissolved inorganic nitrogen (DIN) and phosphorus (DIP) concentrations in runoff water (Brodie *et al.*, 2019). Pristine forested catchments export mostly organic forms of nitrogen, which are largely unavailable to phytoplankton (Harris, 2001). Runoff enriched with anthropogenically derived inorganic nutrients is linked to increased primary production and chlorophyll *a* (Chl-*a*) concentrations of the Reef inner-shelf waters and can induce phytoplankton blooms (Woolridge *et al.*, 2006). Estimated anthropogenic derived total nitrogen (TN) and total phosphorus (TP) in the Fitzroy Region is the highest of the GBRCA (TN= 14,000 tonnes/yr, TP=4100 tonnes/yr) (Kroon *et al.*, 2012). This nutrient enriched runoff means the Fitzroy produces 44% of the anthropogenic plume-based Chl-*a* content in the GBRCA (Baird *et al.*, 2021). Herbicides, most notably photosystem-II (PSII) herbicides, affect the relationship between corals and their symbiotic algae. Seventy-eight percent of pesticide samples taken in the Fitzroy Region were classed as 'Category 5' for PSII pesticides from 2005 to 2014, the lowest index level (Gallen *et al.*, 2014). Spikes of the pesticide 'Tebuthiuron' were observed during several years, but the relative potency of this pesticide is significantly lower than other pesticides, presenting a lower risk to coastal ecosystems (Gallen *et al.*, 2014).

The Fitzroy Region has 20% of the mapped seagrass beds on the Reef and many inshore reefs associated with the Keppel Islands. The main threats to seagrass are reduced light availability and smothering from suspended sediment and increased growth of epiphytic algae from excess nutrients. Seagrass monitoring site health in the area has been rated as 'poor' (McKenzie *et al.*, 2021). Inshore coral reefs face the same threats as seagrass. The long-term monitoring sites in the region show distinct differences in benthic composition in relation to the water quality of the site (Thompson *et al.*, 2021). Coral cover in the Fitzroy has declined since

2005 (Thompson *et al.*, 2021). Elevated levels of DIN have been linked to destabilisation of the coral-symbiont relationship that underpins coral health (Fabricius, 2005). After being taken up by phytoplankton, these nutrients travel through the food web and are converted into organic forms (for example, DOC, DON, DOP) (Alongi and McKinnon, 2005). These forms may be deposited onto coastal benthic communities and, in high quantities, can lead to smothering (Fabricius and Wolanski, 2000).

Crown-of-thorns starfish outbreaks are most prevalent on mid and outer-shelf reefs between Mackay and Rockhampton, there have been sightings in the Whitsunday Region (AIMS, 2015). The cumulative loss of coral cover caused by crown-of-thorns starfish on the Reef's inshore reefs is 7% (Thompson *et al.*, 2021). While the Fitzroy Region has avoided crown-of-thorns starfish outbreaks at present, the region may be at risk in the future if water quality is not managed, as outbreaks have been linked to declines in water quality (Woolridge and Brodie, 2015).

Improved land management practices can decrease the stress caused by poor water quality on coastal marine ecosystems given that benthic communities of the inshore reefs respond to gradients in water quality, especially sedimentation and nutrient availability (Thompson *et al.*, 2011, 2016). Concerns about the water quality in the Reef lagoon led to the formulation of the Reef Plan for catchments adjacent to the Great Barrier Reef World Heritage Area by the Australian and Queensland governments in 2003 (The State of Queensland and Commonwealth of Australia 2003). Reef Plan was revised and updated in 2009 and 2013 (The State of Queensland and Commonwealth of Australia, 2009; The State of Queensland, 2013), and further developed into The Reef 2050 Water Quality Improvement Plan (WQIP) (The State of Queensland, 2018). This plan set out ambitious targets to improve catchment and coastal water quality and has the aim of building resilience, improve ecosystem health and benefit communities. One of the main proposed actions is the establishment of the Paddock to Reef program, which aims to reduce threats to the health and resilience of the Reef by promoting the adoption of best management practices (Waterhouse *et al.*, 2018).

Best practice has currently been implemented on 4% of grazing land, 14% of sugarcane land and 73% of banana production land (Great Barrier Reef Marine Park Authority, 2019), however, previous water quality targets were not met. The WQIP estimates the full adoption of class-B best management practice (best practice) will reduce DIN load by 19%, and by 30% if class-A practices (innovative/aspirational practice) are fully adopted (Waltham *et al.* 2021). Complete adoption of best grazing practices could reduce TSS export from the Reef catchments by ~20% (Thornburn *et al.*, 2013; Thornburn and Wilkinson, 2013). However, there is limited data available on the direct efficacy of best practice strategies on water quality (Carroll *et al.*, 2012), and modelled values are used for improvement estimations (Baird *et al.*, 2021, Dougall *et al.*, 2014). Site surveys showed that practicing zero tillage on cropping land (wheat, sorghum and sunflower) in the Fitzroy basin reduced erosion rates by 75% compared to traditional cropping practices and that at a catchment level, using no tillage can reduce sediment yield by ~50% (Carroll *et al.*, 1997). Reducing nitrogen fertilizer application by 47% by increasing nitrogen use efficiency (Thornburn *et al.*, 2011) reduced nitrogen surplus (excess nitrogen left in the soil) by 60% and reduced DIN in runoff and deep drainage water (Webster *et al.*, 2012).

Several types of erosion occur due to heavy rainfall and poor land management. Hillslope erosion, the erosion of topsoil on hillslopes by water runoff, is primarily affected by cattle stocking rates. Increasing grazing pressure removes vegetation cover from the land, leaving the fertile topsoil vulnerable to erosion. Gully erosion is the incision of flowing surface water, creating deep, unstable channels, often leaving the land unsuitable for agriculture. Gully erosion is often the main source of sediment in floodwater (Wasson *et al.*, 2002; de Vente *et al.*, 2005; Huon *et al.*, 2005). Streambank erosion arises when grazing occurs too close to vulnerable streambanks and riparian cover is not managed. These erosional processes cause

fertile land to lose productive sediments, reducing vegetation, further destabilizing the area. Prolonged dry periods followed by intense rainfall causes massive gully erosion.

Sediment erosion can be managed by reducing stocking rates in the more vulnerable areas and slope stabilisation and sediment reinforcement by increasing root bonding (Shen *et al.*, 2017). Various types of restoration have been effective at reducing erosion rates. For example, Hillslope runoff in the Fitzroy Region was 50-90% less in sites with 40-50% ground cover when compared with sites with 10% cover (Owens *et al.*, 2003; Bartley *et al.*, 2006; Hawdon *et al.*, 2008; Silburn *et al.*, 2011). Streambank erosion is greatly reduced by increasing riparian forest buffers. This can reduce erosion rates by 59-91% (Zaimes *et al.*, 2008). This re-introduced vegetation stabilises existing sediments and reduces erosion, but also creates a sediment sink (Askey-Doran *et al.*, 1996; Furnas, 2003). This helps remove excess nutrients from groundwater and overland flooding (Apan *et al.*, 2002) and can capture up to 89% of nitrogen in runoff water (Thibault 1997). Sites along the Fitzroy River with higher riparian condition had better water quality (i.e., lower DOC, TN and dissolved metals), indicating the effectiveness of riparian restoration and management at improving water quality (Chua *et al.*, 2019). Fine sediments contribute 79% of the total nitrogen (TN) reaching the Reef, while DIN accounts for 17% (Kroon *et al.*, 2012). Decreasing erosion rates of agricultural land and the movement of both fine sediment and DIN to local waterways by riparian buffer restoration considerably decreases the TN load of river water (Thornburn and Wilkinson, 2013). However, the Fitzroy Region has only 1.3 million hectares of forested riparian areas, the lowest proportion within the GBRCA. From 2004 to 2008, 12,702 hectares of forested riparian areas were cleared. Sixty three percent of vegetation had been cleared in the region by 1999 and 0.5-0.75% of vegetation in the Fitzroy is currently cleared annually (CRC, 2003).

Climate and cyclone activity

Climate is a major driver of the condition of water quality and ecosystems and can vary substantially between years. It is heavily driven by the El Niño Southern Oscillation (ENSO) cycle. Climate models predict continued warming (IPCC, 2021), increasing intensity of extreme rainfall events and acute disturbances, fewer but more intense tropical cyclones, and more frequent and extreme La Niña and El Niño events (Schaffelke *et al.*, 2017).

Cyclones create waves that resuspend sediment. Several cyclones have impacted the Reef in the past two decades, most notable are the intense category 4 and 5 systems; cyclone Larry (2006) and cyclone Yasi (2011) in the Wet Tropics and Burdekin Regions, and cyclone Debbie (2017) in the Mackay-Whitsunday Region. More locally, the Fitzroy Region was impacted by cyclone Tasha in 2010 and cyclone Marcia in 2015, a category 5 severe tropical cyclone. During the 2019–20 wet season, there was very limited cyclone activity in the Reef and none in the Fitzroy Region. In March 2020, cyclone Gretel remained off the coast as a weak system and had limited impact. The 2020-21 wet season similarly saw minimal disturbances, with neither cyclone Kimi (January 2021) or Niran (February 2021) making landfall.

Due to its large catchment area, the Fitzroy Region is prone to flooding. Acute disturbances, such as heavy rainfall and storms, cause increased sediment load entering coastal waters and resuspension of particles already in the environment. In the Fitzroy flood associated with cyclone Joy (1991), extensive mortality of corals in shallow reefs of the Keppel Islands occurred (van Woosik and Done, 1996). This was primarily attributed to an extended period of low salinity at these sites (Brodie and Mitchell, 1992; O'Neill *et al.*, 1992). A period of compounding large flooding events and storms in the Fitzroy Region between 2006 and 2014 instigated a further decline in coral cover on the inshore reefs and the Keppel Islands (Thompson *et al.*, 2014). Low salinity in the 2011 flooding triggered widespread mortality of coral at 2 m on Peak, Pelican and Keppels South (Thompson *et al.*, 2013). Some sites experienced 100% mortality down to a depth of 8 m (Jones and Berkelmans, 2014). This coincided with high incidences of coral disease, supporting evidence that the confounding effects of low salinity (Haapkylä *et al.*, 2011) and increased organic matter and nutrients, most

notably DOC (Brandt *et al.*, 2013; Kline *et al.*, 2006), can initiate coral disease outbreaks. The cumulative stress of high turbidity (low light) and an increase in algal growth from nutrients hinders corals recovery potential (Diaz-Pulido, 2009; Rogers and Miller, 2006; Roth *et al.*, 2018). Between 2005 and 2014, coral cover declined. Since 2014, coral cover and coral juvenile density has slightly improved but is still classified as 'poor' (Thompson *et al.*, 2016).

Flood plumes on the Reef rarely reach the mid and outer shelf, however, plumes from large flood events from cyclones can affect these reefs. In the Wet Tropics region, the mid shelf reefs are closer to the coast (<30 km), and more easily reached by flood plumes, for example cyclone Sadie (1994). However, the mid and outer shelf reefs of the Fitzroy Region are further from the coast (90 km to the Capricorn and Bunkers, 210 km to the Swains Reefs from Fitzroy River mouth). Physical conditions, such as wind are key factors in the spread of flood plumes. The prevailing winds in the Fitzroy Region are usually south-easterly, keeping flood plumes close to shore. However, the wind during Cyclone Joy (1991) turned to blow offshore, moving the large plume out to the Capricorn and Bunker group, stretching 200 km offshore, lowering salinity on the Capricorn reefs to 27 ppt (Devlin *et al.*, 2001, Prekker *et al.* 1992). Events such as this are seen on a scale of multiple decades, while the reefs associated with the Keppel Islands see extreme impacts from river plumes every 4-6 years, and Barren Island, Hummocky Island and Masthead Island every 10 years (Devlin *et al.*, 2001). Vertical distribution of flood plumes largely affects the salinity, turbidity and nutrient content of the top 3-4 m (Devlin *et al.*, 2001), but physical conditions, such as high winds can lead to deeper mixing during these extreme events.

Movement of water alongshore of the Reef lagoon is seasonal. January to August is the northward-current season and August to December is the southward-current season (Luick *et al.*, 2007). South-easterly trade winds dominate most of the year, creating a strong north-westward longshore movement (Orpin *et al.*, 2010). This transports small, easily suspended particles discharged from the Fitzroy River northward. Water quality in the Whitsundays region has deteriorated since 2007 and it is speculated that this could be partly due to inputs of flood discharge from the Fitzroy River (Baird *et al.*, 2019, Cantin *et al.*, 2019). Analysis of coral cores in the Whitsunday Islands show that Barium/Calcium (Ba/Ca) ratios (which correlates well with flood events) of some sites increased significantly after large flood events in the Fitzroy Region. The Fitzroy River has the largest and longest lasting influence of any river on the water quality of the Whitsunday region. However, the Ba/Ca ratios have not increased significantly from flood events before the period of low water quality in the Whitsunday region (2007-2017). Anomalous high Ba/Ca ratios at Scawfell do not seem to relate to Fitzroy River discharge. Hence, declining water quality in the area is more likely due to marine resuspension than flood plume inputs (Cantin *et al.* 2019). A high percentage of sediment in various sites around the Whitsunday Islands had a grainsize of <63 μm (Thompson *et al.*, 2014), which is easily resuspended during disturbance events.

The natural occurrence of the ENSO is closely linked to wet and dry periods on the east coast of Australia. There has been a moderate La Niña through 2020 and 2021, although annual water discharge has been lower than the long-term median discharge since 2017 (BOM, 2020). During La Niña, tropical cyclones are more common compared to intermediate years, and the first occurrences of cyclones is earlier in the season. This means these years have an increased likelihood of extensive flooding from rain and damage from high winds. Between 2010 and 2012, there was a strong La Niña event, increasing rainfall and causing extensive flooding (NOAA, 2017). Discharge from the Fitzroy River was considerably higher than the long-term median discharge (2.8 million Litres) in 2008 (Devlin, 2008) and 2010–2013 (Jones and Berkelmans, 2014). In 2010–2011, it was nearly 38 million litres, reaching a peak mean daily discharge of 1.16 million mega-litres per day over a period of 18 days (Jones and Berkelmans, 2014).

Future changes to the ENSO due to anthropogenic warming are projected, but are difficult to quantify (Collins *et al.*, 2010). Strong ENSO events are predicted to become more common,

especially extreme El Niño followed by La Niña events (Cai *et al.*, 2021). Tropical cyclones in the South Pacific are expected to become less frequent in future oceans (Murakami and Sugi, 2010; Sugi *et al.*, 2009; Zhao *et al.*, 2009; Gualdi *et al.*, 2008; Emanuel *et al.*, 2008), although by how much is disputed (Walsh *et al.*, 2012). Cyclone intensity, however, is predicted to increase marginally (Windlansky *et al.*, 2019). El Niño years bring drier weather to the Fitzroy Region, and with it, less vegetation growth to stabilise sediment in the catchment. La Niña years are wetter than normal years. If the frequency of intermediate years decreases, more extended dry years followed by major flood events will lead to an increase in erosion as vegetation will not have the time to recover between extreme dry and wet conditions, leaving more bare sediment that is vulnerable to erosion.

D-5 Focus region water quality and Water Quality Index

Fringing reefs are formed around continental islands in Keppel Bay, many of which are used extensively for recreational and tourism activities. Monitoring sites are sampled in this focus region ten times per year, with six sites sampled in ambient conditions during both the dry and wet seasons. The monitoring sites are located in a transect from the river mouth in a north-easterly direction, representing a gradient in water quality. Four sites are located in the open coastal water body, one site is located in the mid-shelf water body, and one site is in enclosed coastal waters (Figure D-1).

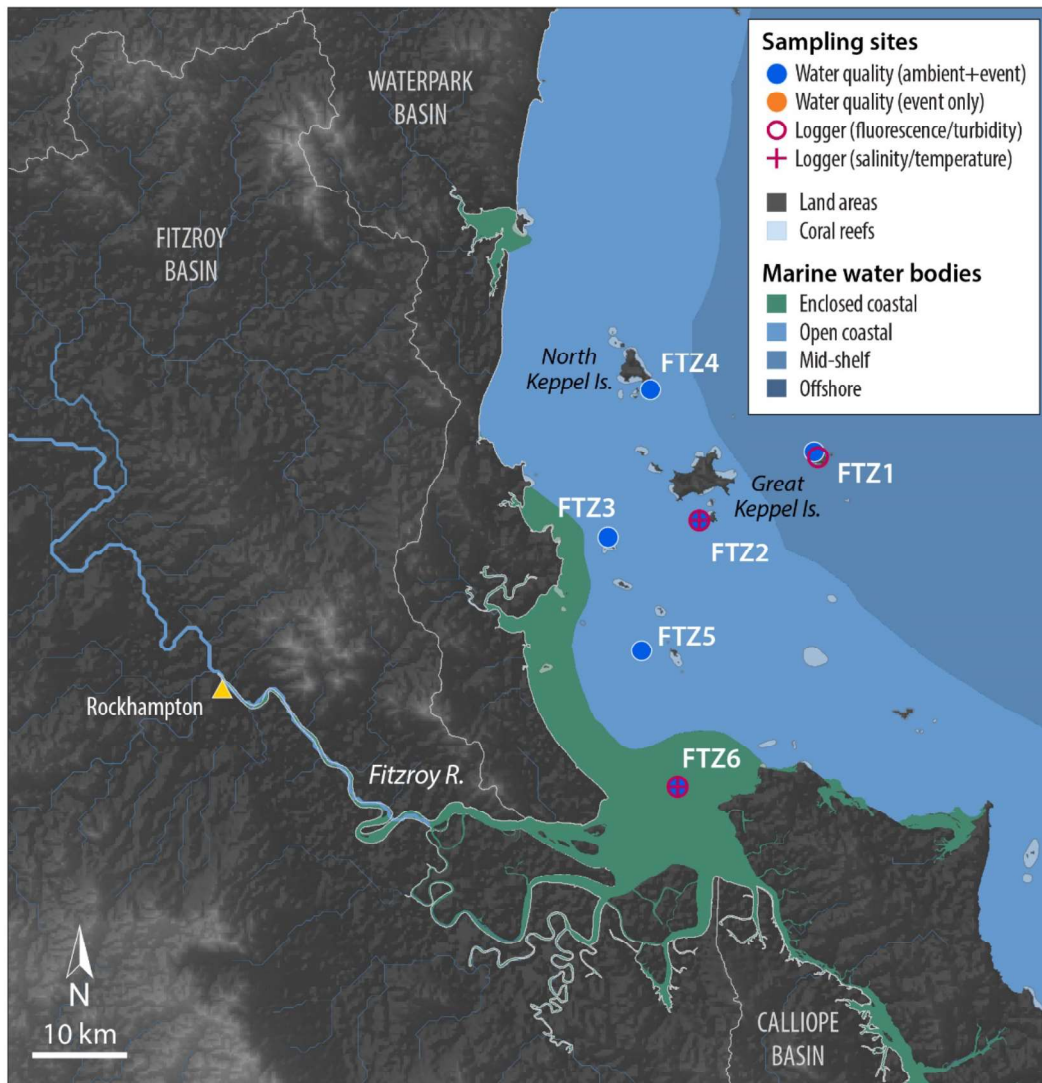


Figure D-1: Sampling sites in the Fitzroy focus area, shown with the water body boundaries. Sites FTZ1–FTZ3 were monitored from 2005–2014 under the Marine Monitoring Program.

From 2008–2013, the Fitzroy NRM region experienced several years of intense flooding with annual discharge from the Fitzroy River exceeding the long-term median in 2008, 2010, 2011, 2012, and 2013 (Figure D-2, Figure 3-5). In four of these years, the freshwater discharge was greater than three times the long-term median, with the 2011 flood event being the largest on record (Figure 3-5). During the 2011 flood, reduced salinity was the likely cause of widespread mortality of corals at 2 m depths of Peak, Pelican, Keppels South (Berkelmans *et al.*, 2012; Thompson *et al.*, 2014). Annual discharge of the Fitzroy River from 2014–2020 was generally close to the long-term median (Figure D-2). Annual discharge for the Fitzroy Basin in 2020–21 was well below (less than one-seventh) the long-term median levels (Figure D-2; Table 3-1). The combined discharge and loads calculated for the 2020–21 water year were (or amongst) the lowest recorded over the past decade. Over the 15-year period:

- discharge has varied from 397 GL (2020–21) to 37,942 GL (2010–11)

- TSS loads ranged from 52 kt (2013–14) to 7,000 kt (2010–11)
- DIN loads ranged from 76 t (2020–21) to 3,900 t (2010–11)
- PN loads ranged from 210 t (2020–21) to 17,000 t (2010–11).

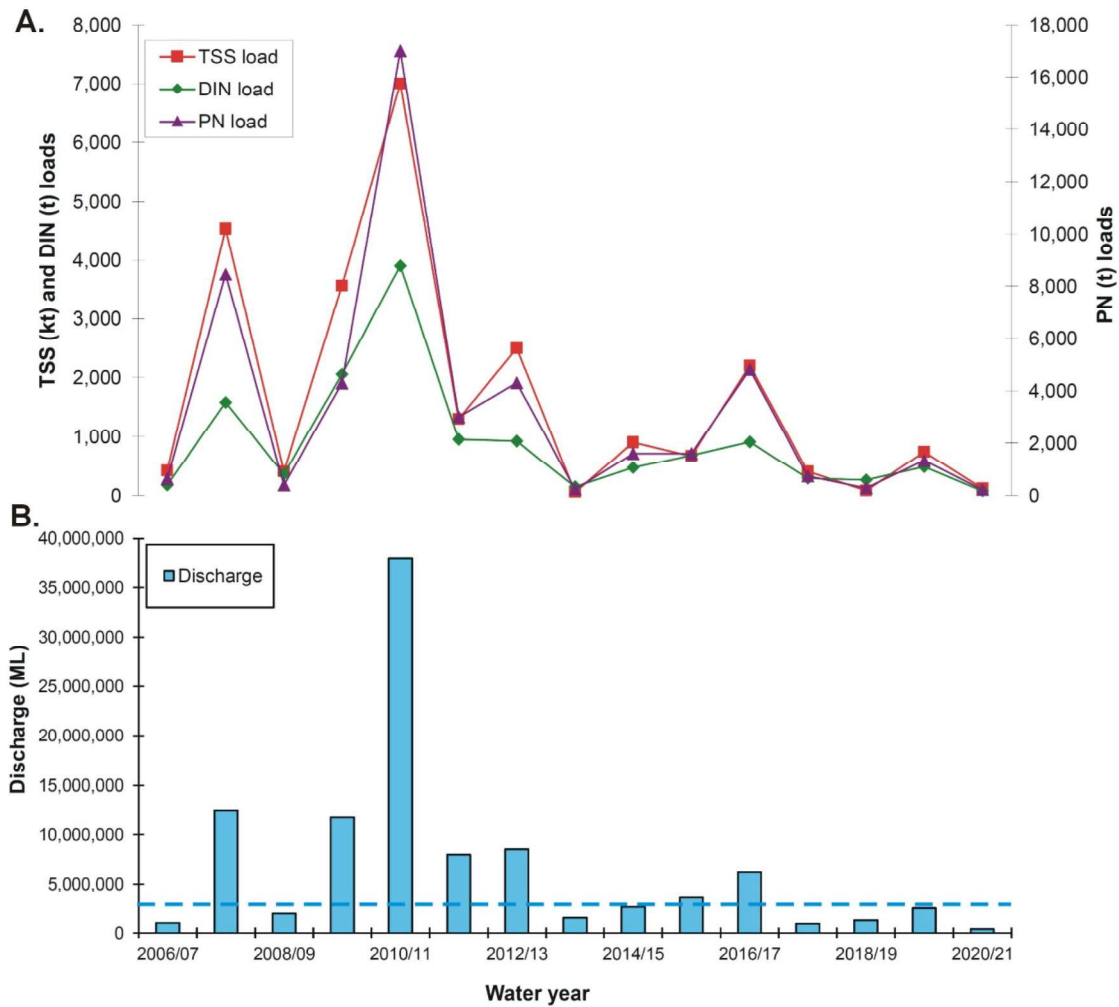


Figure D-2: Loads of (A) TSS, DIN and PN and (B) discharge for the Fitzroy Basin from 2006–07 to 2020–21. The loads reported here are based on the monitoring data from the Fitzroy River as reported in the Great Barrier Reef catchment loads program with a long-term annual mean concentration of the existing data calculated to produce a load for the past two years (where monitored load data have not yet been reported). Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

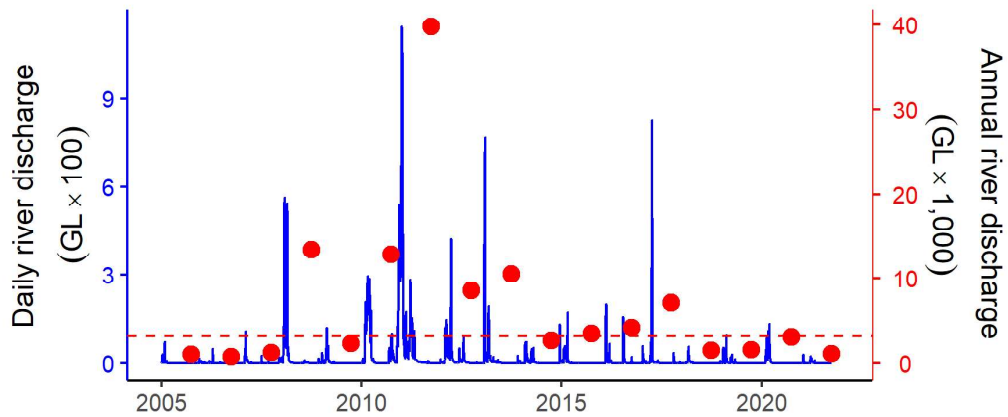


Figure D-3: Total discharge for the Fitzroy region (Table 2-3). Daily (blue) and water year (October to September, red) discharge is shown. Red dashed line represents the long-term median annual discharge.

The total discharge for the Fitzroy region in 2020–21 was below the long-term median (Figure D-3) and was nearly half the long-term median (Table 3-1).

Ambient water quality and the in situ Water Quality Index

Water quality showed trends along the sampling transect (Fitzroy River Mouth (FTZ6) to Barren Island (FTZ1)). Sites located nearest to the river mouth (river mouth = 0 km) had high concentrations of TSS, Chl-*a*, nitrate/nitrite (NO_x) and particulate nutrients (PN and PP), which declined with distance away from the river mouth (Figure D-4). Secchi depths were low at sites near the river mouth (water clarity was poor) and increased (water clarity improved) with distance from the river mouth. In the Fitzroy region, these trends were clear in both wet season and dry season. Wet season and dry season water quality is similar close to the river mouth but improves slightly more rapidly with distance from the river mouth in the dry season than the wet season (Figure D-4). Throughout the dry season, high turbidity, TSS and nutrient concentrations are maintained close to the river mouth by very strong tidal resuspension of muddy sediment materials.

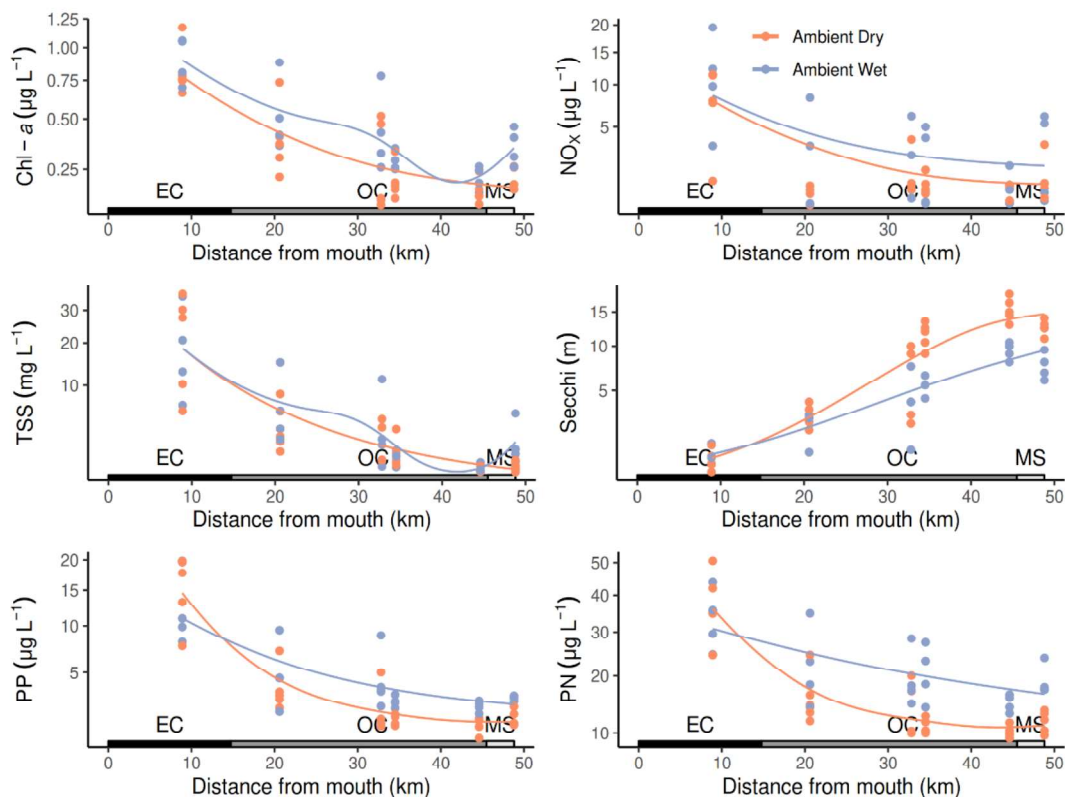


Figure D-4: Water quality variables measured during ambient and event sampling in 2020-21 along the Fitzroy focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the Fitzroy River mouth. Water body classifications are shown along the x-axes: Enclosed coastal (EC) and open coastal (OC). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

Long-term trends in water quality variables measured during ambient periods (i.e., not during flood events) of the dry and wet seasons are presented in Figure D-5. It is important to note that this trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points will have different values compared to raw data. This analysis is designed to detect long-term and regional-scale trends in water quality by removing the effect of short-term changes associated with weather and seasonal differences.

Most water quality variables in this region do not yet show distinct long-term trends (Figure D-5), though there are some signs that Dissolved Organic Carbon (DOC) may be increasing (as it is in the regions monitored under the Great Barrier Reef Marine Park Authority's Marine Monitoring Program) and phosphate (PO_4) may be declining. The gap in observational data between 2015 and 2020 limits the utility of the GAMM models in detecting long-term trends over this interval. The apparent sharp gradients in some water quality variables during the 2020-21 water year (Figure D-5) are almost certainly a statistical artefact of the limited recent data available and are likely to disappear when a few more years of monitoring data become available.

During the 2020-2021 water year, nitrate/nitrite (NO_x) and Secchi depth exceeded water quality guideline values (GVs) in the Fitzroy region (water quality was poor), Chlorophyll *a* (Chl-*a*) met guidelines at all sites except Peak West, Particulate Nitrogen (PN) met guidelines, and particulate phosphorus (PP) and phosphate (PO_4) exceeded guideline values at some monitoring sites and were close to GV at other sites.

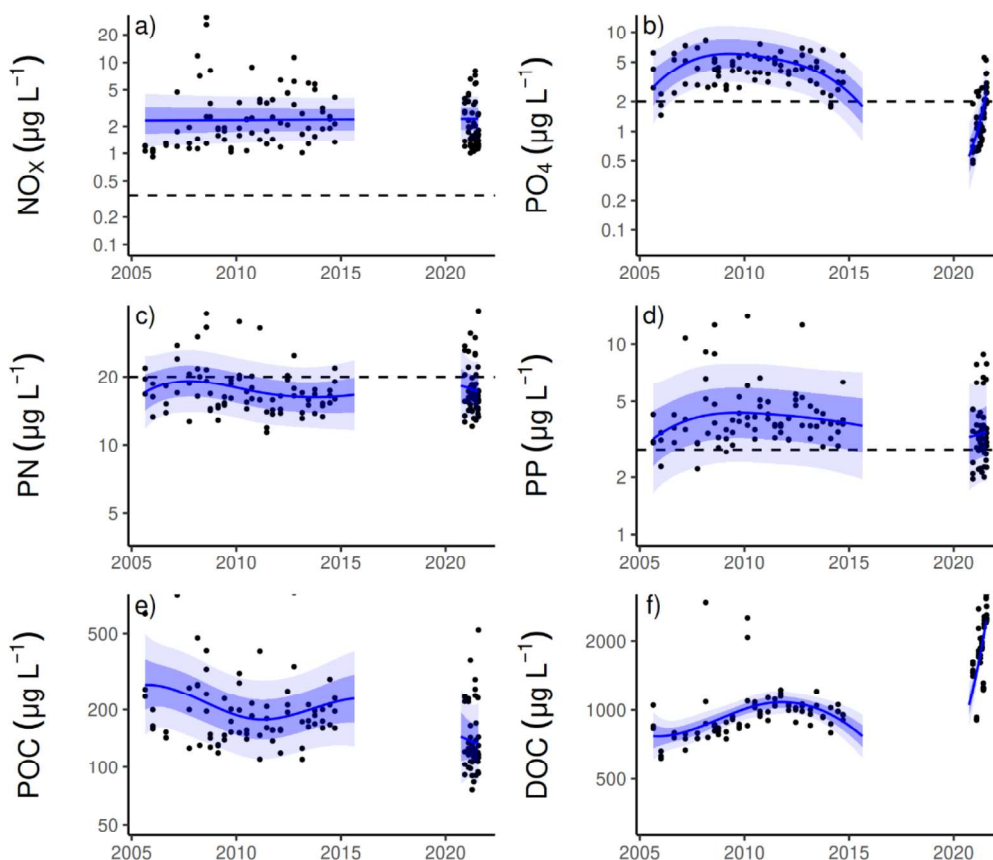


Figure D-5: Temporal trends in water quality variables for the Fitzroy focus region: a) turbidity, b) Secchi depth, c) total suspended solids (TSS), d) chlorophyll *a* (Chl-*a*), e) nitrate/nitrite (NO_x), f) phosphate (PO_4), g) particulate nitrogen (PN), h) particulate phosphorus (PP), i) particulate organic carbon (POC) and j) dissolved organic carbon (DOC). Generalised additive mixed effect models (trends) are represented by blue lines with shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves, tides, and seasons after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, and individual records can be found in Appendix D-6. Dashed horizontal reference lines indicate annual guidelines. The apparent steep gradients in DOC and PO_4 during 2020–2021 are likely statistical artefacts of the lack of data from 2016–2019.

The WQ Index is calculated using two different formulations to communicate: a) the long-term trend in water quality (based on the pre-2015 sampling design) and b) the annual condition of water quality (based on the post-2015 sampling design, which increased the power to detect change). The Methods section and [Appendix B-2](#) contain details of the calculations for both indices.

The long-term WQ Index has historically scored water quality as ‘moderate’ to ‘good’, with some fluctuations (Figure D-6a). The long-term trend has shown a small (for example, change by a single grade) improvement over the time-series since 2010, possibly indicating a gradual recovery from the impacts of large floods in 2008 and 2011. This downward trend has generally been driven by trends in PN and Chl-*a* indicators.

The annual condition WQ Index scored water quality as ‘good’ for the 2020–21 water year, the first year for which it is possible to calculate this index (Figure D-6b). This version of the Index scores water quality parameters against GVs relevant to the season when samples are

collected (wet versus dry GVVs) and includes additional sites in the open coastal water body to better characterise areas affected by river discharge. River discharge was below average in this focus region this year, which likely contributed to a good annual condition score.

It is important to note that the two versions of the WQ Index are designed to answer separate questions and therefore differences in scores between the versions are expected.

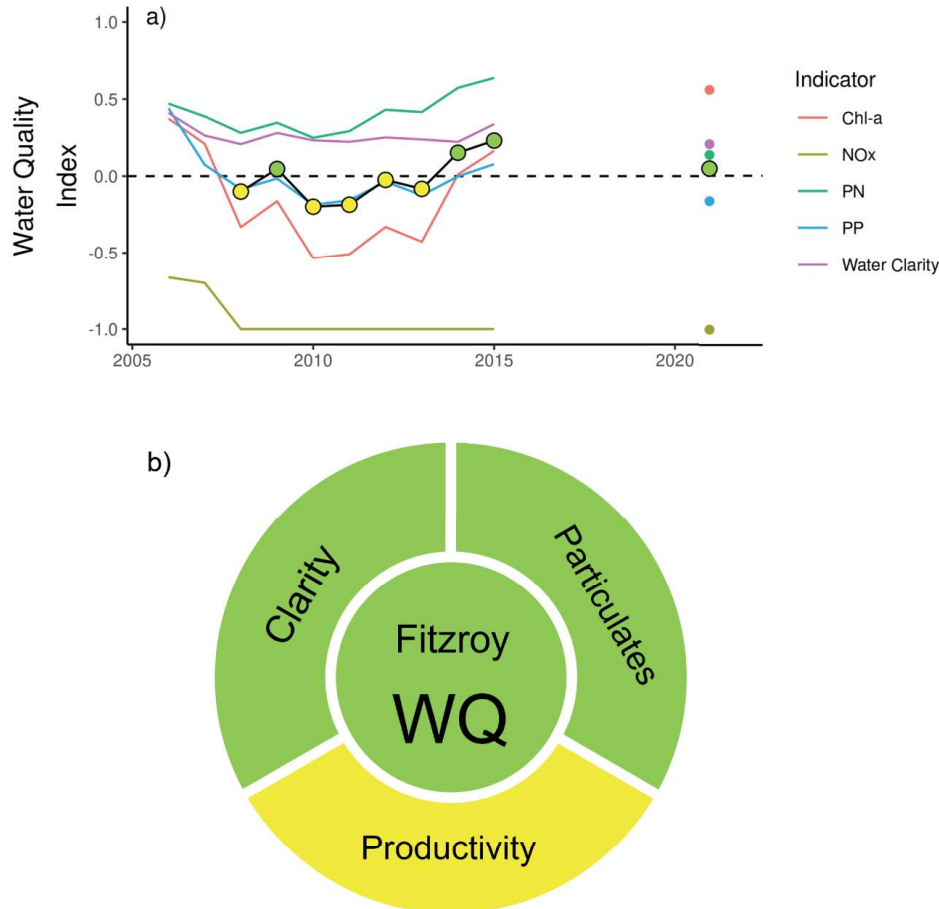


Figure D-6: The Water Quality Index (WQ Index) for the Fitzroy focus region. The WQ Index uses two formulations to communicate: a) long-term trend (based on pre-2015 sampling design) and b) the annual condition (based on post-2015 sampling design). WQ Index colour coding: ● / ◆ – 'very good'; ● / ◆ – 'good'; ● / ◆ – 'moderate'; ● / ◆ – 'poor'; ● / ◆ – 'very poor'. Indicators or sub-indicators that are used to calculate the WQ Index are shown as coloured lines (a) or in the coaster perimeter (b). Error bars (vertical black lines) on the WQ Index represent the 95% quantile intervals. Calculations for both formulations are described in Methods and Appendix B.

D-6 Discussion and Conclusions

The discharge and loads calculated for the 2020-21 water year from the Fitzroy River was well below (less than one-seventh) the long-term median levels (Figure D-2; Table 3-1). The combined discharge and loads calculated for the 2020–21 water year were (or amongst) the lowest recorded over the past decade.

Ambient water quality

Enclosed coastal, open coastal, and mid-shelf waters (for those parameters with guidelines):

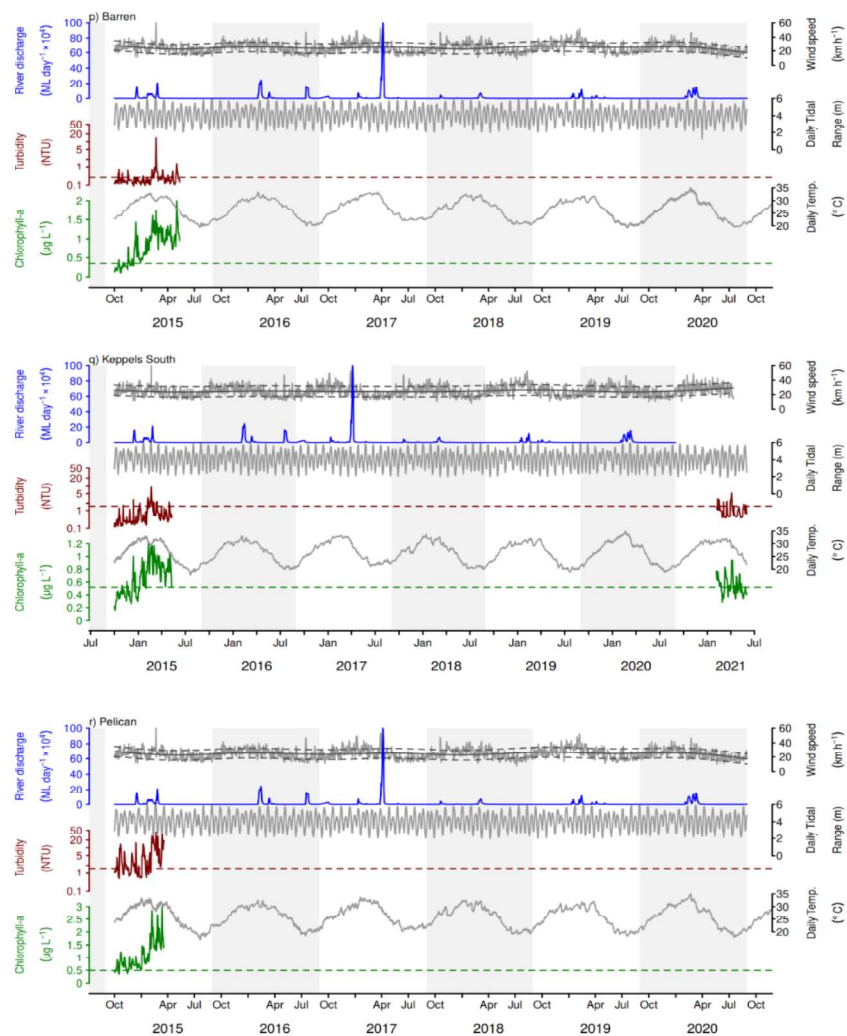
- Exceeded guidelines: NO_x and Secchi depth

- Meeting (below) guidelines: PN (all sites) and Chl-a (all sites except Peak West (FTZ5)).
- Deteriorated over the period 2016–2021: DOC.
- Stable over the period 2016–2021, or not enough data to detect a trend: PO₄, PP, Secchi depth, and TSS.
- Improved over the period 2016–2021: POC.
- For the 2020–21 water year, the Long-Term Water Quality Index score was ‘good’ and is consistent with pre-2015 scores.

Wet season and event water quality

- There were no major flood events in the Fitzroy region during the 2020–21 wet season. There is no event water quality sampling in this region.

D-7 Additional information



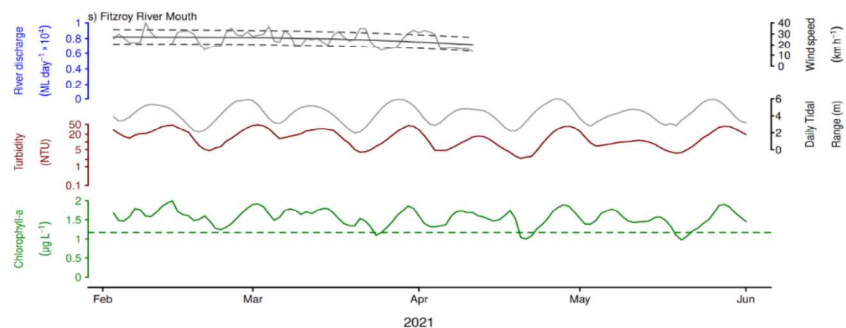


Figure D-7: Time-series of daily means of chlorophyll and turbidity collected by moored ECO FLNTUSB instruments; coloured dashed lines represent the Water Quality GV. Daily river discharge from the nearest river, daily wind speeds from the nearest weather stations, daily tidal range from the nearest tidal gauge, and daily temperature are also shown. Locations of loggers are shown in Figure D-1: a) Barren Island, b) Pelican Island, c) Keppels South, and d) Fitzroy River mouth. Logger data from June to October 2021 were not available at the time of compilation for the report but will be included in next year’s report.

Table D-2: Site-specific Guideline Values (GVs) used for comparison with water quality monitoring data. These GV are used to calculate the annual condition version of the WQ Index for each water quality sampling location and are derived from the Water Quality Guidelines for the Great Barrier Reef Marine Park (Great Barrier Reef Marine Park Authority, 2010, see Table B-1). Basin-level water quality objectives can be accessed online ([Great Barrier Reef Marine Park Authority, Water quality guidelines for the Great Barrier Reef](#)). Seasonal guideline values (i.e., wet vs. dry) are calculated as described in De’ath and Fabricius 2008. See Appendix B for details on Index calculation. DOF is direction of failure (‘H’ = high values fail, while ‘L’ = low values fail). Annual mean GV are applied to annual mean values of monitoring data (and median GV are applied to median data, *et cetera*). Bold GV are those applied to monitoring data.

Short Names	Water Body	Measure	DOF	Annual		Dry	Wet
				Mean	Median	Median	Median
FTZ1	Mid-shelf waters	Chl-a (µg L ⁻¹)	H		0.27	0.32	0.63
		NO _x (µg L ⁻¹)	H		0.50		
		Turbidity (NTU)	H		0.30		
		PN (µg L ⁻¹)	H		12.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	H		2.00		
		PP (µg L ⁻¹)	H		1.90	2.40	3.40
		Secchi (m)	L		12.00		
FTZ2, FTZ3	Open Coastal waters	TSS (mg L ⁻¹)	H		0.40	1.70	2.50
		Chl-a (µg L ⁻¹)	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	H		0.50		
		Turbidity (NTU)	H	1.50			
		PN (µg L ⁻¹)	H	20.00		16.00	25.00
		PO ₄ (µg L ⁻¹)	H	2.00			
		PP (µg L ⁻¹)	H	2.80		2.40	3.40
FTZ4	Open Coastal waters	Secchi (m)	L	10.00			
		TSS (mg L ⁻¹)	H	2.00		1.70	2.50
		Chl-a (µg L ⁻¹)	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	H		0.50		
		Turbidity (NTU)	H		0.50		
		PN (µg L ⁻¹)	H		15.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	H		2.00		
PP (µg L ⁻¹)	H		2.50	2.30	3.30		

Short Names	Water Body	Measure	DOF	Annual		Dry	Wet
				Mean	Median	Median	Median
FTZ5	Open Coastal waters	TSS (mg L ⁻¹)	H		1.00	1.60	2.40
		Chl- <i>a</i> (µg L ⁻¹)	H	0.45		0.32	0.63
		NO _x (µg L ⁻¹)	H		0.50		
		Turbidity (NTU)	H	1.50			
		PN (µg L ⁻¹)	H	20.00		16.00	25.00
		PO ₄ (µg L ⁻¹)	H		2.00		
		PP (µg L ⁻¹)	H	2.80		2.40	3.40
		Secchi (m)	L	10.00			
FTZ6	Enclosed Coastal waters	TSS (mg L ⁻¹)	H	2.00		1.70	2.50
		Chl- <i>a</i> (µg L ⁻¹)	H		1.00		
		NO _x (µg L ⁻¹)	H		3.00		
		Turbidity (NTU)	H			7.00	15.00
		PN (µg L ⁻¹)	H				
		PO ₄ (µg L ⁻¹)	H		3.00		
		PP (µg L ⁻¹)	H				
		Secchi (m)	L				

Table D-3: Summary statistics for water quality parameters at individual monitoring sites from 1 September 2019 to 31 August 2020. N = number of sampling occasions. See Section 0 for descriptions of each analyte and its abbreviation. Mean and median values that exceed available Water Quality Guidelines (DERM, 2009; Great Barrier Reef Marine Park Authority, 2010) are shaded in red.

Region	Site	Measure	N	Mean	Median	Quantiles				Guidelines				
						Q05	Q20	Q80	Q95	DOF	Location	Annual	Dry	Wet
Fitzroy	North Keppel Island (FTZ4)	DIN (µg L ⁻¹)	9											
		DOC (µg L ⁻¹)	9	1742	2020	904	1273	2085	2157					
		DON (µg L ⁻¹)	9											
		DOP (µg L ⁻¹)	9	5.17	5.26	4.29	4.75	5.57	5.85					
		Chl- <i>a</i> (µg L ⁻¹)	9	0.28	0.26	0.17	0.19	0.34	0.43	H	Mean	0.45		
			9	0.28	0.26	0.17	0.19	0.34	0.43	H	Median		0.32	0.63
		NO _x (µg L ⁻¹)	9	2.13	1.02	0.41	0.56	4.20	5.80	H	Median	0.50		
		PN (µg L ⁻¹)	9	14.99	13.59	9.94	11.37	17.50	21.43	H	Median	15.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	9	0.80	0.39	0.31	0.31	1.42	1.89	H	Median	2.00		
		POC (mg L ⁻¹)	9	105.54	89.22	56.17	66.74	142.04	169.28					
		PP (µg L ⁻¹)	9	2.31	2.42	1.45	1.49	3.03	3.14	H	Median	2.50	2.30	3.30
		Secchi (m)	9	10.37	11.00	6.32	7.52	12.70	13.60	L	Median	10.00		
		SiO ₄	9	39.39	37.29	22.02	32.35	52.43	55.42					
	TSS (mg L ⁻¹)	9	1.19	0.64	0.29	0.37	1.23	3.75	H	Median	1.00	1.60	2.40	
	Barren (FTZ1)	DIN (µg L ⁻¹)	9											
		DOC (µg L ⁻¹)	9	1804	2056	888	1217	2141	2407					
		DON (µg L ⁻¹)	9											
		DOP (µg L ⁻¹)	9	5.65	5.50	4.35	5.00	6.38	7.22					
		Chl- <i>a</i> (µg L ⁻¹)	9	0.19	0.18	0.14	0.15	0.24	0.26	H	Median	0.27	0.32	0.63
			9	0.87	0.81	0.34	0.60	0.95	1.53	H	Median	0.50		
		PN (µg L ⁻¹)	9	12.25	11.59	9.43	9.89	14.76	16.13	H	Median	12.00	16.00	25.00
		PO ₄ (µg L ⁻¹)	9	0.92	0.70	0.31	0.40	1.56	1.84	H	Median	2.00		
		POC (mg L ⁻¹)	9	89.24	75.31	51.05	54.89	123.88	151.57					
		PP (µg L ⁻¹)	9	1.86	1.75	1.06	1.36	2.45	2.71	H	Median	1.90	2.40	3.40
		Secchi (m)	9	12.72	13.00	8.40	9.60	15.60	17.40	L	Median	12.00		
		SiO ₄	9	32.89	33.64	17.05	22.44	44.38	49.65					
		TSS (mg L ⁻¹)	9	0.36	0.30	0.27	0.28	0.41	0.57	H	Median	0.40	1.70	2.50
	Keppels South (FTZ2)	DIN (µg L ⁻¹)	9											
		DOC (µg L ⁻¹)	9	1895	2103	883	1190	2273	2835					
		DON (µg L ⁻¹)	9											

Region	Site	Measure	N	Mean	Median	Quantiles				Guidelines					
						Q05	Q20	Q80	Q95	DOF	Location	Annual	Dry	Wet	
		DOP (µg L ⁻¹)	9	4.89	5.03	4.06	4.29	5.48	5.62						
		Chl-a (µg L ⁻¹)	9	0.24	0.25	0.16	0.18	0.30	0.34	H	Mean	0.45			
			9	0.24	0.25	0.16	0.18	0.30	0.34	H	Median		0.32	0.63	
		NO _x (µg L ⁻¹)	9	1.60	0.77	0.33	0.50	2.60	4.60	H	Median	0.50			
		PN (µg L ⁻¹)	9	15.33	12.61	10.09	10.34	20.29	25.75	H	Mean	20.00			
			9	15.33	12.61	10.09	10.34	20.29	25.75	H	Median		16.00	25.00	
		PO ₄ (µg L ⁻¹)	9	0.77	0.77	0.31	0.31	1.25	1.49	H	Mean	2.00			
			9	0.77	0.77	0.31	0.31	1.25	1.49	H	Median				
		POC (mg L ⁻¹)	9	118.05	85.82	58.43	60.99	156.50	251.89						
		PP (µg L ⁻¹)	9	2.12	1.97	1.40	1.45	2.69	3.04	H	Mean	2.80			
			9	2.12	1.97	1.40	1.45	2.69	3.04	H	Median		2.40	3.40	
		Secchi (m)	9	9.37	10.50	4.78	6.10	12.20	13.10	L	Mean	10.00			
			9	9.37	10.50	4.78	6.10	12.20	13.10	L	Median				
		SiO ₄	9	37.04	33.50	23.44	25.63	47.91	58.90						
		TSS (mg L ⁻¹)	9	1.10	0.96	0.44	0.49	1.25	2.53	H	Mean	2.00			
			9	1.10	0.96	0.44	0.49	1.25	2.53	H	Median		1.70	2.50	
		Pelican (FTZ3)	DIN (µg L ⁻¹)	9											
			DOC (µg L ⁻¹)	9	1899	2152	950	1288	2269	2530					
			DON (µg L ⁻¹)	9											
			DOP (µg L ⁻¹)	9	5.02	5.19	3.90	4.18	5.79	5.93					
		Chl-a (µg L ⁻¹)	9	0.35	0.32	0.13	0.14	0.49	0.68	H	Mean	0.45			
			9	0.35	0.32	0.13	0.14	0.49	0.68	H	Median		0.32	0.63	
		NO _x (µg L ⁻¹)	9	1.88	0.91	0.46	0.62	3.12	5.22	H	Median	0.50			
		PN (µg L ⁻¹)	9	16.23	17.03	10.09	10.32	18.87	25.07	H	Mean	20.00			
			9	16.23	17.03	10.09	10.32	18.87	25.07	H	Median		16.00	25.00	
		PO ₄ (µg L ⁻¹)	9	1.74	1.63	0.85	1.36	2.31	2.59	H	Mean	2.00			
			9	1.74	1.63	0.85	1.36	2.31	2.59	H	Median				
		POC (mg L ⁻¹)	9	128.43	123.15	55.33	59.38	171.48	243.25						
		PP (µg L ⁻¹)	9	3.52	3.46	1.43	1.63	4.27	7.30	H	Mean	2.80			
			9	3.52	3.46	1.43	1.63	4.27	7.30	H	Median		2.40	3.40	
		Secchi (m)	9	5.11	4.00	1.49	2.64	8.40	9.65	L	Mean	10.00			
			9	5.11	4.00	1.49	2.64	8.40	9.65	L	Median				
		SiO ₄	9	68.78	69.31	31.70	35.66	89.48	118.60						
		TSS (mg L ⁻¹)	9	3.15	2.03	0.54	0.71	4.10	8.88	H	Mean	2.00			
			9	3.15	2.03	0.54	0.71	4.10	8.88	H	Median		1.70	2.50	
	Peak West (FTZ5)	DIN (µg L ⁻¹)	9												
		DOC (µg L ⁻¹)	9	1923	2254	924	1231	2340	2552						
		DON (µg L ⁻¹)	9												
		DOP (µg L ⁻¹)	9	5.39	4.96	3.93	4.35	5.68	8.01						
		Chl-a (µg L ⁻¹)	9	0.46	0.40	0.25	0.33	0.60	0.82	H	Mean	0.45			
			9	0.46	0.40	0.25	0.33	0.60	0.82	H	Median		0.32	0.63	
		NO _x (µg L ⁻¹)	9	3.61	0.74	0.28	0.30	5.30	13.97	H	Median	0.50			
		PN (µg L ⁻¹)	9	18.96	16.28	12.39	13.74	23.67	30.74	H	Mean	20.00			
			9	18.96	16.28	12.39	13.74	23.67	30.74	H	Median		16.00	25.00	
		PO ₄ (µg L ⁻¹)	9	2.18	2.01	1.02	1.63	2.83	3.39	H	Median	2.00			
		POC (mg L ⁻¹)	9	162.26	146.01	85.69	97.57	202.00	293.71						
		PP (µg L ⁻¹)	9	4.40	3.43	2.21	2.68	5.55	8.52	H	Mean	2.80			
			9	4.40	3.43	2.21	2.68	5.55	8.52	H	Median		2.40	3.40	
		Secchi (m)	9	2.70	2.75	1.34	2.30	3.16	3.76	L	Mean	10.00			
			9	2.70	2.75	1.34	2.30	3.16	3.76	L	Median				
		SiO ₄	9	84.00	85.67	55.07	59.16	106.11	121.24						
		TSS (mg L ⁻¹)	9	5.12	3.34	1.58	2.19	6.78	12.33	H	Mean	2.00			
			9	5.12	3.34	1.58	2.19	6.78	12.33	H	Median		1.70	2.50	
	Fitzroy River Mouth (FTZ6)	DIN (µg L ⁻¹)	9												
		DOC (µg L ⁻¹)	9	2303	2488	1006	1302	2746	3678						
		DON (µg L ⁻¹)	9												
		DOP (µg L ⁻¹)	9	4.89	5.19	3.45	4.24	5.62	5.81						
		Chl-a (µg L ⁻¹)	9	0.86	0.78	0.68	0.73	1.05	1.13	H	Median	1.00			
		NO _x (µg L ⁻¹)	9	9.37	9.80	2.00	5.91	11.78	16.61	H	Median	3.00			
		PN (µg L ⁻¹)	9	35.68	35.53	24.55	27.58	42.75	47.86	H	Median				
		PO ₄ (µg L ⁻¹)	9	5.63	5.57	3.38	4.49	6.89	7.68	H	Median	3.00			
		POC (mg L ⁻¹)	9	394.76	400.96	215.36	270.13	505.29	581.85						
		PP (µg L ⁻¹)	9	14.08	13.18	7.82	9.16	19.69	19.82	H	Median				
		Secchi (m)	9	0.69	0.50	0.38	0.50	0.93	1.26	L	Median				
		SiO ₄	9	135.01	139.40	110.04	122.39	141.98	162.00						

Region	Site	Measure	N	Mean	Median	Quantiles				Guidelines				
						Q05	Q20	Q80	Q95	DOF	Location	Annual	Dry	Wet
		TSS (mg L ⁻¹)	9	20.46	20.75	5.99	8.77	31.99	35.30	H	Median			

Table D-4: Summary of turbidity measurements from moored loggers (site locations in Figure D-1) for the past three water years. N = number of daily means in the time-series; SE = standard error; '% d > Trigger' refers to the percentage of days each year with mean or median values above the site-specific water quality guideline values (Table D-2). Red shading indicates the annual means or medians that exceeded guideline values. '% d > 5 NTU' refers to the percentage of days above 5 NTU, a threshold suggested by Cooper et al. (2007, 2008) above which hard corals are likely to experience photo-physiological stress. There is no data available for Barren due to an instrument failure.

Subregion	Site	Oct 2020 - Sept 2021					
		N	Annual Mean	SE	Annual Median	% d > Trigger	% d > 5 Trigger
Fitzroy	Barren						
	Fitzroy River Mouth	119	18.25	1.18	14.75		86.55
	Keppels South	118	1.16	0.07	0.91	21.19	0.85

D-8 References

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Appendix E: Assessing influences on inshore marine water quality in the dry season

A pilot Study Using Sentinel Satellite images and the Forel-Ule colour scale

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E-1 Introduction

Stretching more than 2000 km along the Queensland coast, in Australia, the Great Barrier Reef (the Reef) Marine Park was inscribed on the World Heritage List in October 1981. With over 2900 coral reefs, it is the most extensive reef system in the world, also sheltering over 43,000 km² of seagrass meadows (Brodie and Waterhouse, 2012, GBRMPA, 2019). The Reef is a complex biological and physical system bounded westward by the Queensland coastline and eastward by the oceanic waters of the Coral Sea.

Many catchments, rivers, and estuaries are connected to the Reef, and the Reef lagoon can be divided into two broad regions: (i) a near-shore, shallow region strongly affected by waves, wind and rivers. In this near-shore region, the influence of surface wind and waves can reach the seafloor and resuspend sediments. (ii) Deeper offshore waters more influenced by oceanic currents and exchanges with the Coral Sea, including upwelling of nutrient-rich water from the deeper ocean. The influence of rivers and ocean currents further varies along the Reef because the lagoon is wide in the south and significantly narrower in the north, and the offshore reefs which form a barrier to exchange with the Coral Sea are dense in some areas and more scattered in others (AIMS, 2021).

Despite its protected status and World Heritage listing, the Reef is under stress from three main threats associated with anthropogenic activities: over-harvesting of marine resources, climate change and land-based pollution (for example, Waterhouse *et al.*, 2017). Sediment and nutrient pollution from agricultural run-off, and to a lesser extent urban and industrial activities, are cited as the main sources of poor water quality entering the Reef. Excess sediment and nutrients reduce light penetration into the water, which affects the growth of important species that need light to photosynthesise such as seagrass and coral. Sediment can smother sessile animals and plants, and nutrients promote the growth of algae which compete for space with corals (Fabricius 2005; Bainbridge *et al.* 2018).

Discharge of pollutants to the Reef occurs mainly during the high-flow events associated with the north Queensland wet season between December to April (Waterhouse *et al.*, 2021). Thirty-five major river basins drain into the Reef all of which vary considerably in length, catchment area, and flow frequency and intensity. Wet Tropic catchments, located between Townsville and Cooktown, have frequent storm and runoff events in generally short, steep catchments, and thus more direct and frequent linkages to coastal environments. In the Dry Tropic catchments, the major flow events may occur at intervals of years, with long lag times for the transport of material through these large catchments (Brodie *et al.*, 2009). Despite regional variations, the Coriolis force and prevailing south-easterly wind regime commonly push flood plumes against the coast and northwards (Devlin *et al.* 2001; Devlin and Brodie 2005, Brodie *et al.*, 2010), concentrating the influence of river run-off on inshore ecosystems.

The focus on improving water quality in the Reef 2050 Plan and the Reef 2050 Water Quality Plan (the Plan – Url: <https://www.reefplan.qld.gov.au/water-quality-and-the-reef/the-plan>) is to reduce land-based impacts from both rural and urban areas. Agriculture is the major land use and the main source of water pollution in the Reef catchment, and is therefore a major focus for action and funding under the Plan. Inshore water quality is improving, but too slowly. In part, this outcome may be partially a result of underestimating the impacts on water quality from physical forces (for example, wind, tides or waves) that can lead to sediment resuspension and light reduction.

Satellite Earth Observation (EO) is a unique tool for allowing high spatial and temporal resolution observations of water quality conditions across very large areas, such as the Reef. It has been successfully used worldwide and in Australia to monitor trends in marine water composition and map riverine plumes over the past two decades (Devlin *et al.*, 2015; Petus *et al.*, 2014a, 2019; Fournier and Lee, 2021). Satellite images provide spatially explicit information on how, when and where land-based sediments and associated contaminants are

transported and which ecosystems are likely to be exposed and likely to be at risk from land-based runoff. However, the Reef is wide and optically complex. While regional quantification algorithms have been implemented for the Reef (for example, King *et al.*, 2014), their development is complex and data intensive as it requires a full characterisation of the Reef regional and seasonal bio-optical properties through *in situ* sampling (Cherukuru *et al.*, 2019). To date, accurate and fully validated algorithms able to quantify the wide range of water quality parameters (for example chlorophyll *a* (Chl-*a*), turbidity, Total Suspended sediments (TSS), Secchi disk depth (SDD), nutrient concentrations) found in the Reef in both the wet and dry season are still in development.

In parallel, the remote sensing component of the Great Barrier Reef Marine Monitoring Program (the Program) has focused on using the apparent colour (hereafter, colour) of the ocean retrieved from satellite imageries to monitor the impact of river plumes on water quality and local ecosystems during the wet season (December – April) (Alvarez-Romero *et al.*, 2013, Devlin *et al.*, 2015, Petus *et al.*, 2014b, c, 2016, Waterhouse *et al.*, 2021, Wenger *et al.*, 2016). Water colour is the result of its marine constituents and their interactions with solar irradiance (Wang *et al.*, 2021). Water colour is used in the Program as an efficient, yet simple, monitoring parameter to cluster Reef waters with similar water quality characteristics, including their TSS, Chl-*a*, and Coloured Dissolved Organic Matter (CDOM) concentrations, and their turbidity and SDD levels. It is used to provide spatially-explicit information on water colour and water quality variability, as well as to monitor the extent of river flood plumes during high flow conditions (GBRMPA, 2021; Gruber, 2020; Waterhouse, 2021).

Catchment run-off in sediment-laden river discharge appears in satellite images as brownish flood plumes, while productive waters appears with a greenish colour and ambient (clear) marine waters with a bluish colour. However, brownish-green waters also appears when sediment are resuspended by wind, tides or waves. They can be visible during times when there is no significant river discharge in both the wet and dry seasons, or amalgamated with flood plume signatures in the higher flow conditions. Water quality and colour trends have been well documented during the high flow periods (Devlin *et al.*, 2015, Waterhouse *et al.*, 2021, Petus *et al.*, 2019). However, there is a need to better understand physical (wind and/or tide and/or wave-induced) influences on inshore marine water quality in the dry season as well as during the driest wet season periods, and how this compares to run-off influence.

This pilot study focused on this knowledge gap, and aimed to develop a preliminary framework for assessing influences on inshore marine water quality in the dry season. It built on the existing wet season mapping approaches developed through the Program to investigate their application for the development of dry season water type maps using Sentinel-3 satellite imagery and the Forel-Ule (FU) colour scale. Specific objectives for this pilot study included: 1) the development of a database of Sentinel-3 images for a selected dry season, 2) the adjustment of methods and tools developed for the wet season to the dry season, 3) the presentation of example images, summary maps and, if available, field water quality data illustrating dry season conditions and difference between the wet and dry season. For this preliminary study, we focused on the 4 first months (18 weeks) of the dry season 2019 (May to August 2019). Ultimately, methods developed a part of this pilot study will help to understand the magnitude, duration and extent of poor water quality in the dry season, when the Reef is not affected by land-based run-off in river discharge; and how this compares to the effects we can attribute to run-off in the wet season.

E-2 Methods

Satellite ocean colour

Trends in Reef marine water composition during the wet season have been successfully monitored over the past six years, using a combination of Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite images and field water quality data collected through the

Program (Devlin *et al.*, 2015, Waterhouse *et al.*, 2021; Petus *et al.*, 2019). Using a “wet season” (WS) colour scale specifically developed for the Reef, MODIS satellite pixels are reclassified into six colour classes, then three distinct water types: the Primary, Secondary and Tertiary water types (Alvarez-Romero *et al.*, 2013). These water types represent typical colour and water quality gradients encountered in the Reef during the wet season (Table E-1):

- **The brownish to brownish-green turbid waters** (colour classes 1 to 4 or primary water type) are typical for inshore regions experiencing river plumes or nearshore marine areas with high concentrations of resuspended sediments found during the wet season. These water bodies in flood waters typically contain high nutrient and phytoplankton concentrations but are also enriched in sediment and dissolved organic matter resulting in reduced light levels.
- **The greenish-to-greenish-blue turbid waters** (colour class 5 or secondary water type) is typical of coastal waters rich in algae (Chl-a) and contain dissolved matter and fine sediments. This water body is found in open coastal waters as well as in the mid-water plumes where relatively high nutrient availability and increased light levels due to sedimentation (Bainbridge *et al.*, 2012) favour coastal productivity.
- **Finally, the greenish-blue waters** (colour class 6 or tertiary water type) correspond to waters with slightly-above ambient water quality concentrations. This water body is typical for areas towards the open sea or offshore regions of river flood plumes. The ecological relevance of the water quality concentrations in the tertiary water type is not well understood but expected to be relatively minor.

Table E-1: Comparison between MA-WS and S3-FU-equivalent water types (from Petus *et al.*, 2019)

MA-WS			S3-FU		
Water types	Colour classes	Description	Water types	Colour classes	Description
Primary	1-4	Waters with high sediment concentration, but also enriched in Chl-a, and CDOM resulting in reduced light levels	Primary-equivalent	FU \geq 10	Waters with high phytoplankton levels and increasing sediment and dissolved organic matter
Secondary	5	Waters rich in algae and also contains dissolved organic matter and fine sediment	Secondary-equivalent	FU 6-9	Waters with colour still dominated by algae, but increased dissolved organic matter and some sediment may be present
Tertiary	6	Waters with slightly-above ambient water quality concentrations	Tertiary-equivalent	FU 4-5	Waters with high light penetration
Marine	No number	Waters with high light penetration	Marine-equivalent	FU 1-3	Waters with high light penetration

Several monitoring products were then derived each wet season from the MODIS water type maps to report on water quality trends during the wet season (December to April). This includes daily flood plume and sediment resuspension maps, weekly panel maps of environmental and marine wet season conditions, frequency maps of occurrence of water types, exposure maps to above wet season water quality Guideline Values (GVs); and assessment of potential risk from exposure to coral and seagrass ecosystems (Waterhouse *et al.*, 2021, Petus *et al.*, 2019).

However, MODIS sensors are ageing (MODIS-Aqua was launched in 2002) and the quality of the MODIS imagery is declining. The use of the Sentinel-3 Ocean Land Colour Instrument (OLCI) satellite imagery and another colour scale (the Forel-Ule (FU) colour scale) has been proposed for the continuous mapping of Reef waters (Petus *et al.*, 2019). The FU colour scale is an historical colour scale standard to determine the colour and classifies bodies of water worldwide (Novoa *et al.*, 2013). It is composed of 22 colours; from indigo blue to cola brown, and is applicable for all natural waters (inland, estuarine, inshore and offshore) and all environmental conditions, including wet and dry season conditions (Wernand *et al.*, 2012, 2013; Van der Woerd *et al.*, 2016; Van der Woerd and Wernand, 2018).

MODIS-Aqua WS and Sentinel-3 FU colour class maps showed very similar patterns over the 2017–18 wet season in a case study focusing on Wet Tropics and Burdekin regions of the Reef (Petus *et al.*, 2019). In this case study, FU-equivalent water types were defined by grouping the FU colour classes 1–3 (equivalent to marine waters in the WS scale), FU colour classes 4–5 (equivalent to WS Tertiary water type), FU colour classes 6–9 (equivalent to WS Secondary water type) and $FU \geq 10$ (equivalent to WS Primary water type) (Table E-1).

Data

For this project, water conditions in the dry season were mapped using Sentinel-3 images and the FU colour scale (Table E-1). Marine waters were clustered by grouping the FU colour classes 1–3 (FU 1-3), Tertiary waters as FU4-5, Secondary waters as FU6-9 and Primary waters as $FU \geq 10$, as described in Petus *et al.* (2019). Steps followed in this study are described below and summarized in Figure E-1.

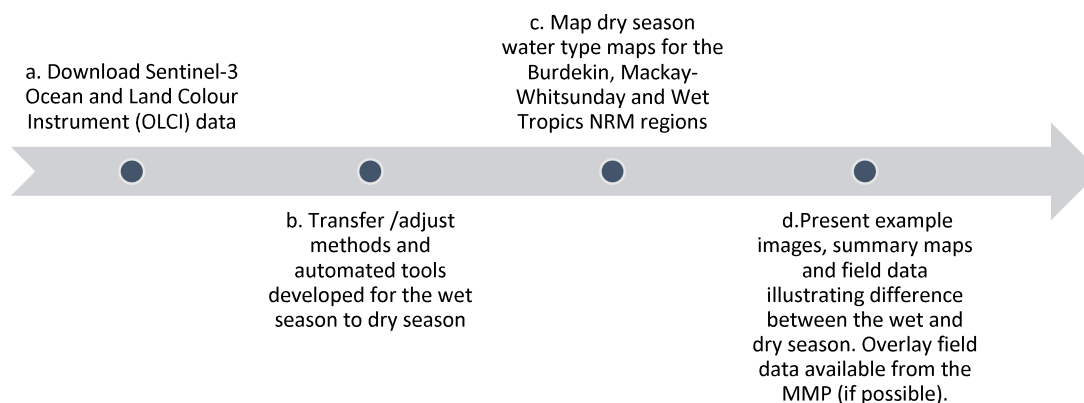


Figure E-1: Methods used to produce preliminary Dry season Sentinel-3 FU summary maps.

We focused on the Burdekin Natural Resource Management (NRM) region, with some references to the Mackay-Whitsunday and Wet Tropics NRM regions, and on the first four months of the dry season in 2019 (May-August 2019, 18 weeks). Environmental conditions over the preceding 2018–19 wet season involved river discharge above the long-term median, and a number of cyclones crossing the coast in the northern Reef. The largest water discharge was in the Burdekin region, which was more than three times the long-term median discharge and the largest discharge recorded since the extreme flows in 2010/2011 (Figure E-2).

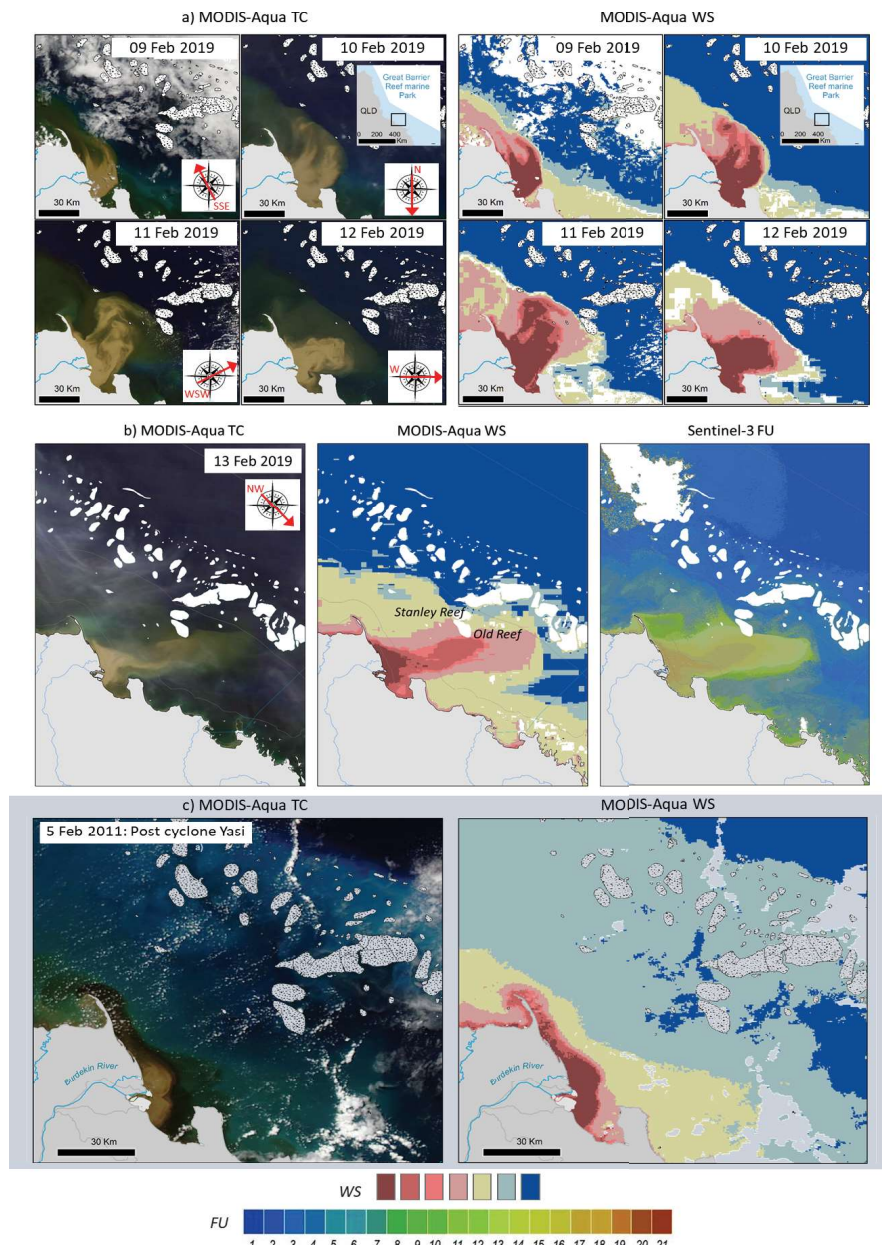


Figure E-2: a) Modis-Aqua true colour (TC, left) and MODIS-Aqua WS (right) maps illustrating the major floods that occurred from the Burdekin River in February 2019. The wind orientation at 9am is indicated with a red arrow (Townsville airport, BOM Climate Data Online) b) Maximum plume extent was recorded on the 13th of February 2019, when Primary plume waters moved offshore and reached Stanley and Old Reefs. This unique situation was documented on both MODIS-Aqua TC and WS and Sentinel-3 FU colour class maps, which both showed very similar colour patterns. c) Reef colour patterns post Cyclone Yasi in February 2011. Heavy flows from the Burdekin River, in conjunction with prevailing weather conditions, including significant northern and eastward winds, resulted in the turbid Burdekin. River plume moving directly offshore during its peak flow (Figure E-2a, b). Typically, Burdekin River plumes move northwards along the coast, and this was a unique situation that hasn't been documented previously (Figure E-2c). Discharges in the Wet Tropics and Mackay-Whitsunday regions were 1.5–2 times above the long-term median, and the largest since the significant flows of the 2010–11 wet season (Gruber *et al.*, 2020).

Dry season rainfall in 2018–19 for all of the basins of the Reef catchment area was widely similar to the long-term average of dry seasons from 1961–1990 (Figure E-3).

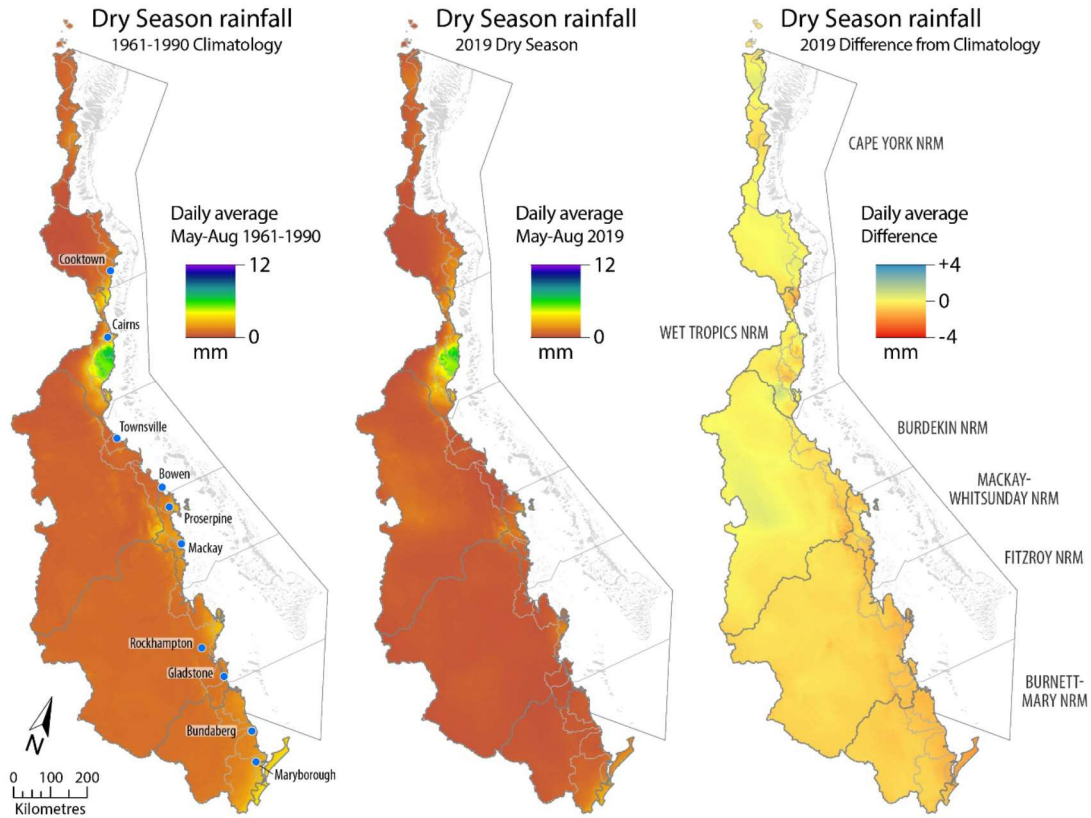


Figure E-3: Average daily dry season rainfall (May-Aug, mm d⁻¹) in the Reef catchment: (left) long-term daily average (1961–1990), (centre) 2019–20 and (right) the difference between the long-term average and 2019–20 rainfall. Source data: Bureau of Meteorology (2021).

- **Sentinel-3 FU maps:** Sentinel-3 OLCI Level-2 (hereafter, Sentinel-3) imagery of the study area was downloaded on the EUMETSAT Data centre (URL: <https://www.eumetsat.int/eumetsat-data-centre>) (Figure E-1a). Sentinel-3 images were atmospherically corrected and processed with the FU Satellite Toolbox implemented in the Sentinel Application Platform (SNAP, URL: <https://step.esa.int/main/toolboxes/snap/>). Automated tools (python scripts and ArcGIS toolboxes) developed through the Program for the wet season marine monitoring were adjusted and upgraded to produce dry season Sentinel-3 FU maps of the study area (Figure E-1b). The FU satellite algorithm converts satellite normalised multi-band reflectance information into a discrete set of FU numbers using uniform colourimetric functions (Van der Woerd *et al.*, 2016, Van de Wored and Wernand, 2018). The derivation of the colour of natural waters is based on the calculation of Tristimulus values of the three primaries (X, Y, Z) that specify the colour stimulus of the human eye. The algorithm is validated by a set of hyperspectral measurements from inland, coastal and marine waters (Van der Woerd *et al.*, 2016, Van de Wored and Wernand, 2018). Technical details about the FU scale algorithm are synthesised through the European citclops (URL: <http://www.citclops.eu/>) and Eye on Water project webpages (<https://www.eyeonwater.org/>).
- **Weekly composite maps and cleaning:** Weekly FU composite maps were produced to minimise the amount of area without data per image due to masking of cloud cover and sun glint (Figure E-1c). The maximum FU value of each pixel/week was used to keep the colour class with the highest turbidity level for each wet season week. The weekly composite maps were cleaned to remove single or small clusters of cells occasionally misclassified by the FU satellite algorithm in the offshore regions of the Great Barrier Reef (including, for example, around coral reefs due to bottom interference and residual glint contamination). The method involved sequentially infilling contiguous areas one FU class at a time from FU1 through to FU21 then replacing nearshore pixels in FU classes ≥ 10 with the original pixels using Python 2.7.3 (Python Software Foundation, 2012) and ArcGIS 10.2 (ESRI, 2013). In order to produce weekly Primary, Secondary and Tertiary (PST)-equivalent maps, marine waters were clustered by grouping the FU colour classes 1–3 (FU 1-3), Tertiary waters as FU4-5, Secondary waters as FU6-9 and Primary waters as FU ≥ 10 .
- **WQ data:** *In situ* water quality measurements of Chl-*a*, TSS, CDOM and SDD measurements were collected in the study area as part of the Program during the first 18 weeks of the dry season 2019. Water samples were collected along transects in the Wet Tropic region, but no samples were available for the Burdekin and Mackay-Whitsunday regions. *In situ* surface water samples for TSS and Chl-*a* concentrations were collected using a polyethylene bucket, with 1 L collected for analysis of TSS and 1 L collected in a dark bottle for Chl-*a* analysis. TSS (in mg L^{-1}) was measured gravimetrically, Chl-*a* concentrations (in $\mu\text{g L}^{-1}$) determined using a fluorometer instrument and CDOM samples were measured on a Shimadzu UV Spectrophotometer. Methods are described in full details in GBRMPA (2019, 2021).
- **Weekly composites and analyses:** Panels of weekly composites were presented to illustrate the potential of the Sentinel-3 FU data to map Reef marine water quality during the dry season (Figure E-1d). The FU colour class category corresponding to the location and week of acquisition of each dry season water quality sample was extracted using ArcGIS 10.6. Average concentrations of TSS, Chl-*a*, CDOM and SDD measured *in situ* in each water type were calculated and compared to long-term wet season values reported in the Program (Waterhouse *et al.*, 2021). The confidence in

the estimated dry season concentration is low given samples were only collected in the Wet Tropics NRM region only. In order to summarise dry season colour patterns, the mean weekly water type value recorded in each marine waterbody of the Burdekin region was extracted and visualised in a 2D time series plot. The mean weekly water type values were also extracted for each week of the 2018–19 wet season and plotted in the same 2D time series plot, and one example image was produced to illustrate the differences between the wet and dry season patterns.

- **Frequency and exposure maps:** Dry season frequency maps were produced to predict the areas affected by the primary and secondary water types combined and the three wet season water types (primary, secondary and tertiary water types) individually (i.e., of the brownish, greenish and greenish-blue waters, respectively) (Figure E-1d). Dry season exposure maps were also produced using the exposure assessment framework developed in the Program (GBRMPA, 2021; Waterhouse *et al.*, 2021). These dry season summary maps were compared to the frequency and exposure maps of the 2019 wet season to illustrate differences existing between the wet and dry seasons.

E-3 Results

Sentinel-3 FU water type maps

The Sentinel-3 FU plume map from the 13 Feb 2019 showed patterns very similar to the MODIS-Aqua WS map (Figure E-2b). Similarly, the weekly FU (Figure E-4a) and PST-equivalent Figure E-5 and Figure E-6) maps successfully illustrated the spatial and temporal variability in reef water colour during the first 3 months of the dry season in 2019. This confirmed the potential of using Sentinel-3 FU imagery for mapping Reef marine water bodies in both wet and dry season conditions.

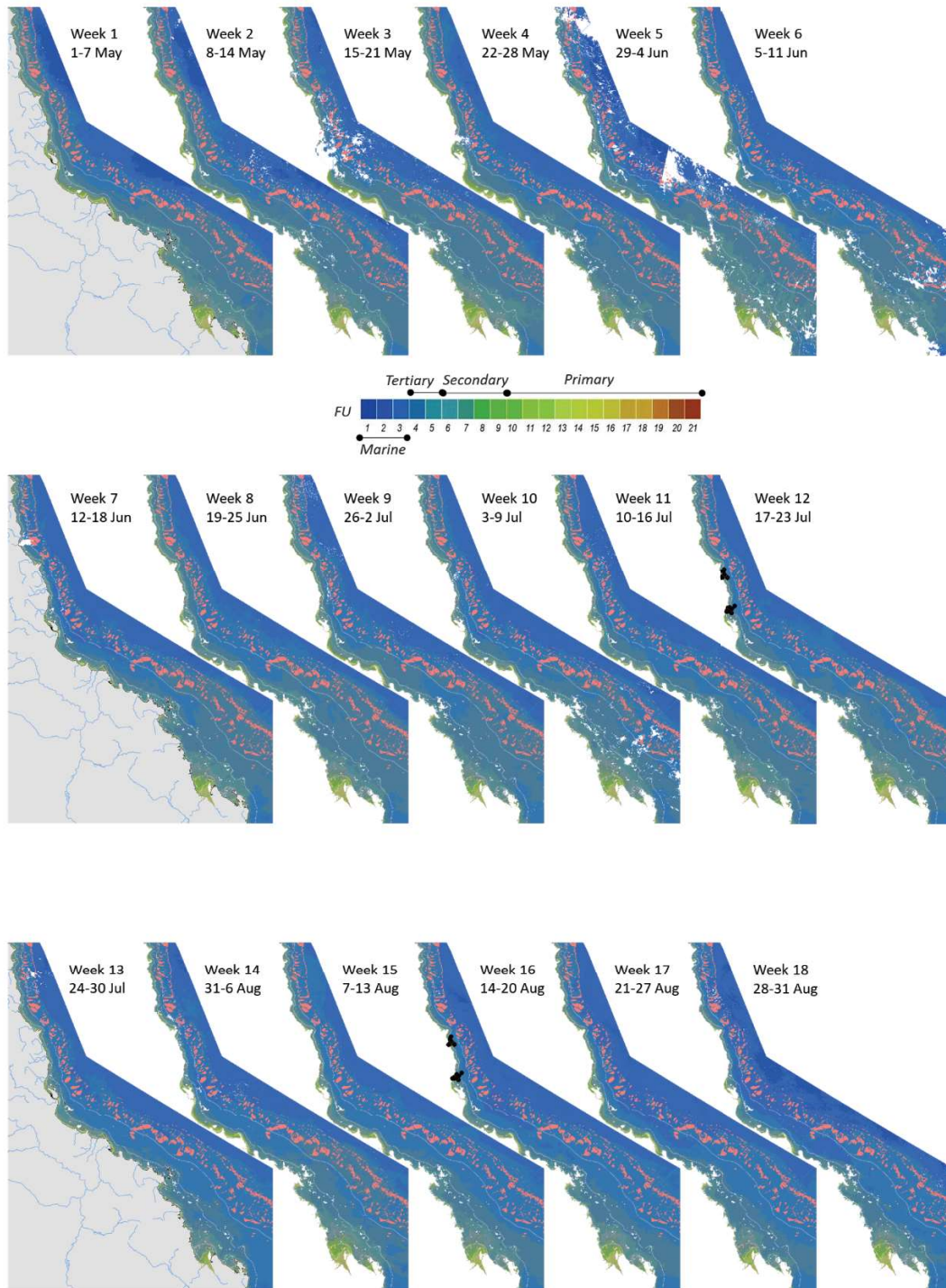


Figure E-4: Weekly FU composite maps of the dry season 2019. Black dots (●) in weeks 12 and 16 region indicates field data collected by AIMS in the Wet Tropics region. P: Primary, S: Secondary and T: Tertiary water type.

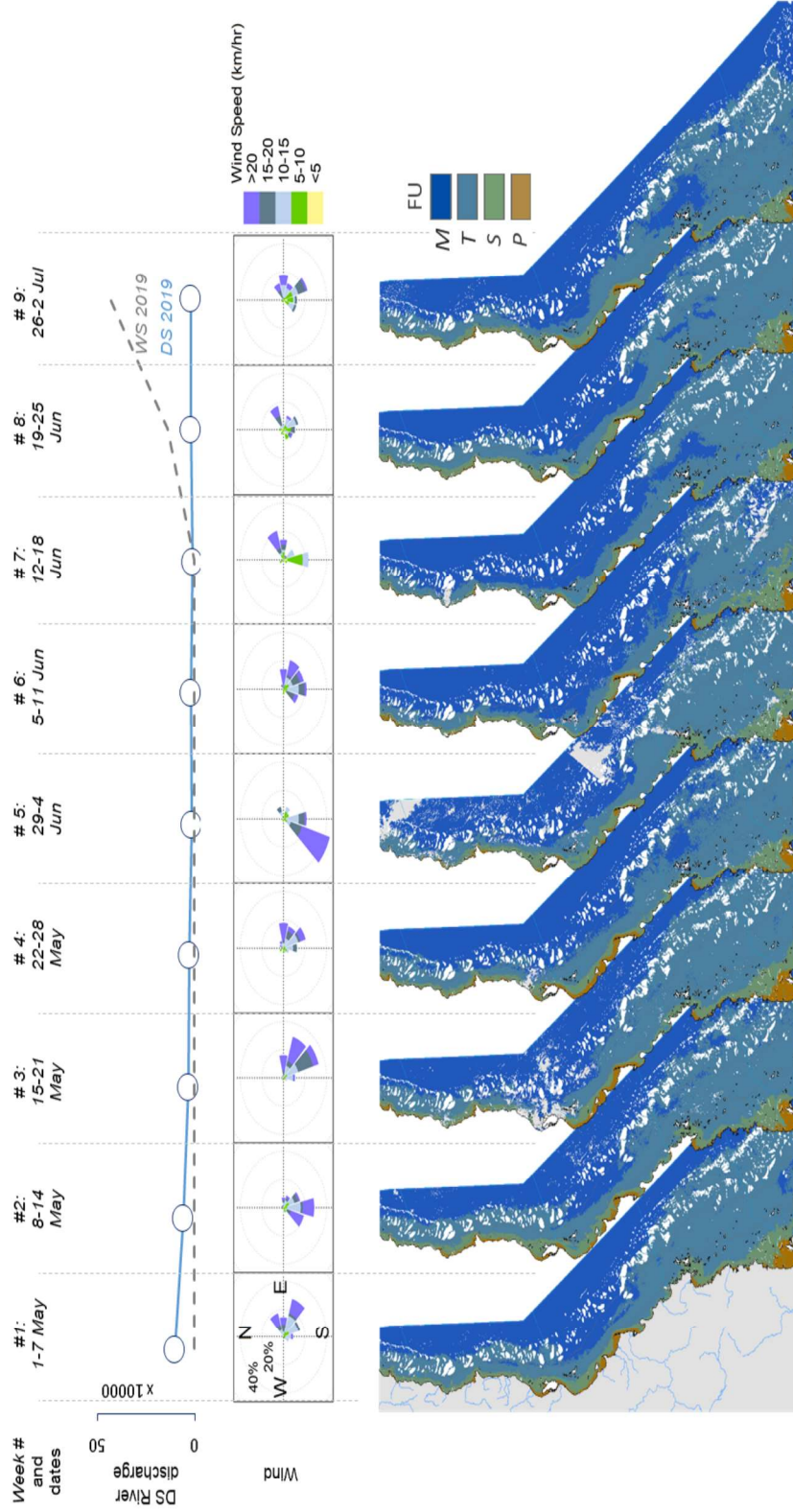


Figure E-5: Panel of water quality and environmental characteristics in the study area throughout the 2019 dry season period: weeks 1 to 9. Includes: Burdekin dry season weekly river discharge (ML, blue line) and wet season water type maps. The Burdekin wet season weekly river discharge is indicated by a dotted grey line for comparison. Weekly river discharges are the sum of discharge (ML) from the Black, Ross, Haughton, Burdekin and Don rivers.

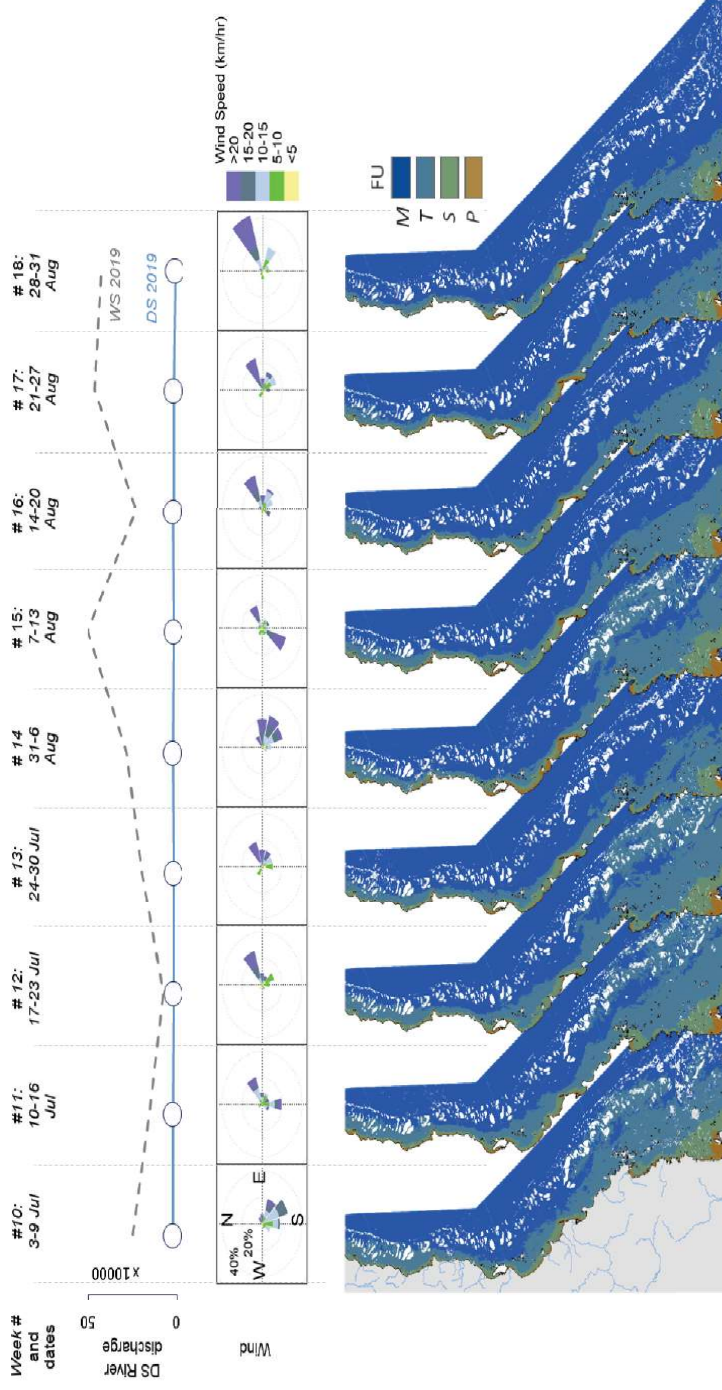


Figure E-6: Panel of water quality and environmental characteristics in the study area throughout the 2019 dry season period: weeks 10 to 18. Includes: Burdekin dry season weekly river discharge (ML, blue line) and wet season water type maps. The Burdekin wet season weekly river discharge is indicated by a dotted grey line for comparison. Weekly river discharges are the sum of discharge (ML) from the Black, Ross, Haughton, Burdekin and Don rivers.

Mean water quality concentrations

There were no *in situ* water quality measurements available for the Burdekin or Mackay-Whitsunday regions during the 1 May to 1 Sept 2019 period, however, water quality data were collected in the Wet Tropics region during weeks 12 and 16 (Figure E-7a, black dots, n=58). The mean dry season TSS, CDOM and SDD calculated across the PST-equivalent water types showed patterns consistent with the long-term wet season patterns (Waterhouse *et al.*, 2021), even though dry season concentrations were in the lower wet season ranges (Figure E-7 and Table E-2). Mean SDD values were very similar to the long-term wet season patterns, and confirmed that water clarity increase (i.e., turbidity decrease) from the Primary to the Tertiary water types in both dry and wet seasons.

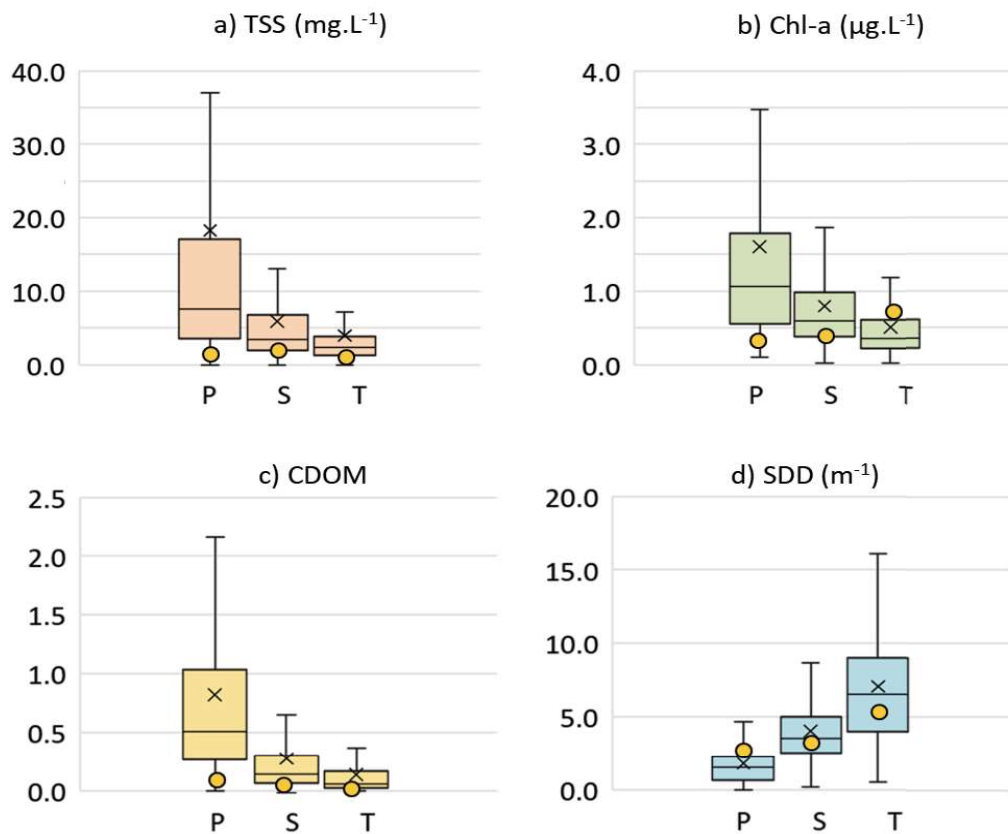


Figure E-7: Long-term wet season optical water quality (WQ, 2004–2019) concentration and Secchi disk depth (SDD) boxplots for each wet season water type (P = primary, S = secondary, T = tertiary, Waterhouse *et al.*, 2021). The mean is plotted as a cross, the interquartile range is delimited by the box and the median by the line inside the box. Whiskers indicate variability outside the upper and lower quartiles. Data beyond the whiskers range are considered outliers and are not plotted. Mean dry season WQ recorded during the first 18 weeks of the dry season 2018 in the Wet Tropics are indicated with orange dots.

Mean dry season Chl-a values, as well as PP and PN, were however higher in the tertiary waters (Figure E-7 and Table E-2) and over guideline values (Table E-2). The number of field data collected in the tertiary waters was limited both spatially and temporally (Figure E-4, n = 36) and these higher concentrations were linked to a single sample collected west of Franklands Island, 20 July 2019. More field and satellite match-ups in the dry season months will be necessary to further validate and refine these preliminary results.

Table E-2: Dry and wet season mean water quality in the Primary, Secondary and Tertiary water types. The confidence in the estimated dry season concentration is low given samples were only collected in the Wet Tropic region during weeks 12 and 16 of the 2019 dry season. Reef-wide guideline values (GVs) and magnitude scores used to calculate the exposure maps are also indicated. The seasonal GVs are based on seasonal adjustments to reef-wide annual GVs (Great Barrier Reef Marine Park Authority, 2010), where wet season guidelines are $\pm 20\%$ for TSS, PN, and PP, and $\pm 40\%$ for Chl-a of annual guidelines (De'ath and Fabricius 2008). Magnitude scores in the exposure mapping are calculated as the proportional exceedance of the GV, using the long-term wet season averages and the wet season, Reef-wide GV (bold numbers): $[\text{magnitude}]_{\text{water type}} = \frac{([\text{Poll.}]_{\text{water type}} - \text{GV})}{\text{GV}}$ and Poll. = TSS, Chl-a, PP or PN. Negative Magnitude score are capped as zero.

Water Quality	Parameter	Chl-a	PN	PP	SS	SDD	CDOM
	Unit	$\mu\text{g L}^{-1}$	$\mu\text{g L}^{-1}$	$\mu\text{g L}^{-1}$	mg L^{-1}	m-1	m-1
Dry season averages (2019, 18 first weeks)	Primary	0.33	22.00	6.48	1.45	2.60	0.09
	Secondary	0.40	24.66	3.77	1.90	3.10	0.05
	Tertiary	0.72	28.70	4.01	1.03	5.23	0.02
Wet season averages (long-term, 2004–2019)	Primary	1.61	60.55	10.87	18.27	1.78	0.82
	Secondary	0.80	25.49	3.45	5.92	4	0.27
	Tertiary	0.51	18.17	2.27	3.92	7.05	0.13
Reef-wide GVs	Wet season	0.63	25.00	3.30	2.40	NA	NA
	Dry season	0.32	17.50	2.30	1.60	NA	NA
	Annual	0.45	20.00	2.80	2.00	10.00	NA
Wet season magnitude scores	Primary	1.55	1.42	2.29	6.61	NA	NA
	Secondary	0.27	0.02	0.05	1.47	NA	NA
	Tertiary	0	0	0	0.63	NA	NA

Burdekin water type time series

The 2D time series plot successfully captured temporal changes in colour patterns across all weeks of the 2018–19 wet season (Figure E-8a – y axis) and the first 18 weeks of the dry season 2019 (Figure E-8b – y axis). Colours represent mean weekly water type values recorded in each marine waterbody of the Burdekin region and summarize cross-shore colour gradients across waterbodies in the Burdekin region (Figure E-8 – x axis):

In the enclosed coastal regions of the Burdekin: waters were nearly always classified as Primary waters, in both the wet and dry seasons. In the dry season, the presence of turbid Primary waters (high TSS and low SDD levels, Figure E-7) in the enclosed coastal Reef area is likely to be related the presence of re-suspended sediments (which may have been originally derived from the discharge of the Burdekin NRM rivers in the previous wet season) and/or to the sea bottom interference (the effects of bottom reflectance on the satellite signal) in the shallower regions. In the wet season, this is enhanced by the direct influence of riverine flood plumes during the higher flow conditions, as illustrated for example by the February 2019 satellite data (weeks 11 and 12 of the wet season, see Figure E-2b and Figure E-5).

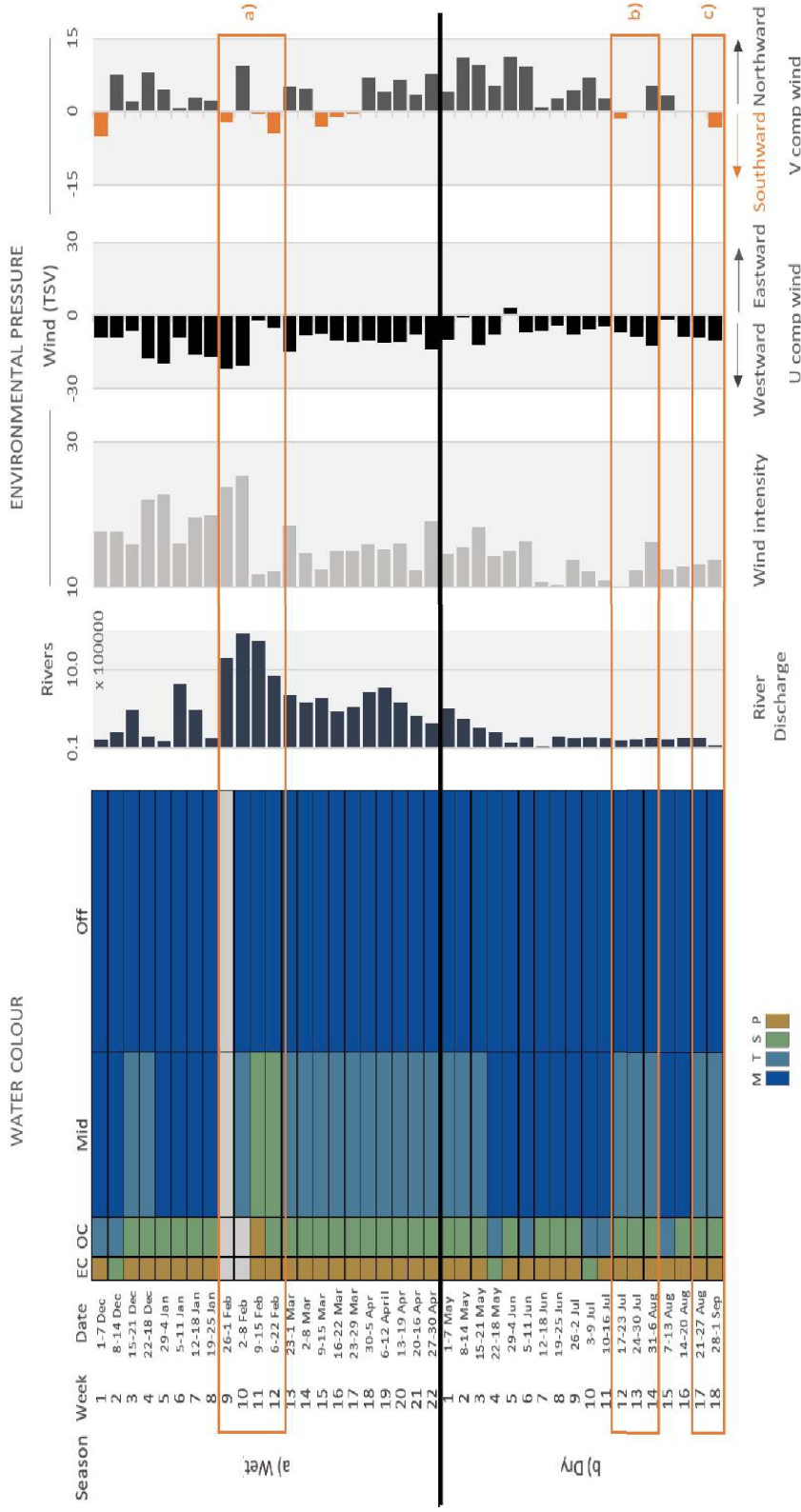


Figure E-8: Left plot: 'Water colour'. Time series illustrating the mean weekly PST-equivalent value recorded in each marine waterbodies of the Burdekin region during the (a) wet season 2018–19 (1 Dec 18 – 31 Apr 19) and dry season period (1 May to 1 Sept 2019). From left to right: EC: enclosed coastal, OC: open coastal, Mid: midshelf and Off: offshore waterbodies. Each horizontal bar corresponds to a weekly water type: Primary (P), Secondary (S), Tertiary (T) and Marine waters (M). The grey colour represent clouds. Right plots: 'Environmental pressures': from left to right: weekly Burdekin River discharge (dark blue) and mean weekly intensity (light grey), u component (black) and v component (dark grey) of the wind measured at Townsville airport. Winds heading toward the South (Northerlies, negative v component) are coloured in orange.

In both the open coastal and midshelf waters the mean water colour was more variable and both waterbodies were overall clearer during the dry season period than during the wet season 2018–19.

During the wet season, open coastal waters were directly influenced by river discharge rates and the Secondary and Tertiary water types of flood plumes (Figure E-8). This was likely enhanced by the presence of wind-driven resuspension sediments (wave driven). Open coastal waters were classified most weeks as Secondary during the wet season, and only one week as Primary when the significant southward and eastward winds pushed the Burdekin riverine plume eastward in February 2019 (Figure E-2a, b, Figure E-8a orange box a, and Figure E-9a). During the first 18 weeks of the dry season, river discharge rates decreased progressively, but open coastal waters stayed classified most weeks as Secondary and intermittently as Tertiary waters, most likely as fresh suspended sediments settled and were sporadically resuspended by winds (Figure E-8b, week 13 and 17) tides or waves (but no adequate data were available in this study to support this hypothesis).

During the wet season, the midshelf waters were also influenced by the rivers and colour patterns were related to river discharge rates. Midshelf waters were classified most weeks as Tertiary - low potential risk – waters, except when the significant south and eastward winds pushed the Burdekin secondary plume eastward in February 2019 (Figure E-2a,b, Figure E-8a orange box a). Turbidity in midshelf waters remained over ambient marine levels three weeks after the end of the wet season (Figure E-8b, weeks 1-3 - Tertiary waters) but quickly decreased as the dry season progressed and the river discharge decreased (illustrated in Figure E-8). During the dry season period, midshelf waters were classified most weeks as marine waters, but water clarity also temporally decreased while river discharge rates were low (Figure E-8b, weeks 12-14 and 17-18). This was associated with northerly wind conditions and may be linked to wind, tide or wave driven resuspension (Figure E-8, orange boxes b and c). Northerly winds have been reported to attenuate the northward motion of turbid riverine plumes in Moreton Bay and to spread it across the shelf (Yu *et al.*, 2014). This could also be linked to local primary production, but no adequate data were available in this study to support this hypothesis). Tertiary waters have low risk of detrimental ecological effects (even though this is not well researched, particularly during the dry season).

Finally, offshore waters were always classified as marine, very clear, waters in both the wet and dry seasons 2019.

Frequency and Exposure maps

Dry season frequency maps showed patterns similar to the wet season maps (in Gruber *et al.*, 2019): there was a higher frequency of exposure to the Primary and Secondary water types in inshore areas, with mid-shelf to offshore areas most frequently exposed to the Tertiary water type only (Figure E-9a and b). However, except in the enclosed regions and very inshore open coastal waters, the frequency of exposure to Primary and Secondary water types combined was lower in the dry season weeks than during the wet season 2019 (Figure E-9a and b). The Primary and Secondary waters extended less offshore and were mainly contained in the inshore (enclosed + open coastal) regions of the study area, which supported the weekly results described above.

Similarly, exposure maps indicated a lower risk from exposure during the dry season weeks, than during the 2019 wet season, with - 42% of the Burdekin enclosed coastal waters and - 36% of the midshelf waters exposed to combined risk categories II-IV during the dry season (Figure E-10). The enclosed coastal water had a high percentage (99%) of exposure to risk categories II to IV in both the wet and dry seasons, even though the percentage of exposure to the highest potential risk category (IV) was higher during the wet season.

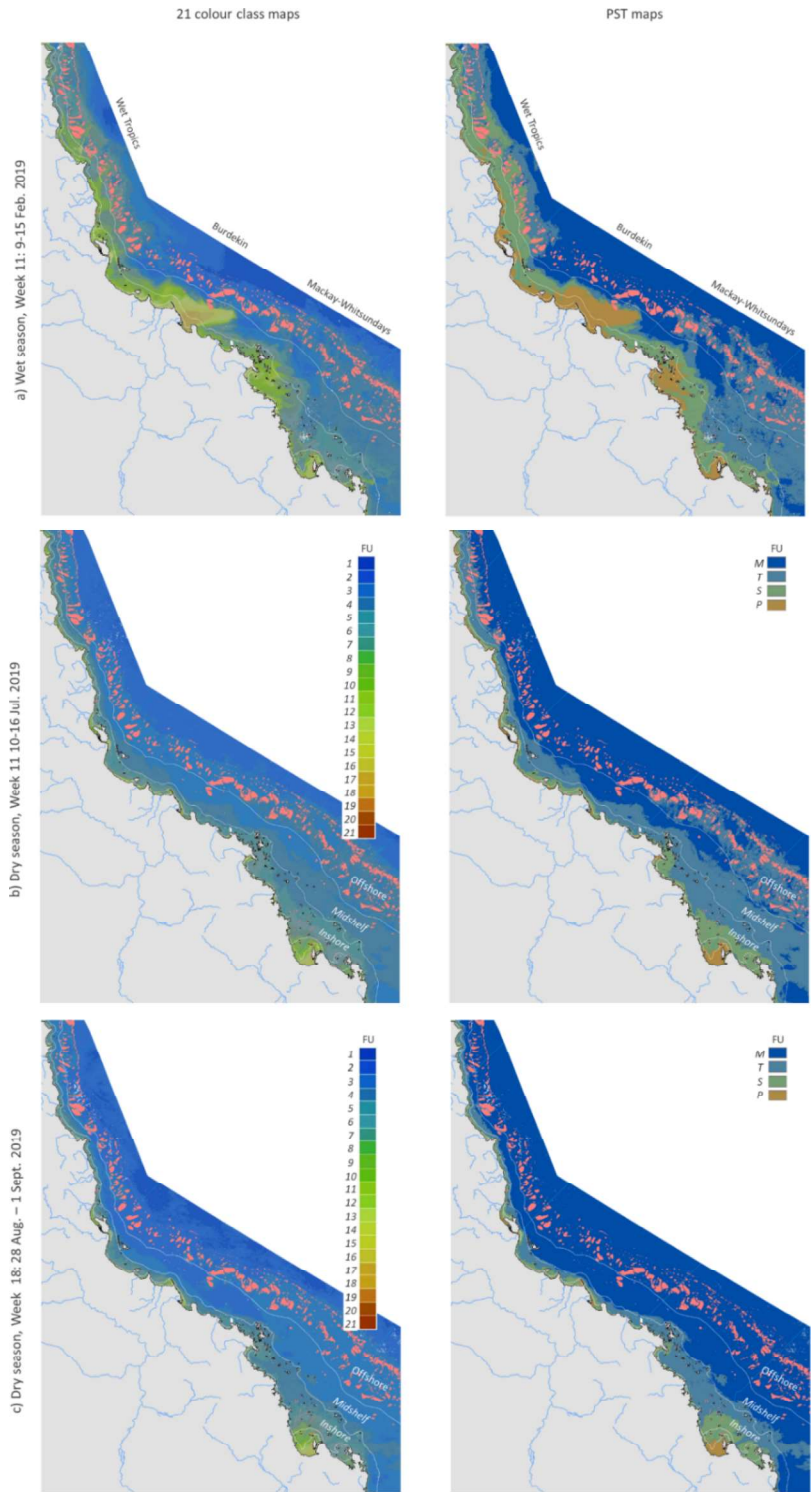


Figure E-9: Example maps showing (a) wet season and (b, c) dry season colour patterns: (left) 21 colour class weekly maps and (right) PST-equivalent weekly maps.

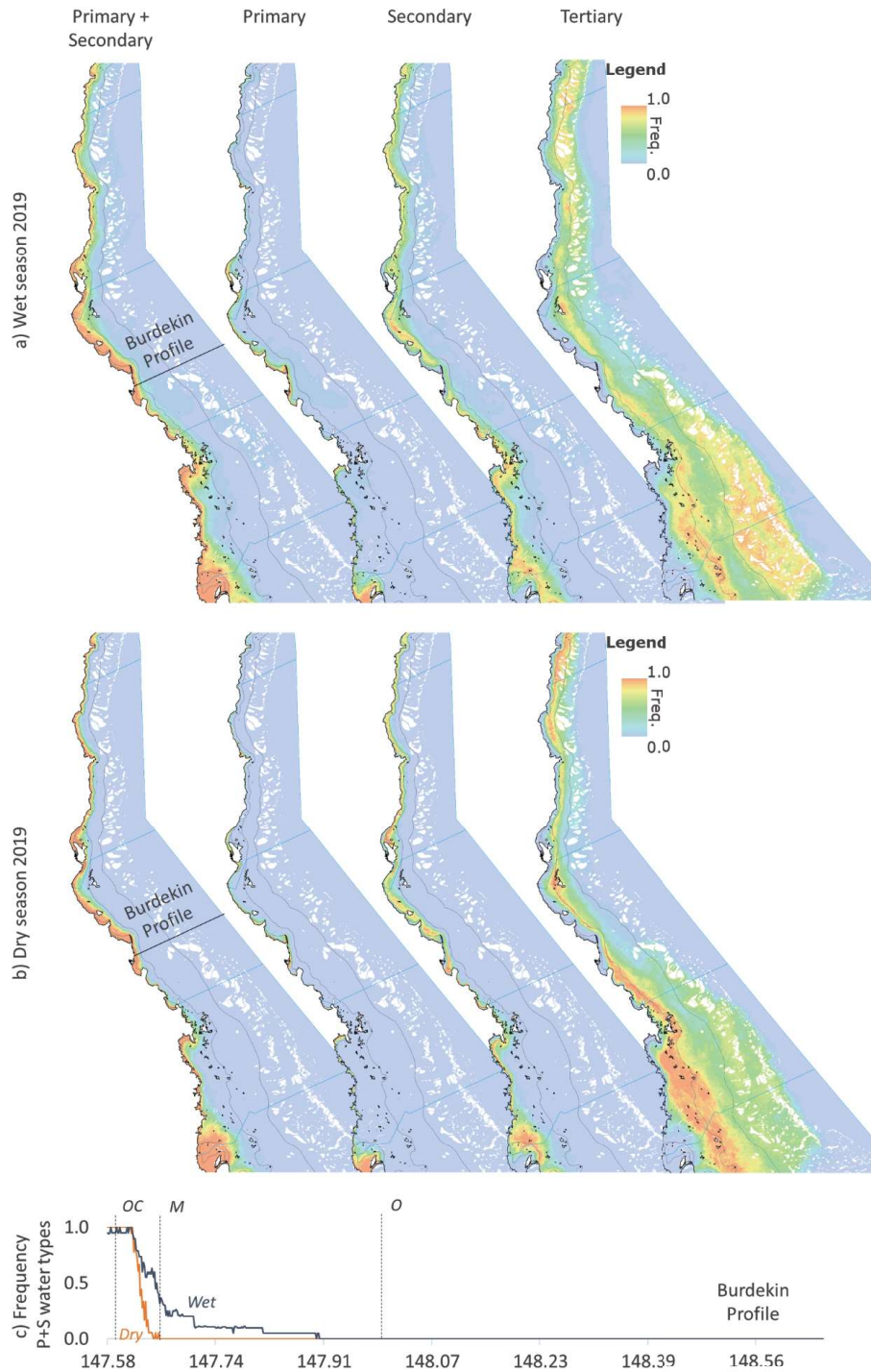


Figure E-10: Maps showing the frequency (0-1) of FU-equivalent water types in the (top) wet season 2019 (22 weeks) and (bottom) first 18 weeks of the dry season 2019: a) combined (primary + secondary), b) Primary, c) Secondary and d) Tertiary.

Spatial exposure 2019 Sentinel-3 FU

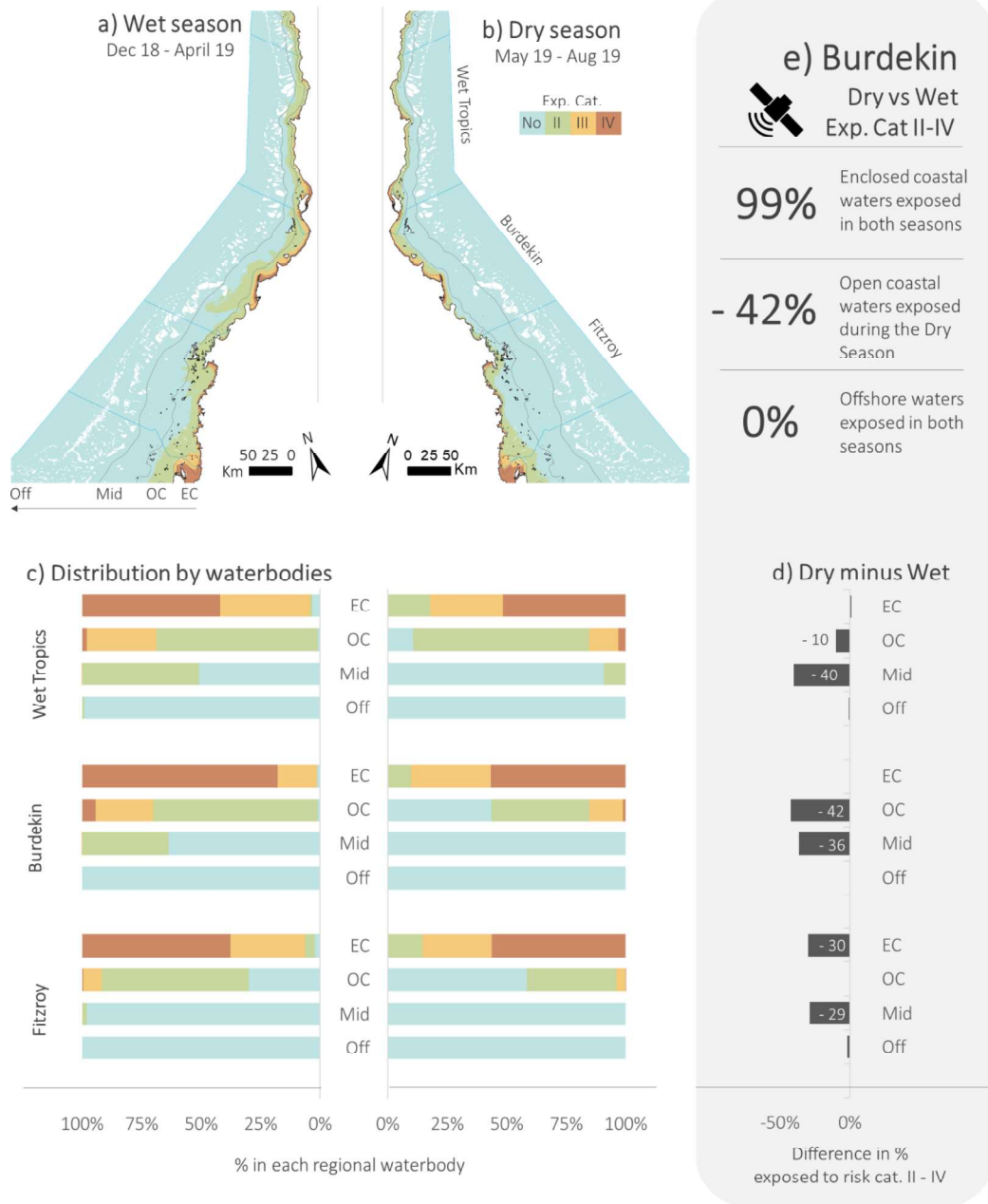


Figure E-11: Map showing the reclassified surface exposure in the a) Wet season 2019, b) dry season 2019 (first 18 weeks) c) Percentage of the Wet Tropics, Burdekin and Fitzroy waterbodies affected by different risk categories of exposure during the wet and dry season periods, d) differences between % affected to combine risk categories II-IV in the wet season and dry season period and e) key numbers for the Burdekin region.

In both seasons, the offshore waters were classified as no/very low risk. A total of 92% of the Burdekin NRM region was exposed to no or very low potential risk in the dry season period.

It is important to note that, given the low number of dry season field data available, wet season magnitude scores from the Program were used to map the potential risk from exposure in May–August 2019 (Figure E-11). Wet season magnitude scores are calculated as the proportional exceedance of the guideline, using the mean wet season water quality concentrations and the wet season GVs (bold values in Table E-2). Magnitude scores would need to be adjusted (using mean dry season water quality concentrations and/or dry season GVs values) if dry season maps were to be produced more operationally in the future.

E-4 Discussion and Conclusions

This pilot study presents a framework which aims to develop dry season water type maps of the Reef. Methods and automated tools developed for the wet season through The Program funding were successfully adjusted to produce Sentinel-3 FU maps of the dry season 2019. Results are encouraging and confirmed that Sentinel-3 satellite data and the FU scale are useful for mapping inshore marine water colour patterns in both the wet and dry seasons. Summary maps (weekly, frequency, exposure composite maps) used in the Program can be adjusted to report on water quality trends in the dry season.

This pilot study focused on an above average river discharge year for the Burdekin region and the following eighteen dry season weeks. It showed that waterbodies were overall clearer during the dry season period than during the wet season 2018–19, with 42% of the Burdekin enclosed coastal waters exposed to a potential risk (combined risk categories II–IV) during the dry season.

Colour changes mainly occurred in the open coastal and midshelf regions of the Burdekin. River discharge combined with the wind intensity and direction were the main factors affecting water colour in the wet season, while colour changes were more likely driven by the wind direction in the dry season. Eastward and/or Southward winds seemed to punctually spread both freshly delivered and resuspended sediments toward the open coastal and midshelf areas in both seasons, but this will need more investigation in the future. Midshelf waters were, however, largely classified as Tertiary or marine waters in both seasons and had a likely low to no risk of detrimental ecological effects, as measured in the potential risk maps and assessment. These observations will have to be validated with more data.

Enclosed coastal waters remained largely turbid (Primary waters) in both the wet and dry seasons. There is a high chance that this may be influenced by the presence of resuspended sediments and/or to sea bottom interference, enhanced by river plume influences during the wet season. It is impossible to fully separate the direct influences of riverine plumes from wind- and wave-driven sediment resuspension events (some of which may have been originally derived from the Burdekin River discharge) in optical satellite images. However, results presented in this study highlight the potential of using Sentinel satellite data and the Forel Ule scale, in combination with environmental datasets, to report and tease out water colour patterns in both wet and dry seasons. Finally, offshore waters were always classified as marine, very clear, waters in both the wet and dry seasons in 2019.

It is important to remember that this study focused on the first 18 weeks of the dry season 2019 (May to August) and not the whole dry season period and following an above average wet season. Results may change if all weeks of the 2019 dry season were considered, (pending the assumption that sediment would further settle as the dry season progresses), or if a drier year was considered. Also, magnitude scores and risk maps would need to be adjusted (using mean dry season water quality concentrations and/or dry season GVs) if dry season maps were to be produced more operationally into the future. Magnitude scores per

se. have no ecological significance but are used in the risk framework as a relative measure to assign potential risk grading for each water type.

Future work should focus on progressing the presentation and analyse of the Sentinel-3 FU data for a larger number of dry seasons, including all weeks of the dry season, to characterise the variability that may exist between dry seasons that follows particularly wet wet season compared to dry seasons that follows drier wet seasons. Key objectives should include (i) a better characterisation of water quality concentrations across water types in the dry season, and how this compares to wet season conditions, and; (ii) a better understanding of the environmental characteristics (wind, tide, waves and/or discharge) driving the dry season colour patterns. For example, it would be interesting to re-plot the time series (Figure E-8) but using the 21 FU colour class instead of the PST classification, to see if some specific colours are present during the wet season weeks and not the dry season weeks. Furthermore, while weekly composite data are very useful to summarise seasonal or longer-term patterns, some information will inevitably be lost in the aggregation process. Daily satellite maps and metocean datasets, as well as zooms on smaller areas of interests would allow a finer description of specific events and should be considered along the weekly summary panels for the next steps of this project. Finally multi-parametric statistical analyses, using daily datasets, would be particularly useful to disentangle physical influences that can lead to water colour changes across waterbodies, these are very important steps to better understand water quality trends in both wet and dry seasons as well as the response of Reef ecosystems to flood waters and the conditions and physical influences that promote their recovery through both the wet and dry seasons.

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Wang, S., Li, J., Zhang, W. *et al.* A dataset of remote-sensed Forel-Ule Index for global inland waters during 2000–2018. *Sci Data* 8, 26 (2021). <https://doi.org/10.1038/s41597-021-00807-z>

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Appendix F. Scientific publications and presentations associated with the program, 2020–21

F-1 Publications

Great Barrier Reef Marine Park Authority (2021). Great Barrier Reef Marine Monitoring Program Quality Assurance and Quality Control Manual 2019–20. Great Barrier Reef Marine Park Authority, Townsville, 310pp.

Howley, C. Natural and anthropogenic drivers of water quality in the Normanby Basin and Princess Charlotte Bay. PhD thesis, Griffith University, November 2020.

Lønborg, C., L. I. W. McKinna, M. M. Slivkoff and C. Carreira. 2021. Coloured dissolved organic matter dynamics in the Great Barrier Reef. *Continental Shelf Research* 219: 104395.

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Data used for model validation:

During the 2020/21 financial year, MMP Water quality data has been used by several external groups, including:

- Validation of the eReefs marine models for the Great Barrier Reef, led by Mark Baird at CSIRO. An extensive list of resulting publications is available from: <https://research.csiro.au/ereefs/models/further-reading/>
- Validation of remote sensing ocean colour algorithms, led by Thomas Schroeder at CSIRO.
- As input data for machine learning algorithms for forecasting TN in the Great Barrier Reef, in work led by James Cook University PhD candidate Mohammed Jahanbakt. This work is currently under review for publication in the journal, *Environmental Modelling & Software*.

Baird, M. E., K. Wild-Allen, J. Parslow, M. Mongin, B. Robson, J. Skerratt, F. Rizwi, M. Soja-Woźniak, E. Jones, M. Herzfeld, N. Margvelashvili, J. Andrewartha, C. Langlais, M. Adams, N. Cherukuru, S. Hadley, P. Ralph, T. Schroeder, A. Steven, U. Rosebrock, L. Laiolo, M. Gustafsson, and D. Harrison (2020). CSIRO Environmental Modelling Suite (EMS): Scientific description of the optical and biogeochemical models (vB3p0). *Geoscientific Model Development*.13:4503-4553.

Skerratt, J. and M. Baird. 2020. Technical assessment of the eReefs biogeochemical (BGC) simulation [gbr4_H2p0_B3p1_Chgd_Dcrt] against observations and comparison with BGC version B3p0. Commonwealth Scientific and Industrial Research Organisation.

Skerratt J.H., M. Mongin, K. A. Wild-Allen, M. E. Baird, B. J. Robson, B. Schaffelke, M. Soja-Wozniak, N Margvelashvili, C. H. Davies, A. J. Richardson, A. D. L. Steven (2019) Simulated nutrient and plankton dynamics in the Great Barrier Reef (2011-2016). *J. Mar. Sys.* 192, 51-74.

Steven, Andrew D. L., Mark E. Baird, Richard Brinkman, Nicholas J. Car, Simon J. Cox, Mike Herzfeld, Jonathan Hodge, Emlyn Jones, Edward King, Nugzar Margvelashvili, Cedric Robillot, Barbara Robson, Thomas Schroeder, Jenny Skerratt, Sharon Tickell, Narendra Tuteja, Karen Wild-Allen & Jonathan Yu (2019): eReefs: An operational information system for managing the Great Barrier Reef, *Journal of Operational Oceanography*, DOI: 10.1080/1755876X.2019.1650589

Related papers – linking to MMP data:

Bainbridge, Z., Lewis, S., Stevens, T., Petus, C. *et al.* (2021). Measuring sediment grain size across the catchment to reef continuum: Improved methods and environmental insights. *Marine Pollution Bulletin* 168, 112339.

Lambert, V., Bainbridge, Z., Collier, C., Lewis, S. *et al.* (2021). Connecting targets for catchment sediment loads to ecological outcomes for seagrass using multiple lines of evidence. *Marine Pollution Bulletin* 169, 112494.

Canto, M., Fabricius, K., Logan, M., Lewis, S. *et al.* (2021). A benthic light index of water quality in the Great Barrier Reef, Australia. *Marine Pollution Bulletin* 169, 112539.

F-2 Presentations

Moran D. *AIMS Inshore Water Quality Research*. Presented to Jaragun ecoservices and Wanjuru-Yidinji representatives at AIMS site visit, Townsville, QLD, 2 September 2021.

Robson B. *Water Quality Research at AIMS*. Presented to Women in Sugar Committee Groups for Herbert & Burdekin regions at AIMS site visit, Townsville, QLD, 12 October 2021.

Gruber R. *How and why we monitor water quality on the Great Barrier Reef*. Presented to Weed Innovation Day group (organised by Sugar Research Australia) at AIMS site visit, Townsville, QLD, 17 March 2021.

Gruber R. *How and why we monitor water quality on the Great Barrier Reef*. Presented to Project Catalyst group (Canegrowers, NQ Dry Tropics, Reef Ecologic, Reef Catchment, and Terrain NRM staff) at AIMS site visit, Townsville, QLD, 23 February 2021.

Gruber R. *Inshore water quality: Ambient results and trends*. Zoom webinar presenting 2019–20 MMP WQ findings in lieu of the MERI workshop, 11 February 2021.

Gruber R and R Brinkman. *Water quality research and monitoring at AIMS*. Open Q&A and site visit to Rocks Farming Company with Pioneer Burdekin canegrowers, Burdekin Valley, QLD, November 2020.

Houlden, B. *Great Barrier Reef Marine Monitoring Program*. Presented to the Local Marine Advisory Group members online, Great Barrier Reef Marine Park Authority, Townsville, QLD, 21 October 2021.

Moran D, *et al.* *Water quality research and monitoring at AIMS*. Presented to Pioneer Burdekin region canegrowers at AIMS site visit, Townsville, QLD, November 2020.

GBRMPA. *What is the Great Barrier Reef Marine Monitoring Program?* Video recorded 17 Aug 2020 and published on Youtube 19 Mar 2021: <https://www.youtube.com/watch?v=fpXsZdrJPWU>. All partners contributed content to this overview video of the MMP.

- Gruber, R. *et al.*, Inshore water quality monitoring – 2019–20: Ambient results and trends. Online seminar, recorded February 2021. <https://youtu.be/ul5z5RPfKXU>
- Howley, C. Inshore water quality monitoring – 2019–20: Cape York region. Online seminar recorded December 2020. <https://youtu.be/dasS3He2qw0>
- Waterhouse, J. *et al.*, Inshore water quality monitoring – 2019–20: Wet season monitoring. Online seminar, recorded March 2021. <https://youtu.be/mQJD-n11Egg>
- Waterhouse, J. *Great Barrier Reef Water Quality and Scientific Consensus Statement: Burnett Mary. Paddock to Reef Program Integrated Science Forum*. Online 11 February 2021.
- Waterhouse, J. *Great Barrier Reef Water Quality and Marine Monitoring Program: Lower Burdekin. Paddock to Reef Program Integrated Science Forum*. Online 31 March 2021.
- Waterhouse, J. *Great Barrier Reef Water Quality and Marine Monitoring Program: Tully. Paddock to Reef Program Integrated Science Forum*. Tully 7 May 2021.
- Waterhouse, J. *Great Barrier Reef Water Quality and Scientific Consensus Statement: Fitzroy. Paddock to Reef Program Integrated Science Forum*. Online 20 May 2021.
- Waterhouse, J. *Great Barrier Reef Water Quality and Marine Monitoring Program: Mackay Whitsunday. Paddock to Reef Program Integrated Science Forum*. Mackay 26 May 2021.

Related presentations – linking to MMP data:

- Lewis, S. *Burdekin sediment budgets to the NQ Conservation Council at the 'Ensuring a viable Burdekin Basin' workshop*. Presentation 11 September 2020.
- Lewis, S. *Tracking sediment from the catchment to reef*. RBMS River Fest conference for World Rivers Day Presentation. Presentation 29 September 2020.
- Lewis, S. *Examining the influence of the newly delivered sediment and associated particulate nutrients in the inshore Great Barrier Reef*. NESP conference Cairns 28 April 2021.
- Lewis, S. *Examining the influence of the newly delivered sediment and associated particulate nutrients in the inshore Great Barrier Reef*. Presentation to Great Barrier Reef Foundation 26 July 2021.
- Lewis, S. Panel for the Dry Tropics Partnership Report Card launch addressing questions relevant to the MMP. Townsville, July 2021.
- Waterhouse, J. Paddock to Reef Strategic Planning Meeting, Mission Beach, 5 and 6 May 2021.