MARINE MONITORING PROGRAM

Annual Report for

INSHORE WATER QUALITY MONITORING

2018-19

James Cook University Australia
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The Great Barrier Reef Marine Park Authority acknowledges the continuing Sea Country management and custodianship of the Great Barrier Reef by Aboriginal and Torres Strait Island Traditional Owners whose rich cultures, heritage values, enduring connections and shared efforts protect the Reef for future generations.

DISCLAIMER

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Commonly used acronyms, abbreviations and units

Abbreviations and acronyms

AIMS = Australian Institute of Marine Science

Authority = Great Barrier Reef Marine Park Authority

BOM = Bureau of Meteorology

CDOM = colour dissolved organic matter

Chl-*a* = chlorophyll *a*

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

FU = Forel-Ule (toolbox and colour scale)

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)

PP = particulate phosphorus

QA/QC = Quality assurance/quality control

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*

TSS = total suspended solids

WS colour scale = wet season colour scale

WQ Index = Water Quality Index

Units

GL = gigalitre

m = metre

mg L^{-1} = milligram per litre

ML = megalitre

km = kilometre

kt = kilotonne

t = tonne

µg L^{-1} = microgram per litre

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Executive summary

The Great Barrier Reef Marine Park Authority's Marine Monitoring Program was established in 2005 to monitor the inshore health of the Great Barrier Reef. This document reports on the annual and long-term condition and trend of water quality in the Great Barrier Reef (the Reef).

The program design includes the collection of water 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 simulations are linked with *in situ* monitoring data to estimate the exposure of inshore areas to end-of-catchment loads from rivers.

Trends in key water quality indicators

Water quality indicators are used to derive an 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 guidelines. Trends are not yet available for the Cape York region as there is insufficient data.

The Index derived from monitoring showed long-term inshore water quality (insensitive to year-to-year variability) has:

- **declined** in the Wet Tropics region since 2006, though has stabilised in recent years
- **declined** gradually in the Burdekin region since 2006
- **declined** steadily in the Mackay-Whitsunday region since 2006.

The annual condition Index showed inshore water quality (sensitive to year-to-year variability) was:

- **moderate** during 2018–19 in the Wet Tropics and Burdekin regions, similar to the previous three years
- **moderate** in the Mackay-Whitsunday region as opposed to very poor condition in 2016–17.

Differences in scoring between versions of the Index are expected as they are designed to communicate different sources of variability in water quality.

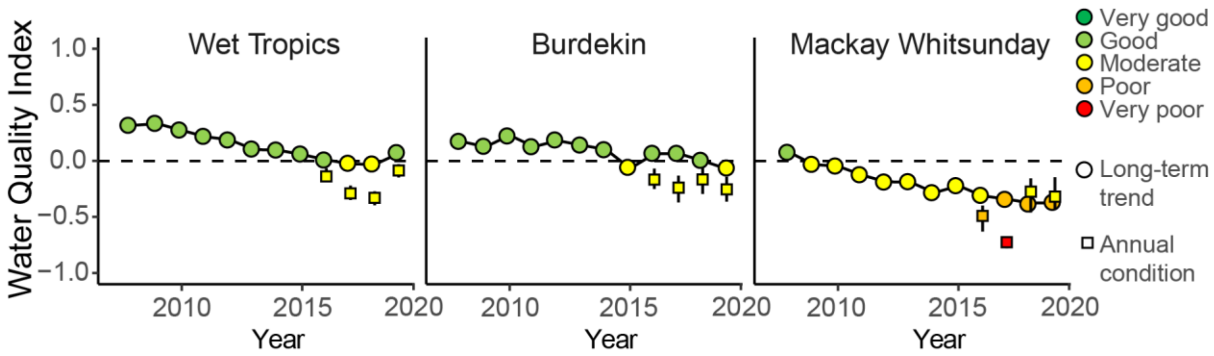

Figure 1: Water Quality Index scores from 2006 to 2019 for the Wet Tropics, Burdekin and Mackay-Whitsunday regions. The Index is calculated to show the long-term trend in water quality since the start of monitoring (circles) based on the initial program design. An updated version communicating annual 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*. Details of calculations can be found in Appendix D.

Changes in some water quality variables have been detected in most regions, including water clarity and concentrations of nutrients. In the Cape York region, concentrations of chlorophyll *a* and dissolved nutrients were elevated relative to the two previous years of monitoring, which was likely related to the above-average river discharge experienced in the region this year. The most notable general trends in the Wet Tropics, Burdekin, and Mackay-Whitsunday regions were:

- mean concentrations of nitrate/nitrite **stable but exceeding guidelines**
- mean concentrations of chlorophyll *a* and total suspended solids **stable but near guidelines**
- mean concentrations of particulate nitrogen and phosphorus **stable but near guidelines**
- **declining** Secchi depth (i.e. water clarity is worsening) across the inshore Reef, which is not meeting water quality guidelines
- **increasing** concentrations of dissolved and particulate organic carbon.

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 2018–19 wet season, saw river discharge above the long-term median and a number of cyclones crossing the coast in the northern Great Barrier Reef, with above-average levels of rainfall in the Cape York region. Major floods also occurred in the Burdekin, Ross, and Herbert rivers in February 2019.

In 2018–19, the north and central regions had the highest level of wet season water discharge recorded in at least seven years. Discharge in the Cape York region was the highest recorded in the time-series (since 2002–03) and was 2–3 times the long-term median. The largest water discharge was in the Burdekin region, which was more than three times the long-term median discharge. 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. River discharge in the Fitzroy region was well below average, and the Burnett-Mary was on its average.

End-of-catchment sediment and nutrient loads were variable between the focus areas. The highest dissolved inorganic nitrogen exports were from the Burdekin-Haughton basins, followed by the Tully-Murray-Herbert and Russell-Mulgrave-Johnstone basins.

Models of river discharge showed that sites in open coastal waters had weeks of exposure, especially for the Normanby, Barron, Russell-Mulgrave, Tully, and Burdekin rivers. Sites in mid-shelf and offshore water bodies were also exposed to river plumes for short periods, especially from the Normanby, Barron, and Burdekin rivers. A new approach to dispersion modelling of river-derived loads showed dispersion similar to other years with similar river discharge conditions, and typically greater loading than the long-term average (2003 to present). Comparison with modelling of pre-European conditions identified the Wet Tropics and Burdekin regions as the dominant areas of anthropogenic influence for dissolved inorganic nitrogen, and the Burdekin region as the dominant area of anthropogenic influence for total suspended solids and particulate nitrogen.

Satellite imagery showed a high frequency of the primary water type in open coastal areas, with mid-shelf to offshore areas most frequently exposed only to the tertiary water type. 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 relatively clear, but with detectable signals, that have a low risk of detrimental ecological effects.

Exposure maps showed that approximately 16 per cent of the total area of the Reef was exposed to a potential risk in 2018–19, which was higher than the long-term average area (13 per cent). The areas of coral reef and seagrass exposed to potential risk categories were greater than the average long-term areas, with the majority of the increased exposure occurring in the Cape York, Wet Tropics, and Burdekin regions. This is consistent with the relatively wet conditions of these regions.

Case studies

Annual case studies are conducted every year. Case study one investigated the composition of dissolved organic matter during wet and dry seasons at Wet Tropics, Burdekin, and Mackay-Whitsunday sites. Fluorescence analysis identified six main components of dissolved organic matter, including three humic-like compounds (likely derived from river discharge) and three amino acid-like compounds (likely derived from phytoplankton production).

Case study two documents the spatial variability of river plumes in the Reef, including the periodicity of influence on the mid-shelf, and the dispersal of suspended particulate matter in the estuarine mixing zone. The amount of light reduction as a result of plumes is examined, and the length and exposure of such events quantified. A first-order estimate of sediment transport in the plumes is presented, and the implications of increased sediment supply since European settlement.

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 km^2 of coral reefs (Figure 1-1). It also includes large areas of seagrass meadows, estimated to be over 43,000 km^2 or ~12.5% of the total area of the Great Barrier Reef Marine Park (the Marine Park). The Reef catchment is divided into six natural resource management (NRM) regions (Figure 1-1), each with differing land use, biophysical and socio-economic characteristics.

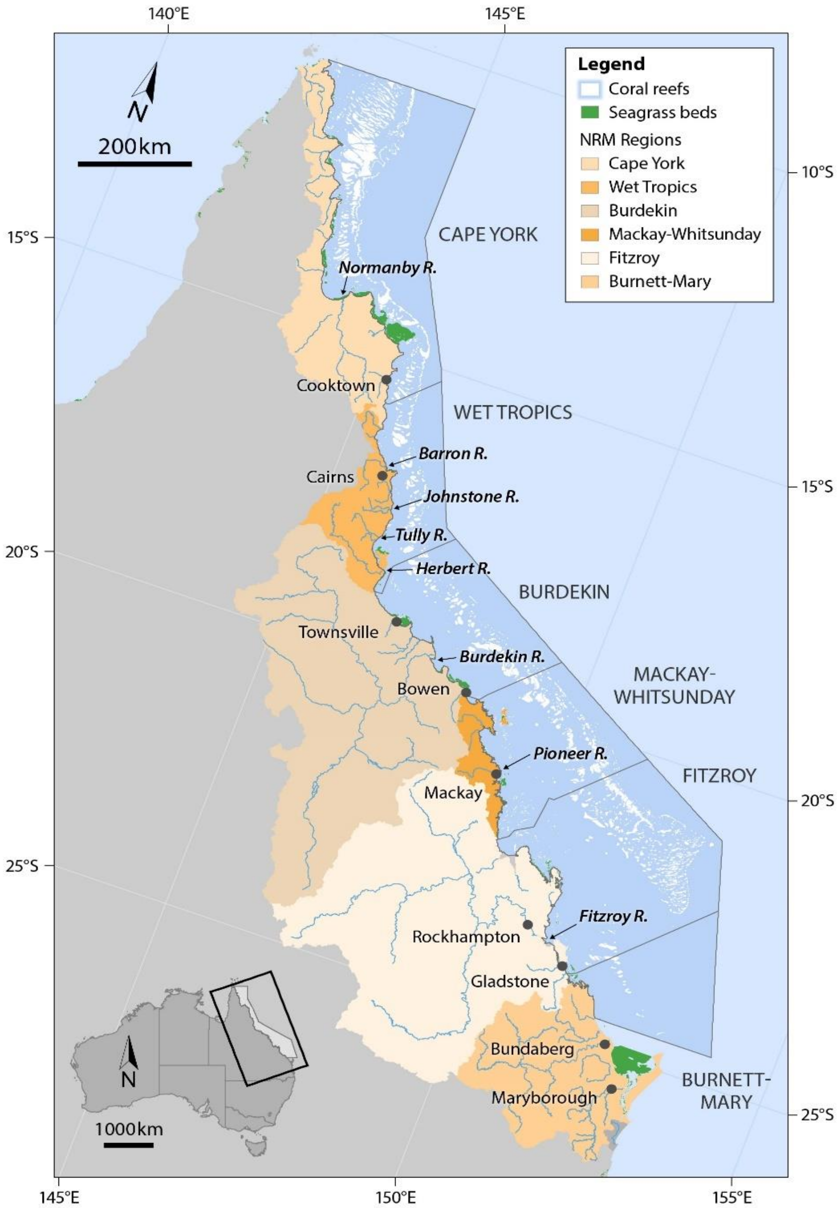

Figure 1-1: Locations of major marine ecosystems (coral reefs and surveyed seagrass beds) in the Great Barrier Reef Marine Park, NRM regions, marine NRM regions (delineated by dark grey lines) and major rivers.

1.2 Water quality monitoring in the Marine Monitoring Program

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, 2014a, b).

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 recently updated by the Australian and Queensland governments, and integrated as a major component of the Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia, 2015)[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 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) publish separate annual reports detailing the condition and trend of these ecosystems in relation to multiple stressors, including water quality data presented in this report (e.g. McKenzie et al., 2020; Thompson et al., 2020). In previous years, inshore pesticide monitoring has been discussed in a separate report (e.g. Thai et al., 2020). Loading of sediments, nutrients, and pesticides within rivers are monitored by the Catchment Loads Monitoring Program (Huggins et al., 2017).

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.

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 1-2). 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 loading. An overall Discussion and Conclusions are given in Sections 6 and 7, respectively. Case studies (Appendices A and B) are conducted annually on topics related to coastal water quality and are used to provide a deeper understanding and interpretation of monitored data. Detailed tables and figures of monitoring data are included in Appendix E.

[1] http://www.environment.gov.au/marine/gbr/reef2050

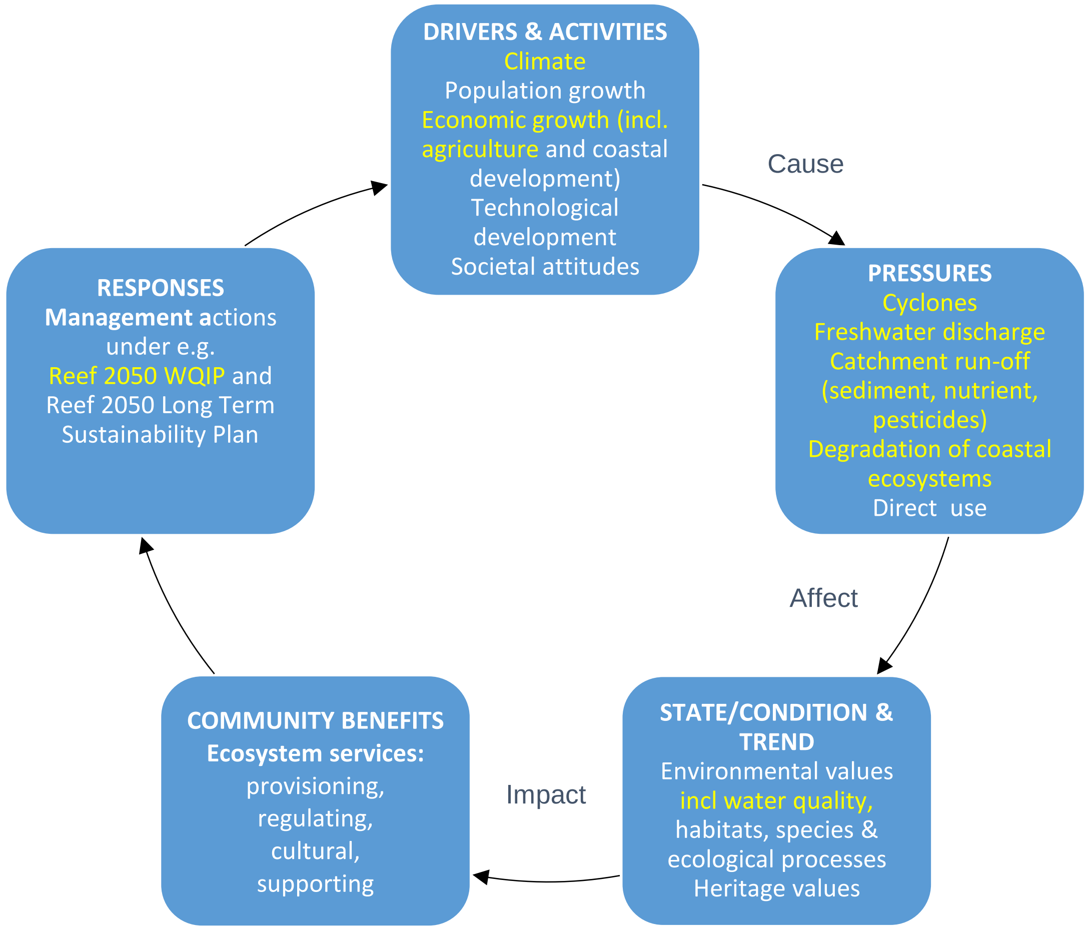

Figure 1-2: DPSIR framework used to guide the structure of the MMP, derived from the Great Barrier Reef Strategic Assessment (Great Barrier Reef Marine Park Authority, 2014a). The aspects highlighted in yellow are included in this report.

2. Methods summary

This Section provides an overview of the sampling design and indicators that are monitored as part of the MMP. More details are presented in the Appendices and in a separate quality assurance/quality control (QA/QC) report published annually (Great Barrier Reef Marine Park Authority, 2019).

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. The program covers four geographic areas—the Russell-Mulgrave, Tully, Burdekin, and Mackay-Whitsunday focus regions—that were chosen based on water quality risk assessments (Brodie et al., 2013). Monitoring site locations were selected along expected water quality gradients related to exposure to terrestrial 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).

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. 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.

Ambient water quality monitoring has been conducted since 2005 under the MMP, although the program design (site location, site number, monitoring frequency) has changed over time. From 2005 to 2014, monitoring occurred ~3 times per year at 3 sites in the focus areas listed above and additionally in the Fitzroy region (discontinued in 2015). An independent statistical review of the MMP (Kuhnert et al., 2015) showed that additional sites and higher sampling frequency were needed to meet program objectives. 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. Additional sites were added in all focus regions listed above, which currently have 5–6 sites each. The frequency of ambient water quality monitoring was also increased in 2015, and sites are now visited 5–10 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 January 2017, monitoring began in the Cape York region at four focus areas around the Pascoe, Normanby-Kennedy, Annan-Endeavour and Stewart Rivers. Sites were chosen along transects in a similar manner as described above and are monitored by the CYWMP.

The map in Figure 2-1 shows the geographical locations of the current monitoring sites. Appendix C lists all ambient and event-based sites monitored in the MMP and gives details of their monitoring frequency.

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 15 sites
- 58 ambient sites with more frequent sampling during the wet season (85 sites in total)
- 27 event-based sites sampled during flood conditions.

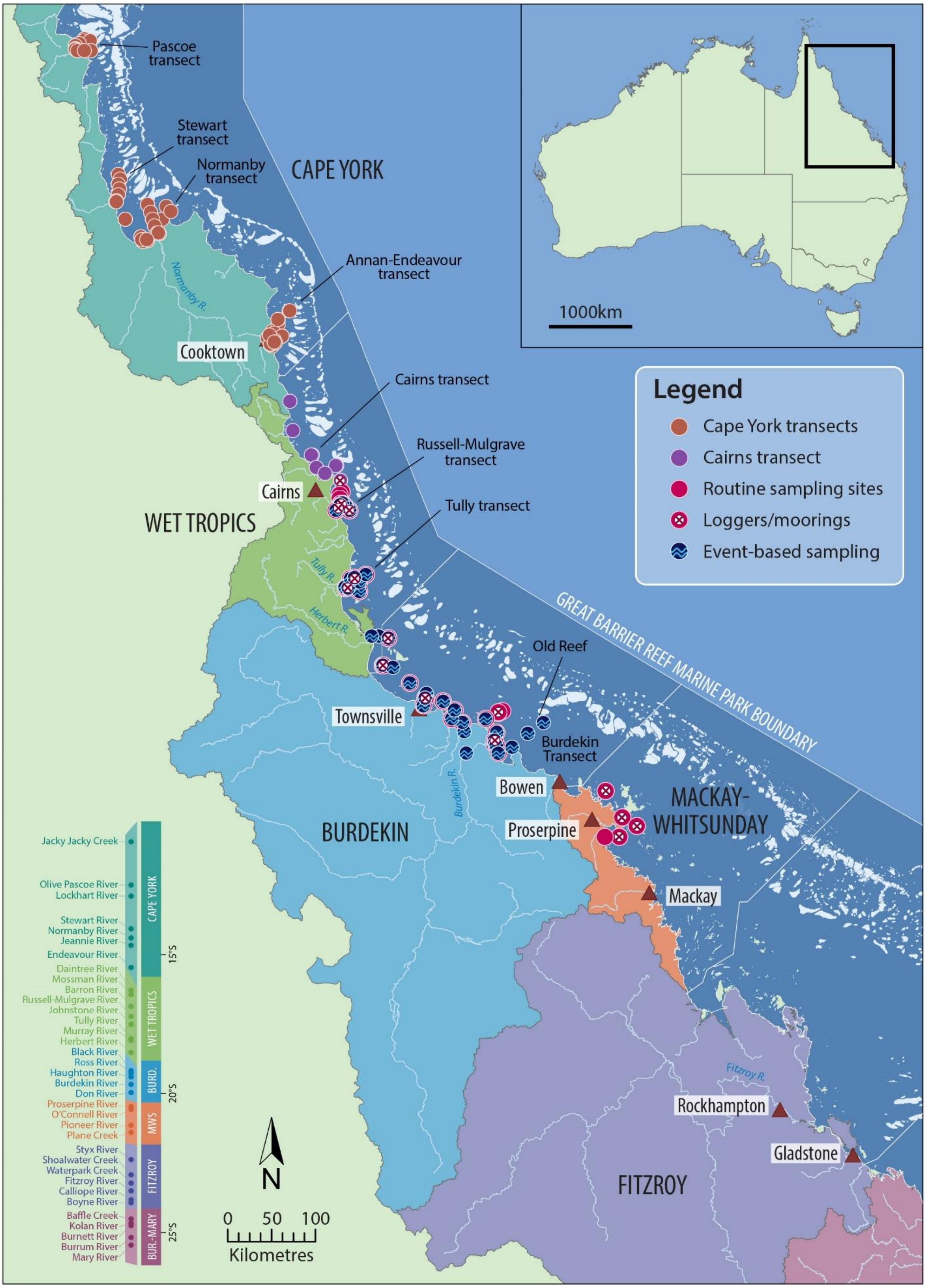

Figure 2-1: Sampling locations of the water quality monitoring sampled from 2015 onwards. Note that the Cape York transects were added in 2017. NRM region boundaries are represented by coloured catchment areas with grey lines extending these boundaries into the Reef.

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	µg L^{-1}
	Nitrite[2]	NO_2	µg L^{-1}
	Nitrate[2]	NO_3	µg L^{-1}
	Dissolved inorganic phosphorus	PO_4	µg L^{-1}
	Silica	Si	µg L^{-1}
	Particulate nitrogen	PN	µg L^{-1}
	Particulate phosphorus	PP	µg L^{-1}
	Total dissolved nitrogen	TDN	µg L^{-1}
	Total dissolved phosphorus	TDP	µg L^{-1}
	Particulate organic carbon	POC	µg L^{-1}
	Dissolved organic carbon	DOC	µg L^{-1}
Biological	Chlorophyll-*a*	Chl-*a*	µg L^{-1}

[1]Derived from vertical profiles of photosynthetically active radiation and not sampled at all sites
[2] note that 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 C), 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, 2019).

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, 2019). 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:

- **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.
- **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 (NH_3, NO_X, PO_4 and Si)** measure the amount of readily available nutrients for plankton growth in water samples. Inorganic nitrogen (NH_3, NO_x) and phosphate (PO_4) 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 (e.g. plankton uptake, upwelling, nitrogen fixation, and remineralisation) and anthropogenic (e.g. 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 (e.g. bacteria, phytoplankton) and a major fraction of detritus (e.g. 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 by degraded by sunlight.

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 15 sites (Appendix C), which were deployed 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 collected by the ECO FLNTUSB instruments are presented as time-series graphs in Appendix E (Figure E-1). Annual means and medians of turbidity were also calculated for each site based on the DERM 'water year' (1 October to 30 September) and compared with the guideline value (GV) (Table E-3).

Salinity and temperature loggers (Sea-Bird Electronics SBE37) were deployed at eight locations, with three of these being placed on fixed moorings near the Russell-Mulgrave, Tully and Burdekin River mouths (Figure 2-1, Appendix C). See the QA/QC report (Great Barrier Reef Marine Park Authority, 2019) for detailed descriptions of logger pre- and post-deployment procedures. Site-specific time-series from these loggers can be found in Appendix E (Figure E-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. Summary statistics for all water quality variables are presented for all monitoring sites in Appendix E. Concentrations were compared to site-specific GVs

(Table E-9), which are defined for Chl-*a*, PN, PP, TSS, Secchi depth, NO_x, and PO_4. 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. Enclosed coastal waters GVs are derived differently, and because they do not have GVs defined for all variables their inclusion would create 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 (which allow flexible modelling of non-linear relationships by incorporating penalised regression spline types of smoothing functions into the estimation process), 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). Trend analysis results are presented for each focus region in Section 5. Water quality measurements are likely to be influenced by the oceanographic conditions at the time of sampling. For variables that are sampled infrequently, variations in these physical conditions can add substantial noise to the data that can reduce detection and confidence in the underlying temporal signals.

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, 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.

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 D 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 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:

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
    - 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 5 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 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)
    - both AIMS and JCU monitoring data are used
    - a running mean is not applied
    - the Index is a hierarchical combination of scores for 5 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 D.

2.6 Data analyses – Remote sensing monitoring products

Several monitoring products have been developed combining MODIS satellite imagery and the water quality variables measured. They focus on the wet season period (December to April) and aim to:

- map Reef 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 were 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) (Table D-3); and
- 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 longer-term or reference trends in water composition.

2.6.1 Characterising composition of Reef water types

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 D); therefore, the water quality parameters measured during this (2018–19) and previous (2002–03 to 2017–18) wet seasons could 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 (Appendix D and following Section for description of the wet season water types and colour classes). 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) (Table D-3) were investigated by plotting the mean long-term water quality concentrations against their water type and colour class categories.

The mean long-term water quality concentrations were calculated using all surface data (<0.2 m) collected between November and April by JCU (since 2004), AIMS and the CYWMP (since 2016–17). 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). During the previous wet seasons, 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.

2.6.2 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 (km^2) and percentage (%) of coral reefs and seagrass meadows affected by different relative categories of exposure (or potential risk) was tabled. Details are in Appendix D.

- **Wet season water type maps** were produced using daily MODIS-Aqua (hereafter, MODIS) quasi true colour (hereafter true colour) imagery (see Appendix D) reclassified to six distinct colour classes defined by their colour properties (Álvarez-Romero et al., 2013) and typical of colour gradients existing across coastal waters, including river plumes during the wet season (Figure 2-2). To complement this dataset, MODIS-Terra true colour images are also occasionally downloaded from the National Aeronautics and Space Administration (NASA)'s EOSDIS worldview website) and processed to daily water type maps. MODIS-Terra are only used when MODIS data are too cloudy or unavailable, and when satellite information are required in near-real-time (rapid response mapping of flood events). Available MODIS 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.

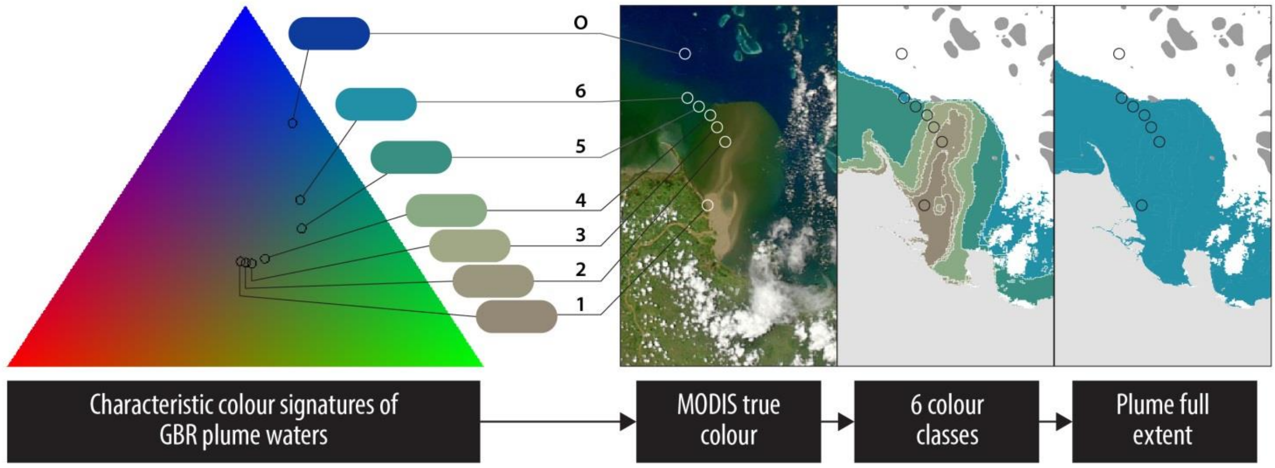

Figure 2-2: Triangular colour plot showing the characteristic colour signatures of the wet season water types in the Red-Green-Blue (RGB or true colour) space. Álvarez-Romero et al. (2013) developed a method to map these characteristic coastal water masses in the Reef using a supervised classification of MODIS true colour data (modified from Devlin et al., 2015).

Colour classes are characterised by different colour and concentrations of optically active components (e.g. TSS, CDOM, and Chl-*a*), 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.

Wet season colour classes were further grouped into three wet season water types:

- primary—classes 1 to 4,
- secondary—class 5, and
- tertiary—class 6.

The brownish to brownish-green turbid waters (colour classes 1–4 or primary water type) are typical of inshore regions of the Reef that receive terrestrial discharge and have high concentrations of resuspended sediments during the wet season (Figure 2-2). 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 water (colour class 5 or secondary water type) is 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 et al., 2012). 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 of areas towards the open sea or offshore regions of river flood plumes, and the ecological relevance of these conditions is likely to be minimal although not well researched.

- **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 minimum colour-class value of each cell/week were used to map the colour class with the maximum turbidity per pixel for each week of the wet season (i.e., assuming the colour classes represented a gradient in turbidity i.e., CC1 > CC2 > CC3 > CC4 > CC5 > CC6). This year, four MODIS Terra images (12, 13, 20 and 21 February 2019) were included in the processing of the weekly composites (weeks 11 and 12) as MODIS-Aqua data were of low quality for those four days (corrupted by sun glint and cloud cover). A large dust cloud travelled over the Reef in mid-February 2019 (Nguyen et al., 2019) and corrupted the MODIS-Aqua image of 14 February 2019. This image was removed from 2018–19 satellite database.

Panels summarising weekly environmental (wind, rainfall and river discharge) and marine (wet season colour classes) conditions were produced for each focus region to illustrate the link between environmental drivers and marine conditions across the wet season.

- **Frequency maps** were produced and predicted the areas affected by 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) or the three wet season water types (primary, secondary and tertiary water types) individually (i.e., of the brownish, greenish and greenish-blue waters, respectively).

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 (2018–19), (ii) over previous years (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 D.

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.

Results for 2011 (very wet), 2016 and 2017 (dry) years, 2018 and 2019 were processed using true colour data from the Bureau of Meteorology (BoM) and the slightly modified cloud mask (2017 case study), while all other years were processed using previous methods.

- **Exposure maps** were produced for the whole of the Reef, for all focus regions and over different time frames: for this reporting wet season (2018–19), as an average of previous years

(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. 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).

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 (2004–2019) wet season concentration of pollutants (proportional exceedance of the Reef-wide wet season GV) mapped through the primary, secondary and tertiary water types (section 2.6.1). 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 the proportional exceedance of the GV multiplied by the likelihood of exposure in each of the wet season water types.

The 'potential risk' is influenced by the available MODIS data on cloud-free days, with the likelihood of risk assessment exposure likely underestimated in higher rainfall and cloudy regions like the Wet Tropics and Cape York. Exposure from each map produced is then grouped into potential risk categories (I to IV) based on a "Natural Break (or Jenks)" classification[2]. 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. The area (km^2) and percentage (%) of coral reefs and seagrass meadows affected by the different categories of exposure (I to IV) was calculated as a relative measure between regions and the long-term mean. The methods are described in further detail in Appendix D.

2.7 River discharge

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 (2100–2200 km^2); 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 2-2; Department of Natural Resources and Mines [DNRM], 2019). The total annual discharge for each gauge was then up-scaled using the best information available. The estimations of basin discharge have been revised and greatly improved for the 2018–19 water year with a thorough reanalysis of the available flow gauges which included the addition of extra flow gauges in certain basins to cover a greater basin area. In addition, our upscale area corrections (previous method) were compared to the BoMs G2G model (covered basins from the Normanby to Mary: BoM, 2017; Wells et al., 2018) over a common period (1 January 2007–31 July 2018) and relevant adjustments to the upscale (correction) factor were made where required. Where a flow gauge did not exist in a basin (e.g. 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

[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).

Cape York basins) or the BoM G2G model. The calculation of the long-term medians for each basin has also now been anchored to cover the 30-year period from 1986–87 to 2015–16 water years.

Table 2-2. 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**
	Herbert River	116	9,844	Herbert River at Ingham	87	1.1
Burdekin	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
	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
Mackay-Whitsunday	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
	Plane Creek	126	2,539	Sandy Creek at Homebush + Carmila Creek at Carmila	16	1.8**

NRM Region	Basin	AWRC No.	Basin area (km^2)	Relevant gauges	Percentage of Basin covered by key gauges	Correction factor
Fitzroy	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
	Calliope River	132	2,241	Calliope River at Castlehope	57	1.7
	Boyne River	133	2,496	Calliope River at Castlehope*	0	0.43
Burnett-Mary	Baffle Creek	134	4,085	Baffle Creek at Mimdale	34	1.7**
	Kolan River	135	2,901	Kolan River at Springfield + 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 Leesons + 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

2.8 Zones of influence for river discharge

Hydrodynamic models are a valuable tool for identifying, quantifying, and communicating the spatial impact of discharges from various rivers into the Reef lagoon. Hydrodynamic models can simulate the three-dimensional transport and fate of material delivered to the marine environment and can 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 in an identical fashion to physical variables such as temperature and salinity; however, they play no dynamic role in physical or biogeochemical processes. Importantly, simulation of the transport of unique tracers 'released' from different rivers enables the identification of marine regions influenced by 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 was developed for the Reef lagoon. Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracer concentrations, mixing coefficients, and sea level. Inputs required by the model include forcing due to wind, atmospheric pressure gradients, surface heat and rainfall fluxes and open-boundary conditions such as tides, low frequency ocean currents and riverine inputs. The model is described in detail by Schiller et al. (2015). For this study, outputs from the regional ~4 km horizontal spatial resolution model were used.

Hindcast simulations were performed for the wet season, which was defined as 1 October until 1 May of the following year. River-tagged passive tracers were released from each of the major gauged rivers discharging into the Reef lagoon. The influence of the Normanby, Annan, Endeavour, Baron, Russell-Mulgrave, Tully, Burdekin, and O'Connell Rivers was examined. 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.

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 x 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 x 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:

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

where,

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

and $\text{Conc}_{threshold}$ 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 $T_{\text{end of wet season}}$ = 1 May. Cumulative exposure is calculated for each grid point in the model domain.

2.9 Load mapping

A revised approach has been developed for estimating the dispersion of river-derived DIN, TSS and PN loads in to 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.

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:

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

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 2019 water year (1 October 2018 to 30 September 2019) was calculated and compared to the pre-development loads (which have a degree of uncertainty). This can be interpreted as 'anthropogenic' fine sediment, DIN or PN loadings, highlighting the areas of greatest change with current land use characteristics.

A similar approach to the tracer maps can be taken to calculate the total effective 'dose' of TSS, DIN or Total N received by each map location. The dose maps were produced by taking the cumulative sum of the concentrations of a constituent (e.g. DIN) predicted to occur at each location. As these outputs are preliminary, they are not presented in this report but can be provided by request.

3. Drivers and pressures influencing water quality during 2018–19

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 Endeavour and Annan River Basin is 2186 km^2 and has a high proportion of nature/conservation land use (52% as of 2015) and closed grazing (40%) (Queensland Land Use Mapping Program [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., 2016a).

  - The Normanby Basin is 24,550 km^2 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, 2010).

  - The Pascoe River has an area of 2088 km^2 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).

- 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 2107 km^2 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 km^2 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 km^2 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 2326 km^2 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 1685 km^2 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 km^2 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 9842 km^2 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 and sugarcane cultivation on the coastal plains (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 2018–19 wet season, there were a number of tropical cyclones and intense low pressure systems that crossed the coast (Figure 3-1):

- Cyclone Owen: A tropical low that moved between the Coral Sea, the northern Reef coast and the Gulf of Carpentaria from 29 November to 17 December 2019. First crossed the coast as a low near the mouth of the Daintree River on 10 December 2018, then crossed the coast at Kowanyama as a Category 3 cyclone on 15 December 2018;
- Cyclone Penny: A tropical low that crossed the coast south of Lockhart River on 30 December 2018, and again as a Category 2 cyclone on 1 January 2019 south of Weipa.
- An intense tropical low in late January and early February resulting in major flooding in the Herbert, Black-Ross and Haughton basins including severe flooding in and around Townsville.
- Cyclone Trevor: A Category 4 cyclone that crossed the coast south of Lockhart River on 19 March 2019. In the 11 years since the MMP began, 11 cyclones have been Category 3 or above and have affected the health of the Reef.

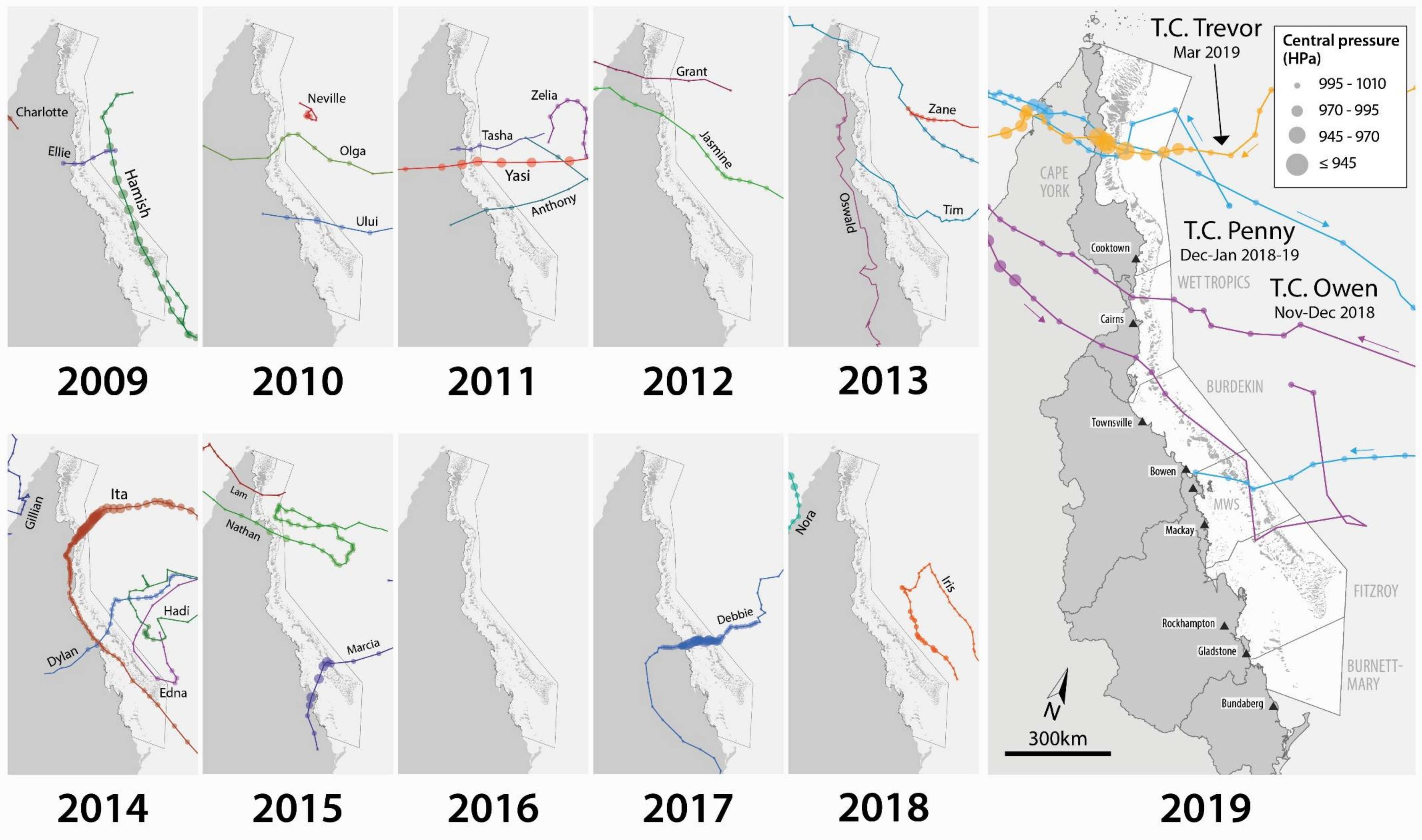

Figure 3-1: Trajectories of tropical cyclones affecting the Reef in 2018–19 and in previous years (2009 to 2018).

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 2018–19 for all of the catchments north of the Fitzroy NRM region (north of the Styx catchment) was above the long-term average of wet seasons from 1961–1990 (Figure 3-2 and Figure 3-3). In most focus regions, this year was much wetter than 2017–18, when only the Wet Tropics catchment had above-average wet season rainfall. The Wet Tropics and Burdekin catchments in particular had well-above-average rainfall, largely associated with an intense tropical low pressure system in late January and early February 2019 (Figure 3-2 and Figure 3-3). Wet season rainfall in the Fitzroy and Burnett-Mary regions was less than the long-term average and reasonably similar to 2017-18 with some variability between individual catchments.

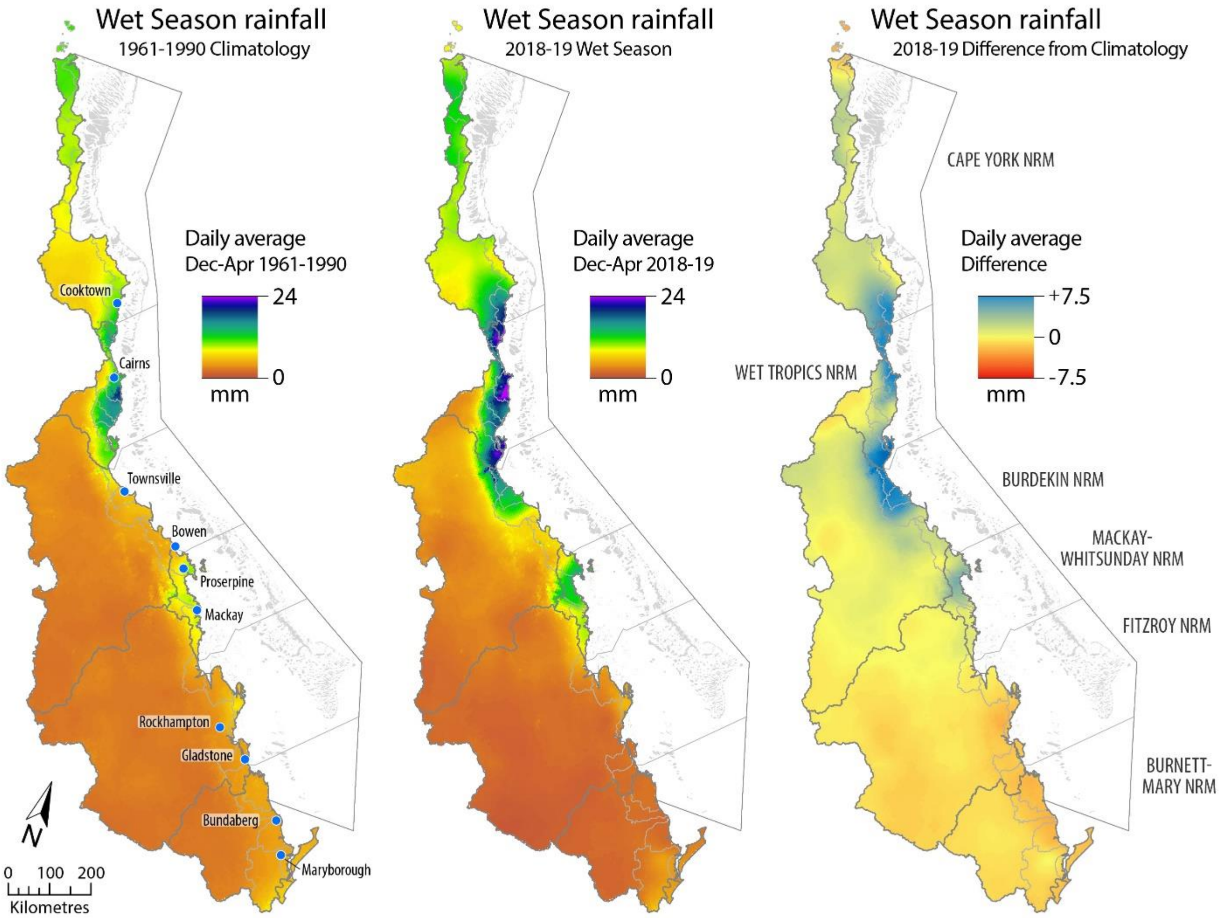

Figure 3-2: Average daily wet season rainfall (mm d^{-1}) in the Reef catchment: (left) long-term daily average (1961–1990; time period produced by BOM), (centre) 2018–19 and (right) the difference between the long-term average and 2018–19 rainfall.

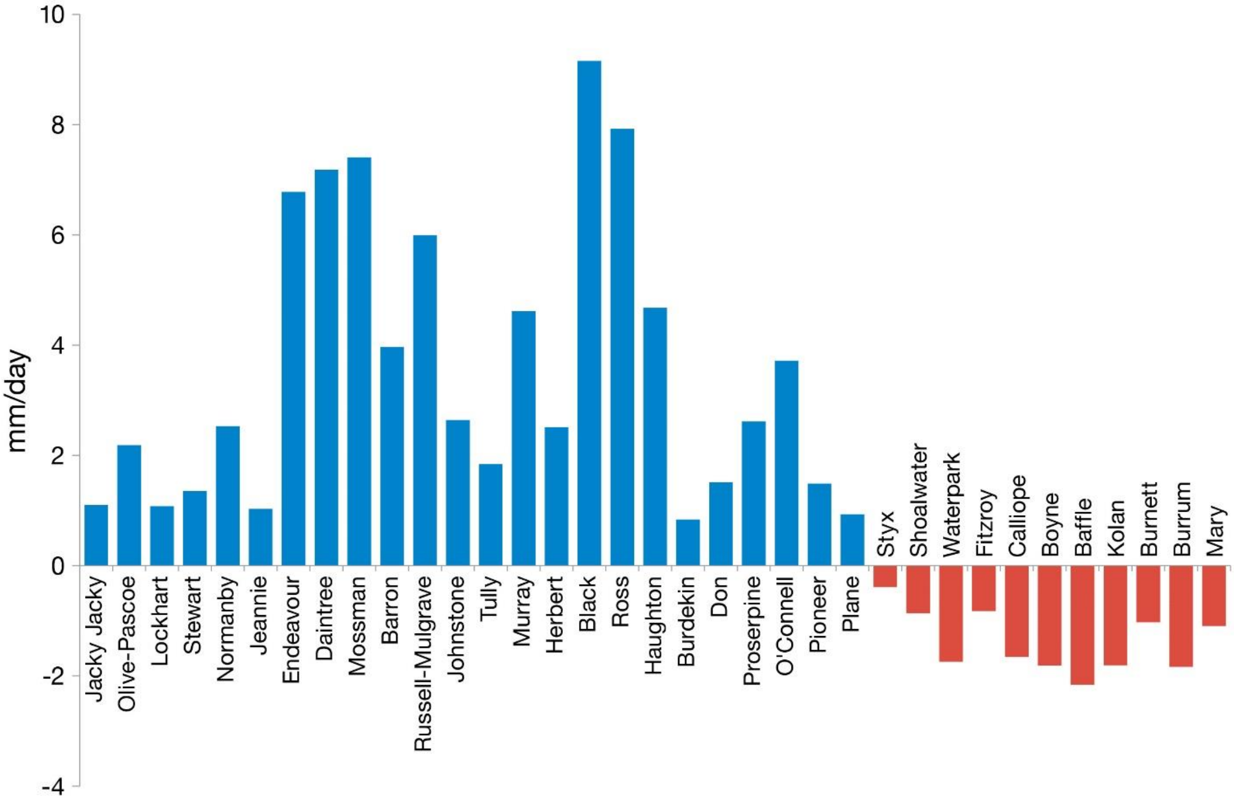

Figure 3-3: Difference between daily average wet season rainfall (December 2018–April 2019) and the long-term wet season rainfall average (from 1961–1990). Red and blue bars denote catchments with rainfall below and above the long-term average, respectively. Note that the catchments are ordered from north to south (left to right).

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 catchments 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 2018–19, all of the northern and central NRM regions had the highest level of wet season discharge recorded in at least seven years. Discharge in the Cape York region was the highest recorded in the data series (2003–04) and was two to three times the long-term median. The most significant discharge was in the Burdekin region, which was more than three times the long-term median discharge. Discharges in the Wet Tropics and Mackay-Whitsunday regions were 1.5–2 times the long-term median, and the largest since the significant flows of the 2010–11 wet season. River discharge in the Fitzroy region was well below average and similar to 2017–18, and the Burnett-Mary average was considerably lower than 2017–18.

Annual discharge for each of the 35 Reef catchment basins in 2018–19 is shown in Table 3-1 and compared to long-term median annual flows for that basin.

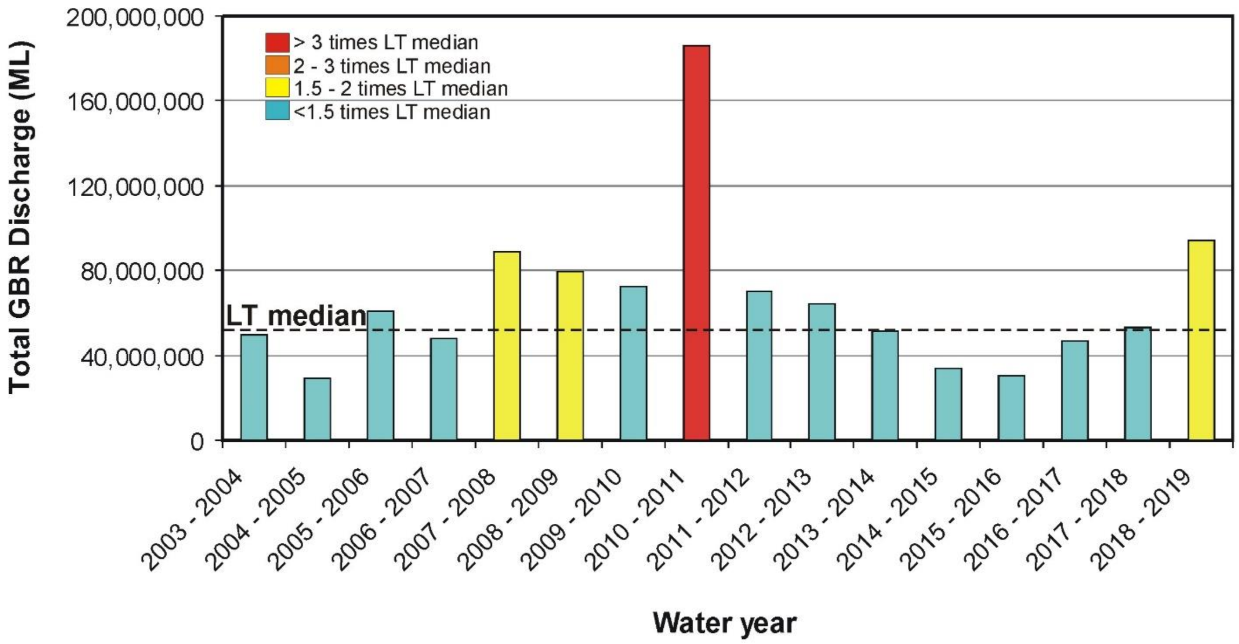

Figure 3-4: Long-term total discharge in ML (water year: 1 October to 30 September) for the 35 main Reef basins. Source: DNRM, http://watermonitoring.dnrm.qld.gov.au/host.htm.

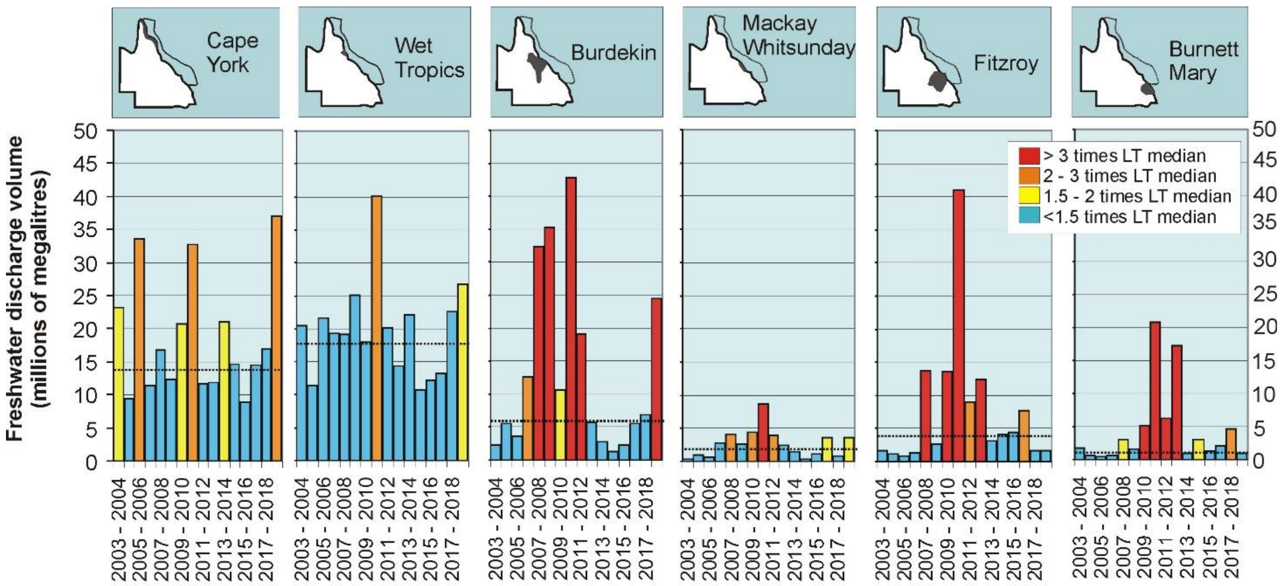

Figure 3-5: Corrected annual water year (1 October to 30 September) discharge from each NRM region (using the correction factors in Table 2-2) for 2003–04 to 2018–19 in (ML per year). Data derived from DNRM (2019).

Table 3-1: Annual water year discharge (ML) of the 35 main Reef basins (1 October 2015 to 30 September 2019, 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	2015–16	2016–17	2017–18	2018–19
Jacky Jacky Creek	2,047,129	913,417	1,701,199	2,689,450	3,124,009
Olive Pascoe River	2,580,727	788,484	2,978,821	3,424,596	6,992,798
Lockhart River	1,634,460	499,373	1,886,587	2,168,911	4,428,772
Stewart River	674,618	311,901	685,263	826,499	3,109,052
Normanby River	4,159,062	3,407,359	3,780,651	4,333,023	12,102,053
Jeannie River	1,263,328	1,581,015	1,746,929	1,721,175	3,350,682
Endeavour River	1,393,744	1,407,701	1,665,116	1,796,913	3,847,478
Daintree River	1,512,054	1,433,059	1,590,225	1,439,220	4,752,327
Mossman River	858,320	885,529	812,585	1,069,336	1,885,921
Barron River	574,567	199,635	313,952	946,635	1,535,892
Mulgrave-Russell River	2,600,465	1,898,065	1,759,178	3,359,834	3,550,093
Johnstone River	3,953,262	2,846,943	3,348,014	4,950,329	4,774,747
Tully River	3,241,383	2,697,539	2,840,476	3,883,954	4,020,452
Murray River	380,472	301,879	293,742	521,465	519,739
Herbert River	3,556,376	1,895,526	2,248,436	6,385,655	5,707,209
Black River	208,308	109,784	64,449	386,030	965,544
Ross River	377,011	32,399	41,177	83,113	2,371,556
Haughton River	419,051	189,006	283,551	598,668	2,363,209
Burdekin River	4,406,780	1,807,104	4,165,129	5,542,306	17,451,417
Don River	508,117	173,549	1,081,946	321,875	1,356,004
Proserpine River	284,542	101,490	539,710	174,183	837,962
O'Connell River	478,097	273,420	894,975	260,937	1,223,297
Pioneer River	692,342	597,117	1,388,687	249,530	1,158,768
Plane Creek	309,931	246,274	761,503	75,052	351,879
Styx River	155,384	284,587	420,353	218,115	109,376
Shoalwater Creek	129,487	237,156	350,294	181,763	91,147
Water Park Creek	97,115	177,867	262,721	136,322	68,360
Fitzroy River	2,852,307	3,589,342	6,170,044	954,533	1,339,964
Calliope River	152,965	148,547	406,321	141,438	2,682
Boyne River	38,691	37,574	102,775	35,775	678
Baffle Creek	215,446	150,710	486,235	1,081,646	930
Kolan River	52,455	120,977	190,476	325,578	4,958
Burnett River	230,755	381,054	536,242	849,051	202,436
Burrum River	79,112	289,364	387,027	715,449	63,972
Mary River	981,183	412,160	499,295	1,630,741	658,014
Sum of basins	43,099,046	30,426,907	46,684,083	53,479,101	94,323,378

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 (Figure 4-1) or the three wet season water types individually (Figure 4-2) from December to April.

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 (e.g. 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).

The frequencies of occurrence of combined primary and secondary water types measured across the Tully-offshore, Burdekin-offshore and Pioneer-offshore transects in 2018–19 (Figure 4-1 f) were greater than frequencies extracted from the averages of previous years (2003–2018) and the representative coral recovery period (2012–2017); and well above the frequencies extracted from the typical dry-year composite (Figure 4-1 a, b and d). The 2018–19 frequencies were similar to (Tully a nd Burdekin transects) or below (Pioneer transect) the frequencies extracted from the typical wet-year composite (Figure 4-1 c and f).

At the Reef scale, the total area affected by primary and secondary water types in 2018–19 exceeded the area affected in the coral recovery period and previous years as well as the typical dry-year composite (Table 4-1). The Area affected this year was slightly below the area affected in the typical wet-year composite. These remote sensing results demonstrate the effect of an above-average discharge year (2018-19 wet season) on coastal waters. The tertiary water type in 2018–19 covered a larger area than all reference periods (extent illustrated in Figure 4-2). This result requires further investigation but could be an indication of other factors such as temperature or shelf nutrient upwelling. Note that these estimates include waters of Hervey Bay, south of the Marine Park boundary, and only include areas where normalised frequencies were above 0.1.

Table 4-1: Areas (km^2) (and percentages, %) of the Reef lagoon and Hervey Bay waters (total 377,776 km^2) affected by the three wet season water types combined during a range of representative periods. Areas and percentage are only calculated for frequencies > 0.1.

	2018-19 wet season	**Average of previous years: 2003-2018**	**Average of coral recovery period: 2012-2017**	**Typical Wet-year composite**	**Typical Dry-year composite**
Water type	**Area affected (km^2)**				
Combined primary + secondary (CC1-5)	88,193 (23%)	69,150 (18%)	68,284 (18%)	101,268 (27%)	48,500 (13%)
Primary	19,877 (5%)	12,989 (3%)	12,817 (3%)	24,424 (6%)	9,013 (2%)
Secondary	81,023 (21%)	63,113 (17%)	62,396 (17%)	91,664 (24%)	44,447 (12%)
Tertiary	221,601 (59%)	176,743 (47%)	176,959 (47%)	211,010 (56%)	145,584 (39%)

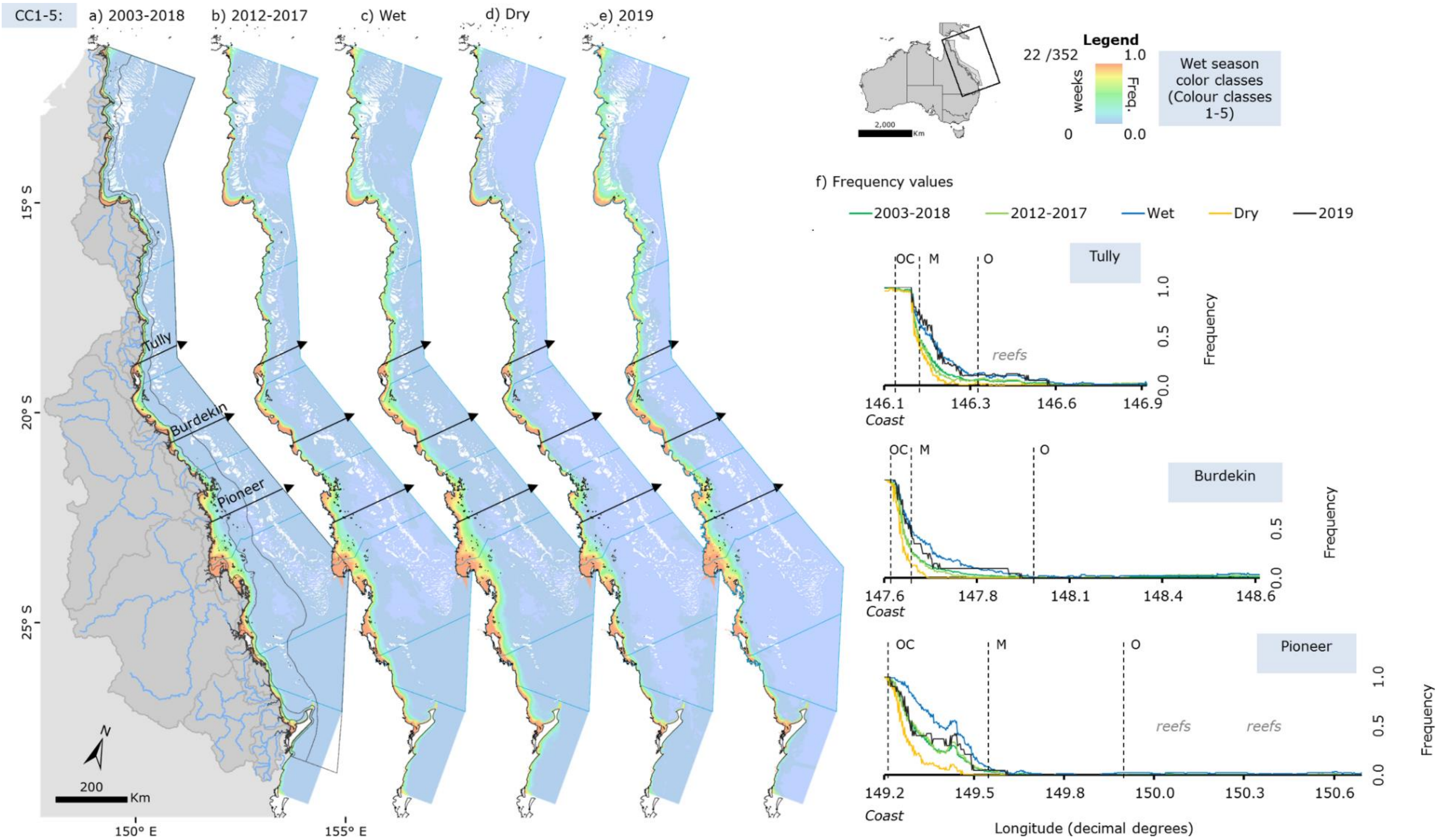

Figure 4-1: Map showing the frequency of primary (CC1–4) and secondary (CC5) water types combined in the a) previous years (2002–03 to 2017–18: 16 wet seasons or 352 weeks), b) representative coral recovery period (2011–12 to 2016–17, 6 wet seasons or 132 weeks), c) typical wet-year composite and d) typical dry-year wet season composites and e) 2018–19 wet season (22 weeks). 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.

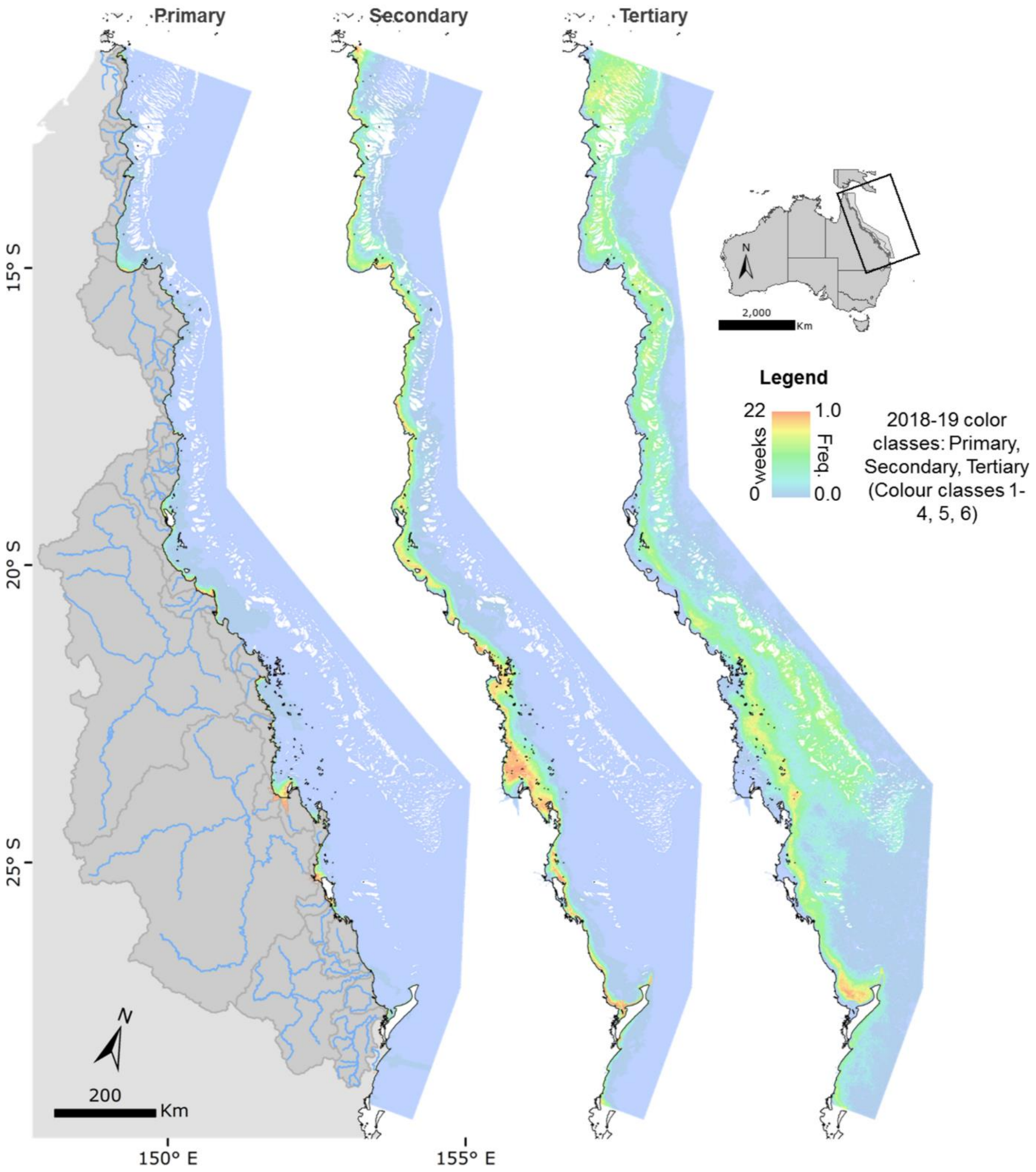

Figure 4-2: Map showing the frequency of primary, secondary and tertiary wet season water types in the 2018–19 wet season (22 weeks). The highest frequency is shown in orange and the lowest frequency is shown in blue. These maps are used in the exposure assessment to represent the spatial likelihood of exposure of each of the wet season water types in 2018–19.

4.1.2 Composition of water types

A summary of long-term average (2004–2019) water quality parameters in the wet season water types and six colour classes is shown in Figure 4-3 and Figure 4-4, respectively. Detailed summaries of water quality parameters for the reporting year are provided in Appendix E. Note that the mean long-term water quality concentrations (2004–2019) are presented here rather than the seasonal mean concentrations in each colour class that were reported in previous years which were considered to be potentially biased by the wet season sampling effort. The latter figures are still presented in Appendix E for consistency.

Most water quality parameters in the long-term dataset (2004–2019) followed historical and published trends, i.e. decreasing values of constituents from the primary (colour classes 1–4) to the tertiary (colour class 6) water type, with the exception of Secchi depth, which increases with colour class (Figure 4-3) The following trends were found for water types:

- Primary: the long-term mean TSS, Chl-*a*, PP, and PN concentrations were above the Reef-wide wet season GVs;
- 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; and
- 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.

Reef-wide wet season 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 Table D-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 Table D-4). The long-term TSS concentrations were above the Reef-wide wet season GVs in each wet season water type (Figure 4-3). However, it is important to note that TSS in coastal waters is highly variable where (mean ± standard deviation): $TSS_{primary}$ = 18.27 ± 45.70 mg L^{-1}, $TSS_{secondary}$ = 5.92 ± 7.99 mg L^{-1} and $TSS_{tertiary}$ = 3.92 ± 5.10 mg L^{-1}. Except for TSS, all long-term water quality concentrations in the tertiary water type met the Reef-wide GVs. The only GV presently available for Secchi depth is an annual mean, and thus comparison with wet season Secchi depth data is not possible. 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.

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 ± 2.37µg L^{-1}) than in the secondary water type (0.80 ± 0.84 µg L^{-1}). Chl-*a* concentrations were higher in colour class 3 (2.28 ± 2.98 µg L^{-1}) than in colour classes 1 (2.20 ± 3.41 µg L^{-1}) and 2 (1.48 ± 1.12 µg L^{-1}) (Figure 4-4). 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 concentrations of water quality parameters showed similar trends between the focus regions, with maximum concentrations measured in the primary and minimum concentrations in the tertiary water types (Figure 4-5). However, there were distinct differences in the concentrations of individual pollutants across regions. The Burdekin region had 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 were measured in the primary water types of the Wet Tropics and Cape York regions, respectively. The greatest mean Chl-*a* concentrations were measured in the primary water types of the Mackay-Whitsunday and Burdekin regions. Except for CDOM and PN concentrations, the Cape York region showed the lowest concentrations of water quality parameters of all regions. 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. The *magnitude scores* for the exposure maps are thus calculated using the mean long-term (2004–2019) water quality concentrations across the whole of the Reef (Figure 4-3).

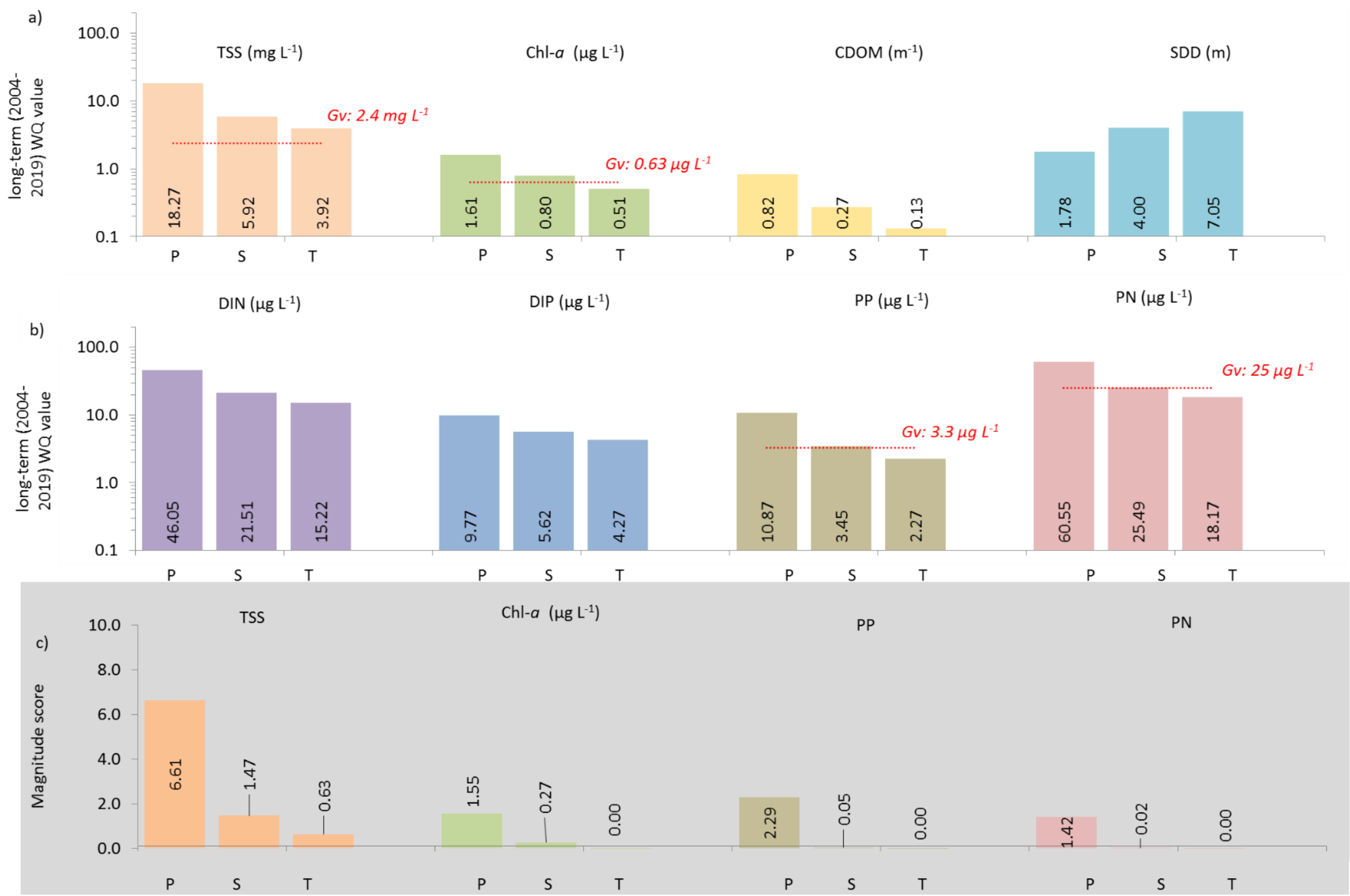

Figure 4-3: (a, b) Mean long-term (2004–2019) water quality concentrations across the three wet season water types. Red lines show the Reef-wide wet season GVs (Table D-3). c) Magnitude scores calculated as the proportional exceedance of the guideline: $magnitude_{water\ type} = ([Poll.]_{water\ type} - GV)/GV$ 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 each reporting year as additional field data is collected to continually improve the characterisation of mean water quality characteristics across wet season water types across all regions of the Reef. Mean long-term water quality concentrations include samples collected from all water bodies (Table D-4).

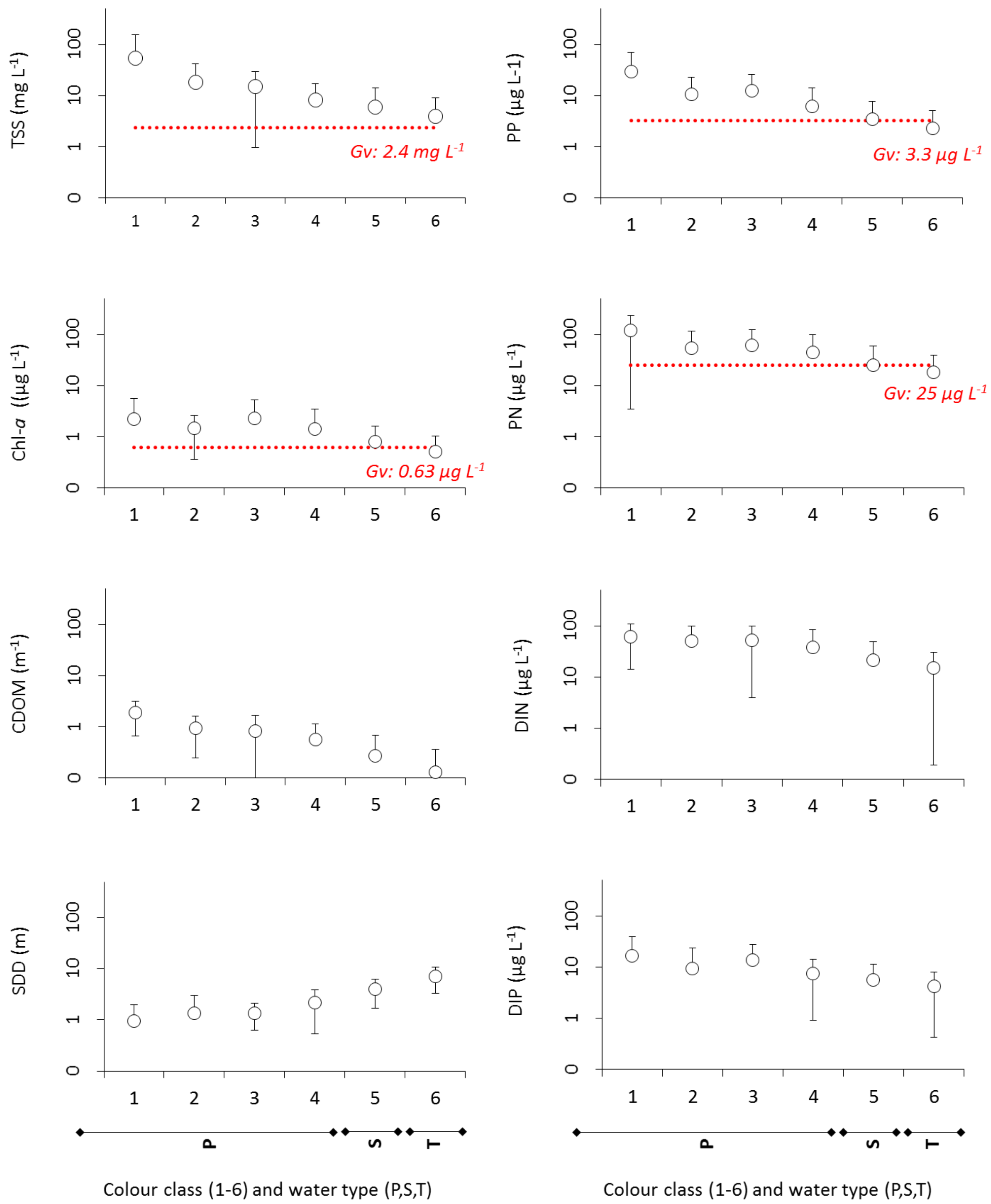

Figure 4-4: Mean long-term (2004–2019) water quality concentrations and standard deviations across the six colour classes Dotted red lines show the Reef-wide wet season GVs (Table D-3). Mean long-term water quality concentrations include samples collected from all water bodies (Table D-4).

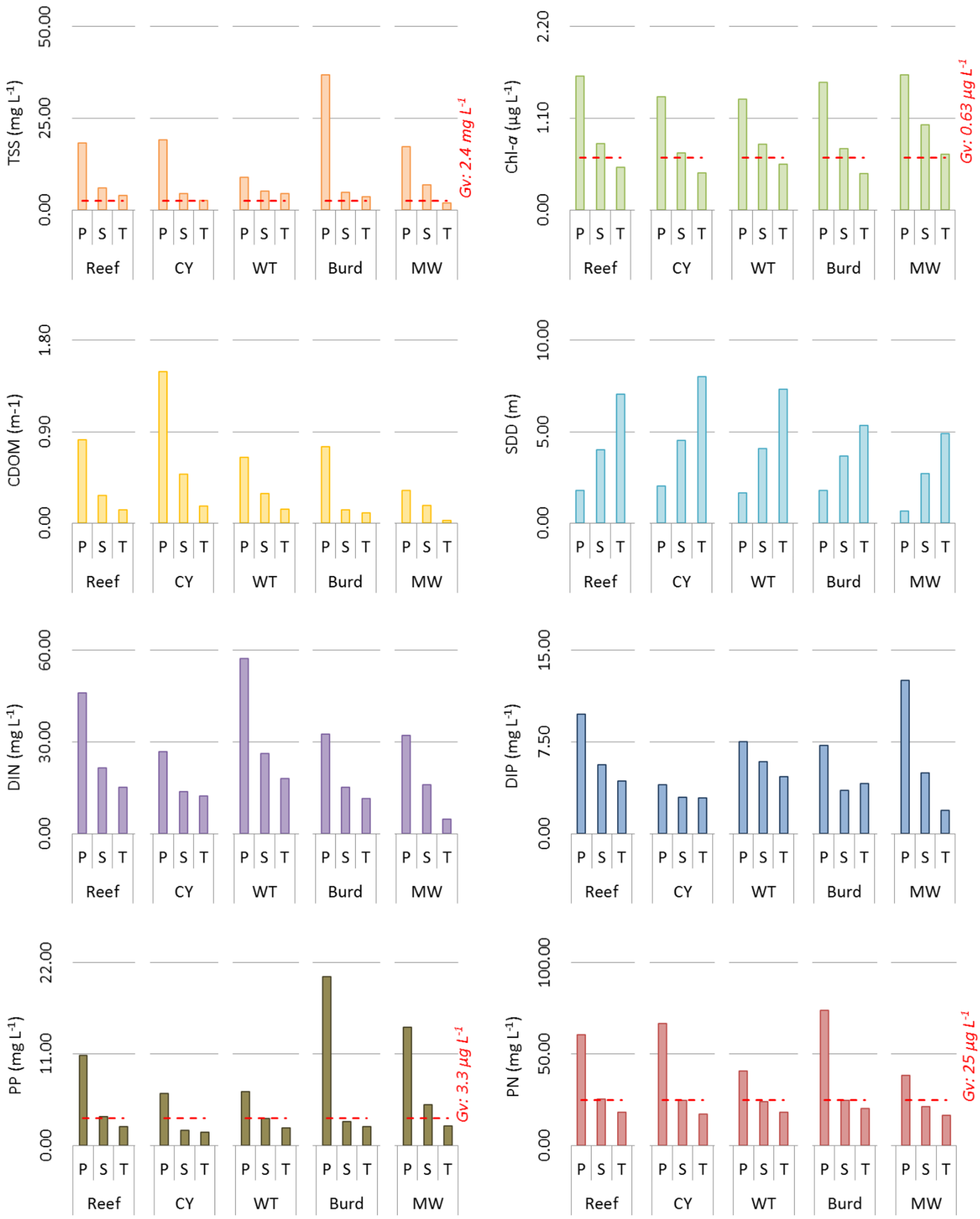

Figure 4-5: Mean long-term (2004–2019) water quality concentrations across the three wet season water types in all focus regions. Red lines show the Reef-wide wet season GVs (Table D-3). Mean long-term water quality concentrations includes samples collected from the enclosed coastal zone (Table D-4), where high TSS, PN and PP concentrations are likely to contribute to exceedances of the Reef-wide GVs.

4.1.3 Potential exposure risk to Reef ecosystems

This section presents the area (km^2) 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 long-term mean concentrations of water quality parameters (Reef-wide) measured across the wet season water types described above (Figure 4-3a, b, Table D-4) were assessed against the Reef-wide wet season GVs derived from De'ath and Fabricius (2008) (Table D-3) to calculate magnitude scores for TSS, Chl-*a*, PP and PN (Figure 4-3c). These magnitude scores were used in combination with the seasonal (Figure 4-2) and long-term frequency maps to derive wet season and long-term surface exposure maps, respectively.

Exposure maps (Figure 4-6) were overlaid with information on the spatial distribution of coral reefs and surveyed seagrass meadows to help identify areas and percentages of these ecosystems that may experience exposure to pollutants during the wet season (Table 4-2). Exposure maps are presented in the contexts of the average of previous years (2003–2018), a 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 average of previous years (2003–2018).

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.

In 2018–19, it was estimated that:

- 16% of the Reef was exposed to combined potential risk categories II–IV. However, only 1.1% of the Reef was in the highest exposure category (IV) and only 2% of the Reef was in category III.
- 18.3% of coral reefs were exposed to combined potential risk categories II–IV. However, only 0.2% of corals were in the highest exposure category (IV) and only 0.6% of corals were in category III.
- 87.1% of seagrasses were exposed to combined potential risk categories II–IV. 15.7% of seagrasses were in the highest exposure category (IV) and 19.5% were in category III.
- The coral and seagrass areas exposed to combined potential risk categories II–IV in 2018–19 were greater than the average long-term areas by +14.1% and +5.9%, respectively. Most of these increases occurred in the Cape York, Wet Tropics, Burdekin and Mackay-Whitsunday regions. These characteristics are consistent with the relatively wet conditions in the northern and central Reef in 2018–19.

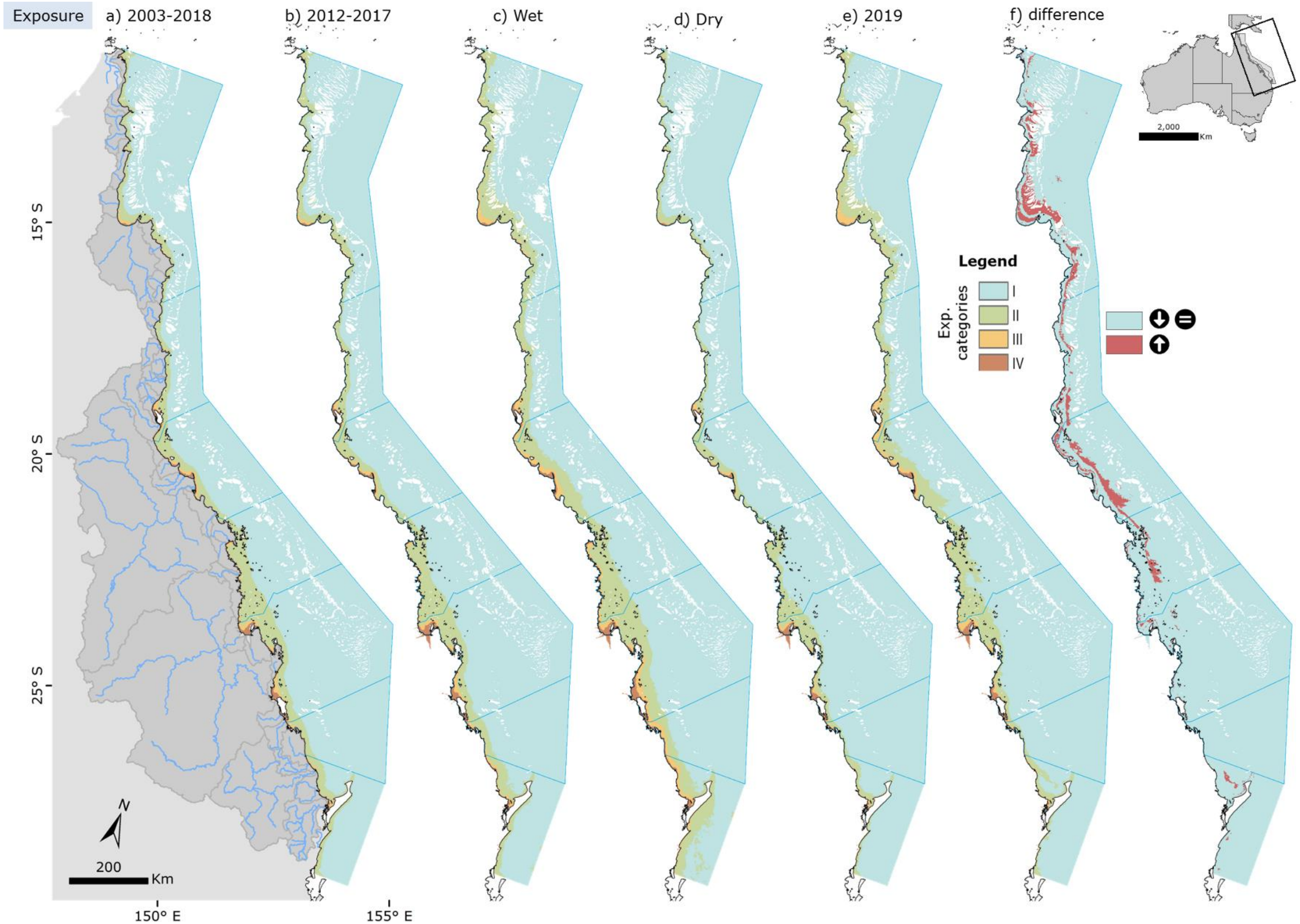

Figure 4-6: Map showing the reclassified surface exposure in the a) average of previous years (2002–03 to 2017–18: 16 wet seasons / 352 weeks), b) representative coral recovery period (2012–2017, 132 weeks), c) typical wet-year and d) typical dry-year wet season composites and e) 2018–19 wet seasons (22 weeks). Relative potential risk categories range from I: no to low risk to IV: highest risk. f) Difference map showing areas with an increase in risk category in 2018–19 (in red, ➊) against long-term trends (calculated as (e) 2019 minus (a) 2003–2018).

Table 4-2: Areas (km^2) and percentages (%) of the Reef lagoon, coral reefs and surveyed seagrass affected by different risk categories of exposure during the 2018–19 wet season and the long-term (2003–2018). The last three rows show the differences between % affected in 2018–19 and the long-term average (red: increase, blue: decrease, and green: no change, difference <1 %). 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**	**IV**	
Surface area	area	348,839	2019	293,050	44,996	6,840	*3,954*	*55,789*
			LT	304,664	35,767	4,853	3,555	44,175
	%	*100%*	2019	84%	13%	2%	1%	16%
			LT	87%	10%	1%	1%	13%
Coral reefs	area	24,149	2019	19,737	4,210	149	*53*	*4,412*
			LT	23,147	861	98	43	1,002
	%	*100%*	2019	82%	17%	1%	<1%	18%
			LT	96%	4%	<1%	<1%	4%
Surveyed seagrass	area	4,640	2019	599	2,406	905	*729*	*4,041*
			LT	875	2,387	691	687	3,765
	%	*100%*	2019	13%	52%	20%	16%	87%
			LT	19%	51%	15%	15%	81%
Difference (2019 – Long Term average)	*Surface area*			-3%	3%	1%	< 1%	3%
	Coral Reef			-14%	14%	<1%	< 1%	14%
	Surveyed seagrass			-5%	<1%	5%	< 1%	6%

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.

4.2.1 River-derived DIN dispersal

2019 water year

The estimated wet season river-derived DIN loading in the Reef lagoon for the 2019 water year is shown in Figure 4-7 (left panel), highlighting that the area between Cooktown and Bowen (in addition to Repulse Bay) had the highest loading. The 'anthropogenic' influence (Figure 4-7, right panel) is predicted by calculating the difference between a pre-development load scenario (Figure 4-7, centre panel) and the 2018–19 loading. This emphasises the influence in the area between Cairns and Bowen and further south near Proserpine which receives inputs from the Wet Tropics and Burdekin rivers and the Proserpine and O'Connell rivers, respectively.

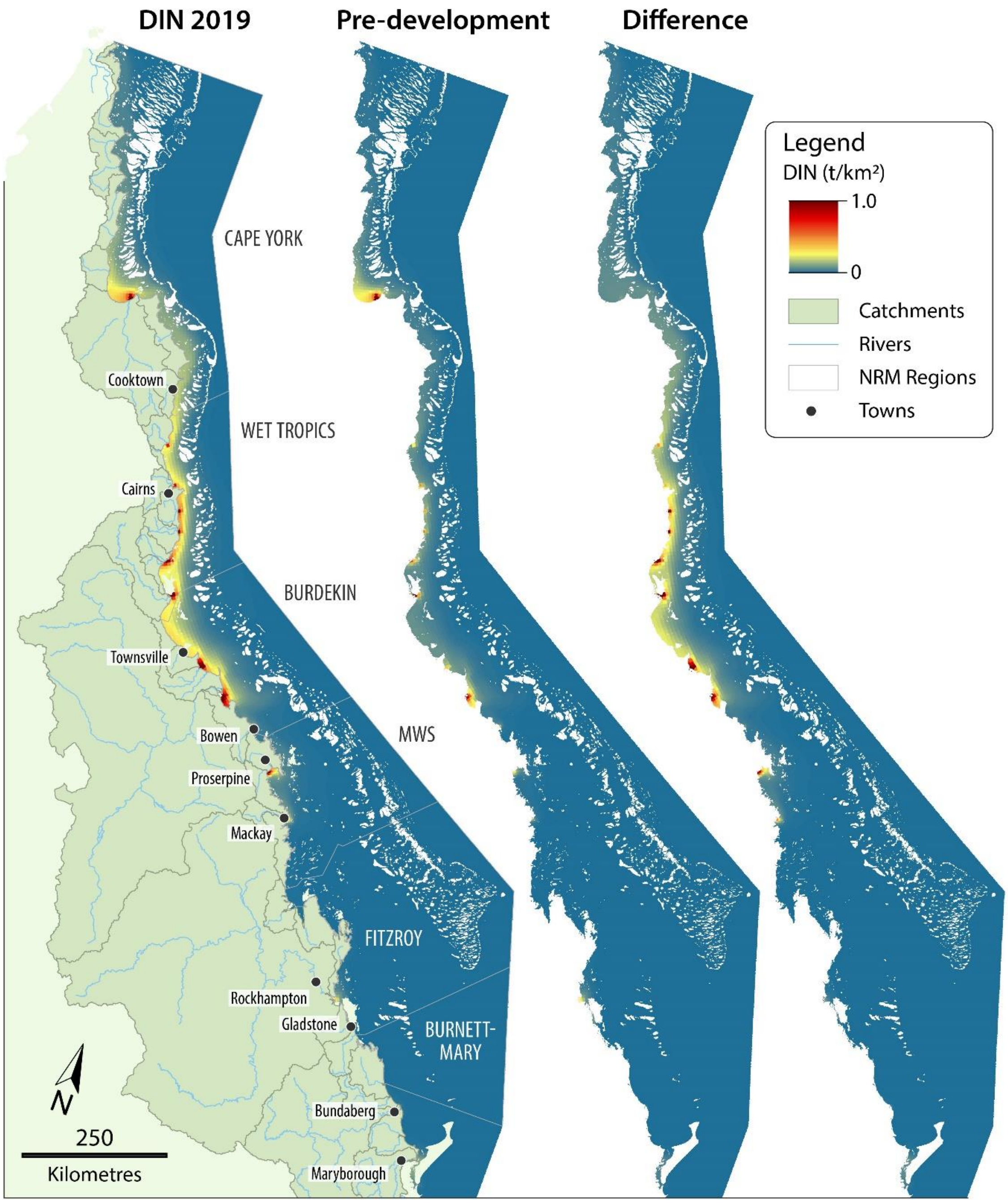

Figure 4-7: River-derived DIN loading (tonnes km^{-2}, relative scale) in the Reef lagoon, modelled for the (left panel) 2019 water year (1 October to 30 September), (centre panel) pre-development loads, and (right panel) difference between the DIN loading for pre-development and 2019 estimates.

Trends in annual river-derived DIN loading to the Reef 2003–2019

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 map highlights spatial and temporal variation in DIN loading. The time series from 2003 to 2019 (Figure 4-8) shows distinct interannual variability, driven by river flow and pollutant loads. 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 MMP reports.

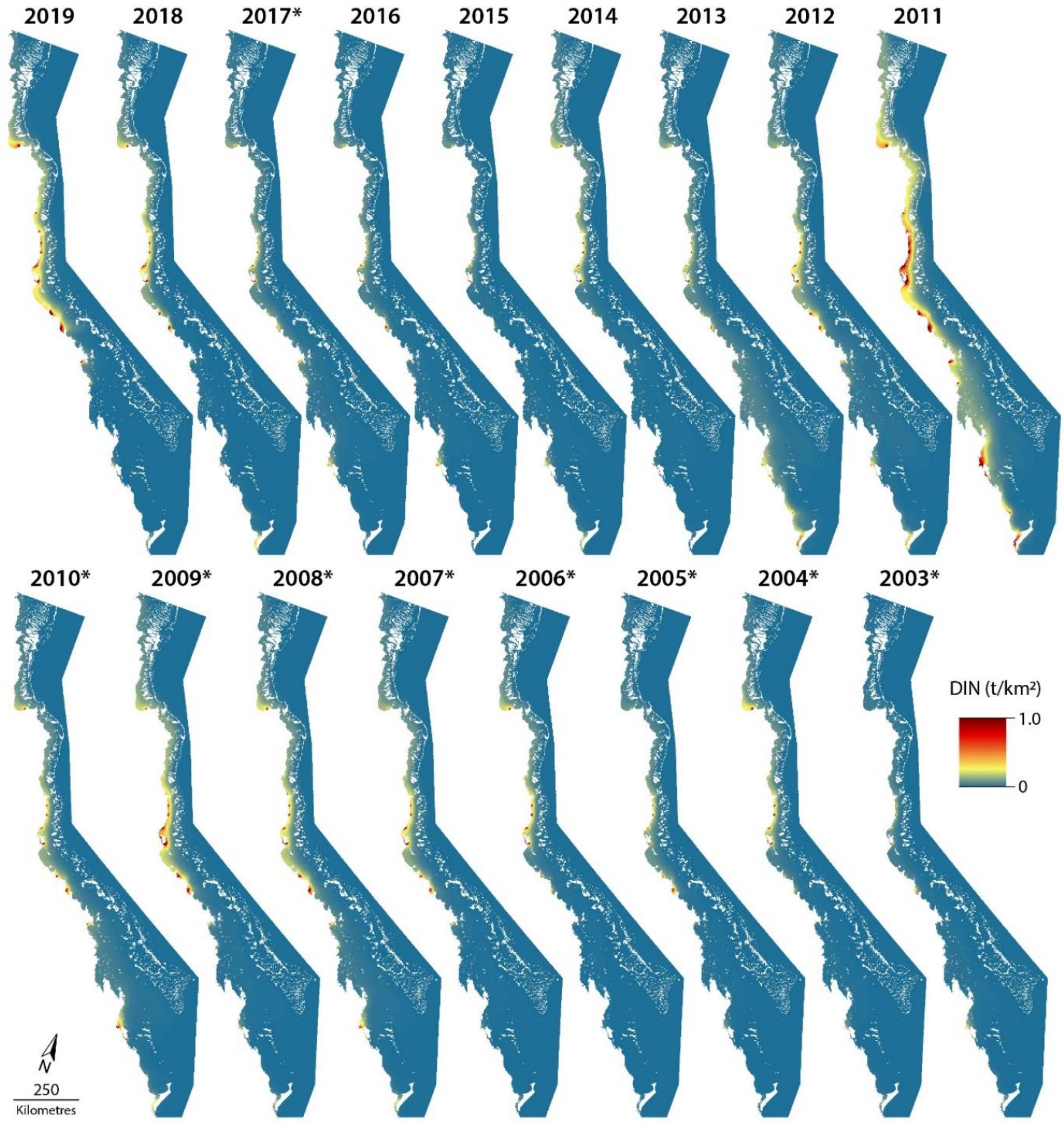

Figure 4-8: River-derived DIN loading (tonnes km^{-2}, relative scale) over the Reef lagoon for the 2003 to 2019 water years (1 October to 30 September). The years marked with asterisks are modelled using a multiannual average tracer.

The areas of influence in 2018–19 are comparable to those years with river discharge above the long-term median (e.g. 2008–09). 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 than in other regions. The greatest incidence of high DIN loading occurred in the Wet Tropics region in all years including 2018 and, within the Wet Tropics, the areas of greatest values were correlated with large river discharge events in 2006, 2007, 2009, 2011, 2014 and 2018. High loading was also observed in each region during different years. For example, high values in the Mackay-Whitsunday region in 2008, each year in 2010–2013 and in 2017 (Figure 4-8).

4.2.2 River-derived TSS dispersal

2019 water year

The estimated wet season river-derived TSS loading for the 2019 water year is shown in Figure 4-9 (left panel), highlighting the highest loadings in the area of Princess Charlotte Bay (receiving the Normanby River discharge) and the area between Cairns and Bowling Green Bay (receiving the discharge from the Wet Tropics and Burdekin region rivers), with the greatest intensity around the Burdekin River mouth.

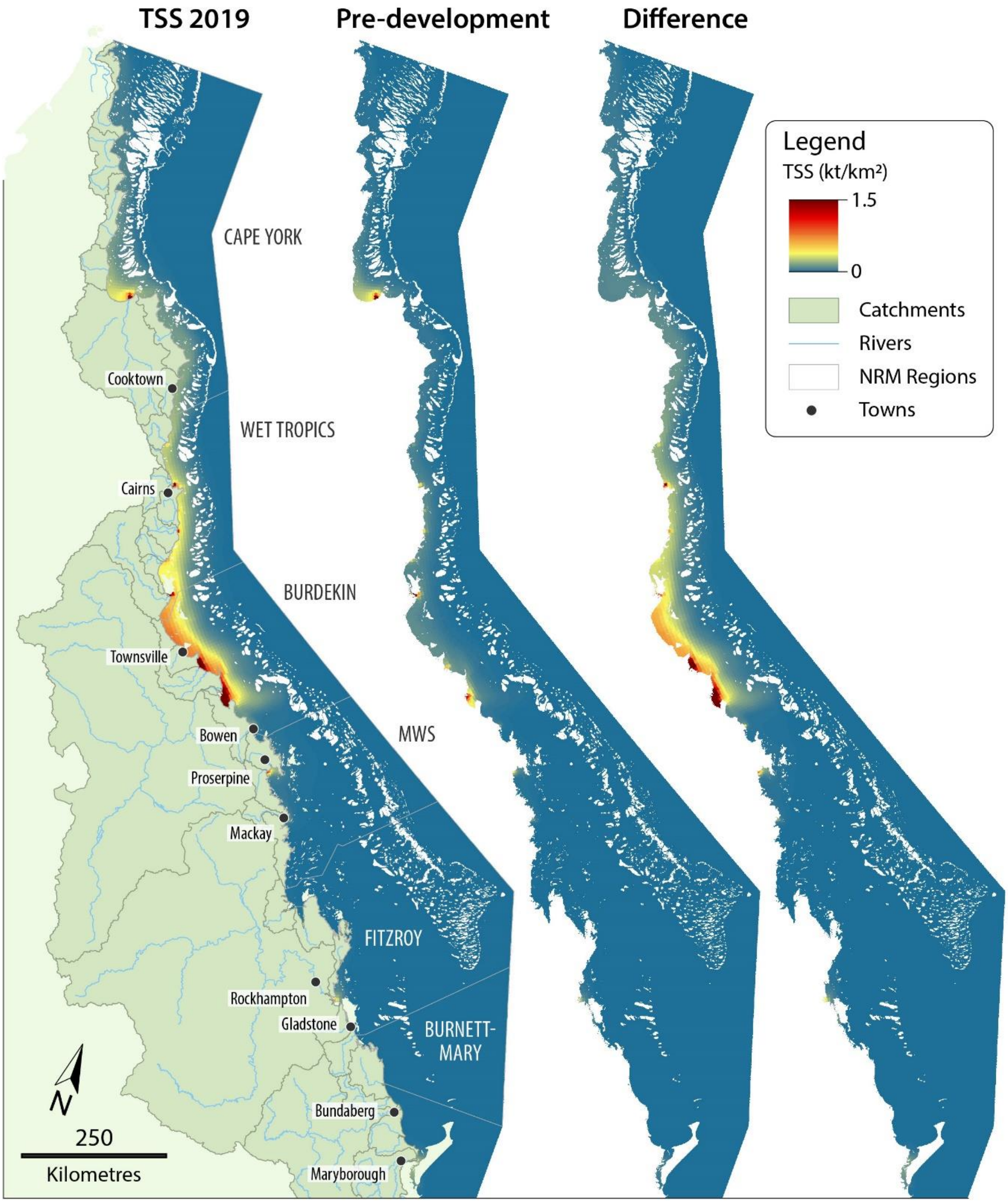

Figure 4-9: TSS (kilotonnes km^{-2}, relative scale) in the Reef lagoon, modelled for the (left panel) 2019 water year (1 October to 30 September), (centre panel) pre-development loads, and (right panel) difference between the TSS loading for pre-development and 2019 estimates.

The ‘anthropogenic’ influence (Figure 4-9,right panel) is predicted by calculating the difference between a pre-development load scenario (Figure 4-9, centre panel) and the 2018–19 loading. This emphasises the intensity of the influence from the Burdekin River, and removes the area of high loading in Princess Charlotte Bay suggesting that this influence could be derived from natural sources. However, the pre-development loads for Cape York and the Normanby River are highly uncertain, based on limited historical data, and Paddock to Reef modelling data assumptions. These assumptions do not fully account for the widespread impact of grazing land uses on the initiation and acceleration of gully erosion post-European settlement (Brooks et al. 2013; Shellberg and Brooks 2013).

Trends in annual river-derived TSS loading to the Reef 2003–2019

Similarly to DIN, the annual model-predicted river-derived TSS loading was examined over 17 years (Figure 4-10). The time-series from 2003–2019 shows distinct inter-annual differences, driven by river flow and pollutant loads. 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 MMP reports. The areas of influence in 2018–19 were comparable to those years with river discharge above the long-term median (e.g. 2008–09 and 2009–10).

The greatest extent model-predicted TSS loading was observed in 2011 associated with heavy rain associated with tropical cyclone Tasha and the subsequent influence of severe tropical cyclone Yasi followed by 2019, 2008, and 2009. 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 in 2005, 2007, 2008, 2009, 2011, 2012, 2017, and 2019. High loading was also observed in each region in different years. For example, high values occurred in the Fitzroy region in 2008, 2010, 2011, 2013, and 2017; in the Wet Tropics region in 2008, 2009, 2011, and 2019; and in Princess Charlotte Bay in the Cape York region in 2004, 2008, 2011, and 2019 (Figure 4-10).

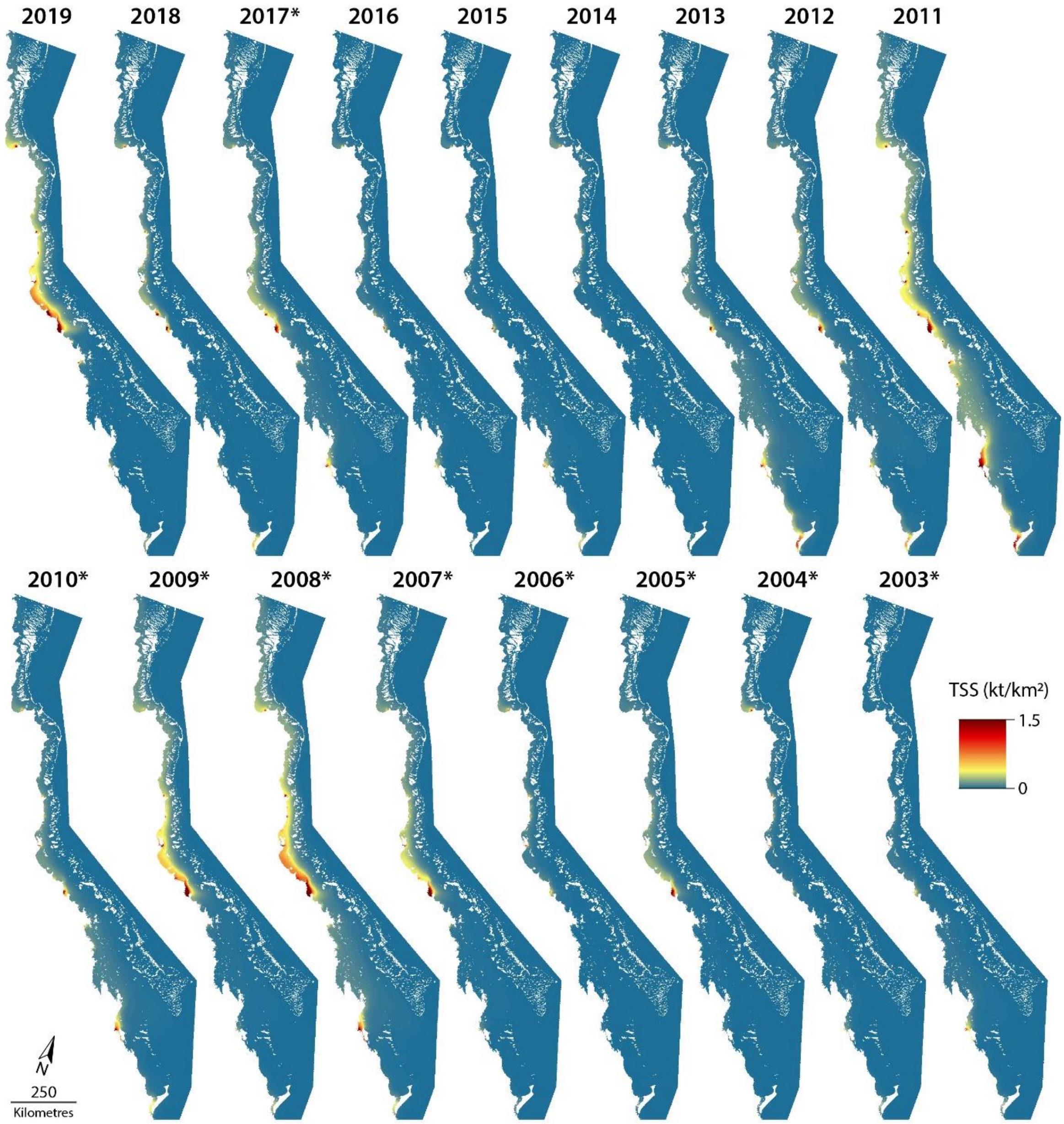

Figure 4-10. TSS loading (kilotonnes per km^2, relative scale) over the Reef lagoon for the 2005 to 2018 water years (1 October to 30 September). The years marked with asterisks are modelled using a multiannual average tracer.

4.2.3 River-derived PN dispersal

2019 water year

The estimated wet season river-derived PN loading for the 2019 water year is shown in Figure 4-11 (left panel) and shows similar patterns to TSS loading maps. Highest PN loadings occurred in the area of Princess Charlotte Bay (receiving the Normanby River discharge) and the area between Cairns and Bowling Green Bay (receiving the discharge from the Wet Tropics and Burdekin region rivers), especially near the Burdekin River mouth. The 'anthropogenic' influence (Figure 4-11 right panel) can be predicted by calculating the difference between a pre-development load scenario (Figure 4-11 centre panel) and the 2018–19 loading. The difference map is reasonably similar to the total loads for 2019, suggesting that PN loading may be largely derived from anthropogenic sources, although this requires corroboration with monitoring data.

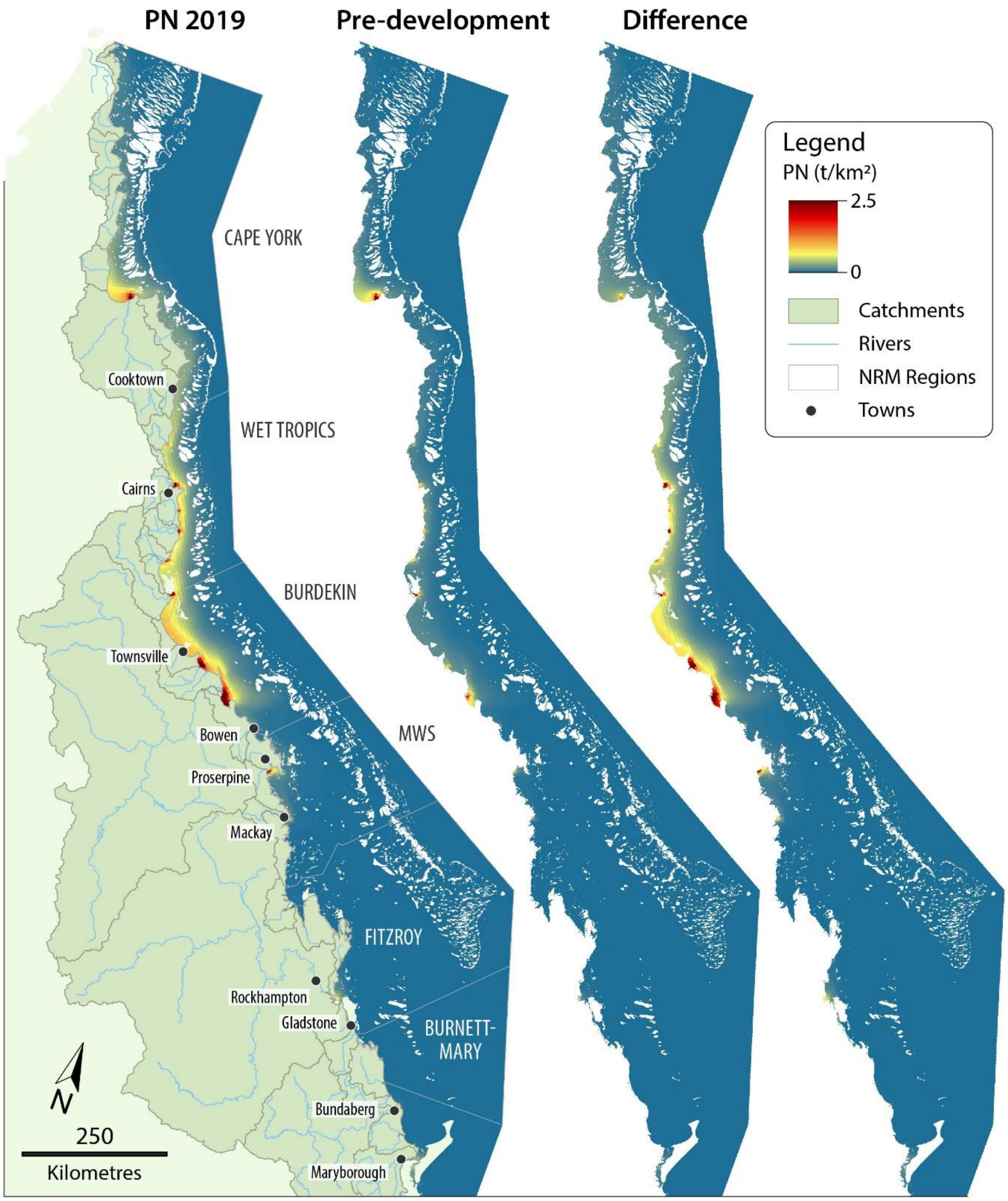

Figure 4-11: River-derived PN loading (tonnes km^{-2}, relative scale) in the Reef lagoon, modelled for the (left panel) 2019 water year (1 October to 30 September), (centre panel) pre-development loads, and (right panel) difference between the PN loading for pre-development and 2019 estimates.

Trends in annual river-derived PN loading to the Reef 2003–2019

Similarly to DIN and TSS, the annual model-predicted river-derived PN loading to the Reef lagoon was examined over 17 years (Figure 4-12). The time-series from 2003 to 2019 shows distinct inter-annual differences, driven by river flow and pollutant loads. 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 MMP reports.

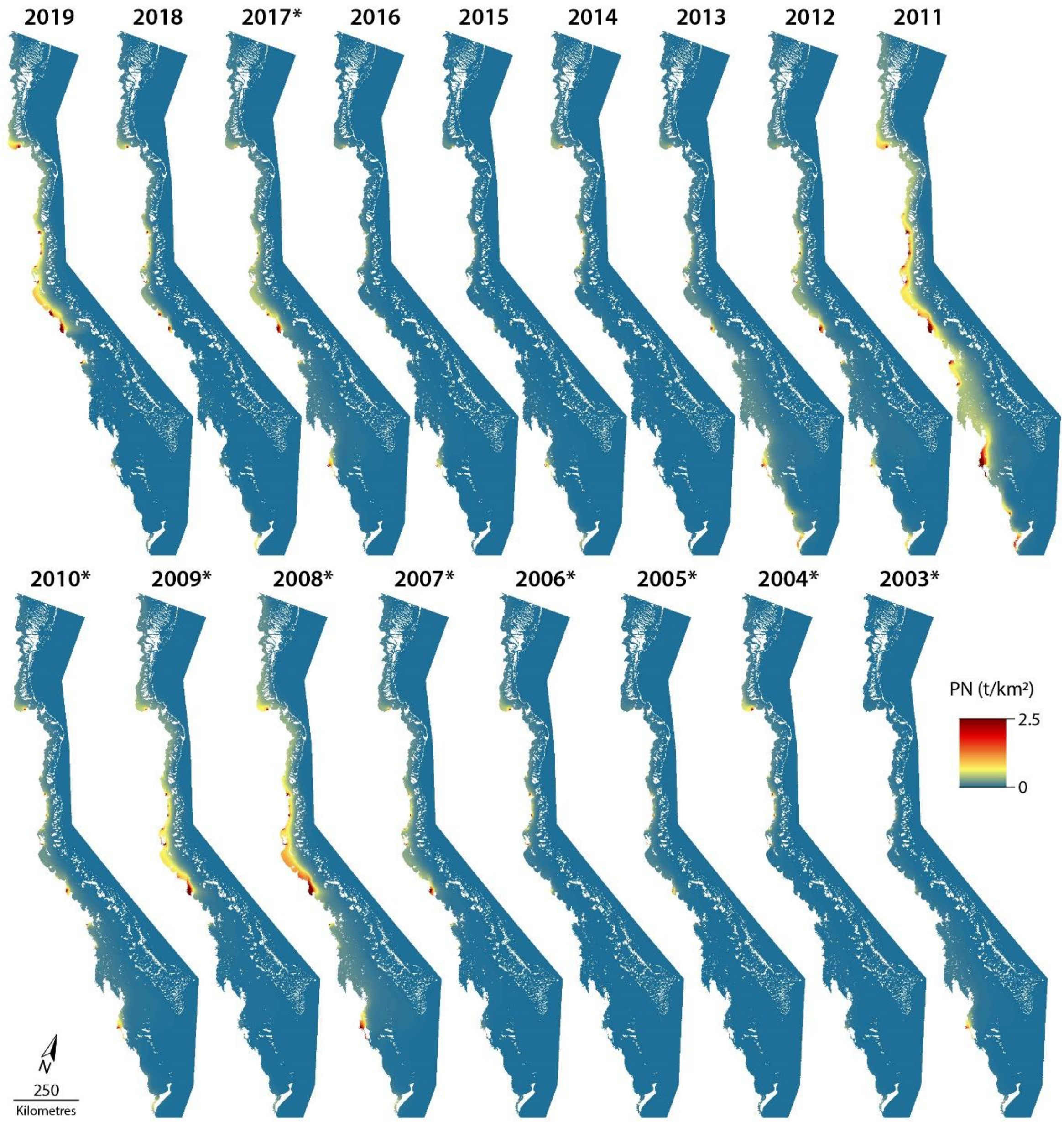

Figure 4-12: River-derived PN loading (tonnes km^{-2}, relative scale) over the Reef lagoon for the 2003 to 2019 water years (1 October to 30 September). The years marked with asterisks are modelled using a multiannual average tracer.

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, and to a lesser extent, Princess Charlotte Bay in Cape York, the Wet Tropics and Fitzroy regions and in some years, the Mary River (e.g. 2010– 2013).

4.2.4 Next steps

As further improvement to the methods for the load dispersal maps, 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).

Issues that still need to be considered to improve on the dose maps as measures of cumulative exposure include:

1) Some of the exposure is independent of river flow (e.g. due to resuspension and marine processes). To address this, a background exposure could be subtracted from the exposure maps. This background exposure could be estimated from typical dry season average conditions, noting that this would not take into account the effects of wind-driven resuspension during storms.

2) River DIN that has been taken up by phytoplankton is still in the water column and affecting conditions. Options:

a) It may be better to use TN rather than DIN, though some proportion of TN will be resuspended sediment N.
b) Alternatively use eReefs simulated DIN + phytoplankton N, which would take into account estimated denitrification and settling losses but would exclude the detrital component.

Next steps could include:

i. Method for producing adjusted/excess dose maps: By taking the mean simulated concentration of nitrogen (or fine sediments) in July-August as an expected “background concentration” and subtracting this from the simulated concentration on each day over the course of a water year, an estimate of the “excess dose” of that constituent at each map location can be obtained. This “excess dose” represents the exposure of each location to nitrogen (or fine sediment) from that year’s river inflows and from other influences specific to the wet season (e.g. enhanced wind mixing associated with wet-season storms).
ii. Separating annual exposure into individual river influence. This would involve separating the cumulative exposure map into rasters of proportional river influence for DIN (or eReefs DIN + phytoplankton N), PN, and fine sediments, using the tracer-derived surface load maps to allocate proportional river influence per pixel. Note that apportioning loads to different rivers based on river exposure is not going to take into account attenuation with distance from the river mouths.

4.3 Cape York region

The three-dimensional cumulative exposure of coastal waters to wet season discharge from several Cape York rivers (Normanby, Annan, and Endeavour) was estimated using a passive tracer in the eReefs hydrodynamic model. This is the first year this method has been applied to the Annan and Endeavour Rivers, and the second year it has been applied to the Normanby River (Gruber et al., 2019), so these results are relatively preliminary with a high level of uncertainty. Results from tracer modelling will show smaller extents of river influence than satellite imagery, as tracer modelling is three-dimensional while satellite imagery observes the surface ocean only.

River gauge data for the Normanby River showed that its 2018–19 discharge was roughly three times greater than its long-term median discharge (Table 3-1). As a result, the three-dimensional extent of Normanby River discharge in 2018–19 was far greater than the 2017–18 wet season. Relatively high exposure to river discharge occurred in enclosed coastal waters of Princess Charlotte Bay during the 2018–19 wet season (Figure 4-13), with exposures exceeding 20 near the Normanby mouth. Open coastal waters of Princess Charlotte Bay had cumulative exposures ~4–10. Mid-shelf and offshore water bodies were also exposed to Normanby River discharge but had exposures <2. Extent of exposure (distance that plumes travel) was high in all directions compared to other rivers modelled. Tracers >1% concentration travelled ~210 km north (to the Lockhart River) and ~130 km east of the Normanby mouth.

River gauge data for the Endeavour River showed that its 2018–19 discharge was roughly three times greater than its long-term median discharge (Table 3-1). Model resolution close to

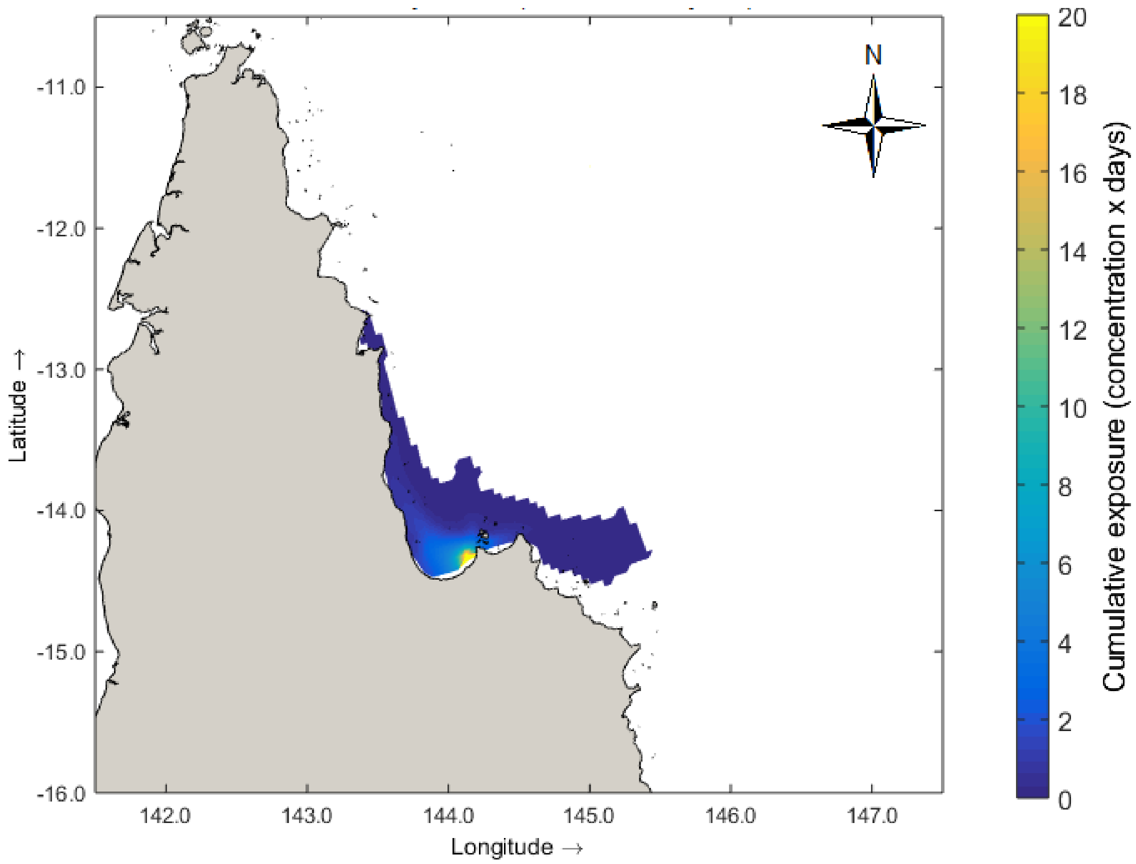

Figure 4-13: Cumulative exposure index for the Normanby River from October 2018 to May 2019. The colour bar indicates the calculated three-dimensional cumulative exposure, defined as the concentration of river water (%) * days of exposure (d). Only concentrations of river water >1% are included in these maps. The colour bar is capped at 20 concentration days.

the coast is not presently sufficient to measure tracer concentrations in enclosed coastal waters near Cooktown; therefore, model results should be interpreted with caution. Relatively low exposure to river discharge occurred in open coastal waters offshore of Cooktown during the 2018–19 wet season (Figure 4-14), with cumulative exposures generally <2. Mid-shelf and offshore water bodies were also exposed to a relatively small amount of river discharge, with exposures <1. Model simulations suggested that the extent of exposure was high south-easterly of the river mouths. Tracers >1% concentration travelled ~100 km southeast (offshore of Cape Tribulation) and ~30km north from the river mouths. These results are preliminary and likely under-represent river exposure in the Cape York region; they would benefit from validation as eReefs simulations in the region continue to improve with available data.

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 4-15 and Figure 4-16) and in Figure 4-17, 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 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. 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 collected by the CYWMP.

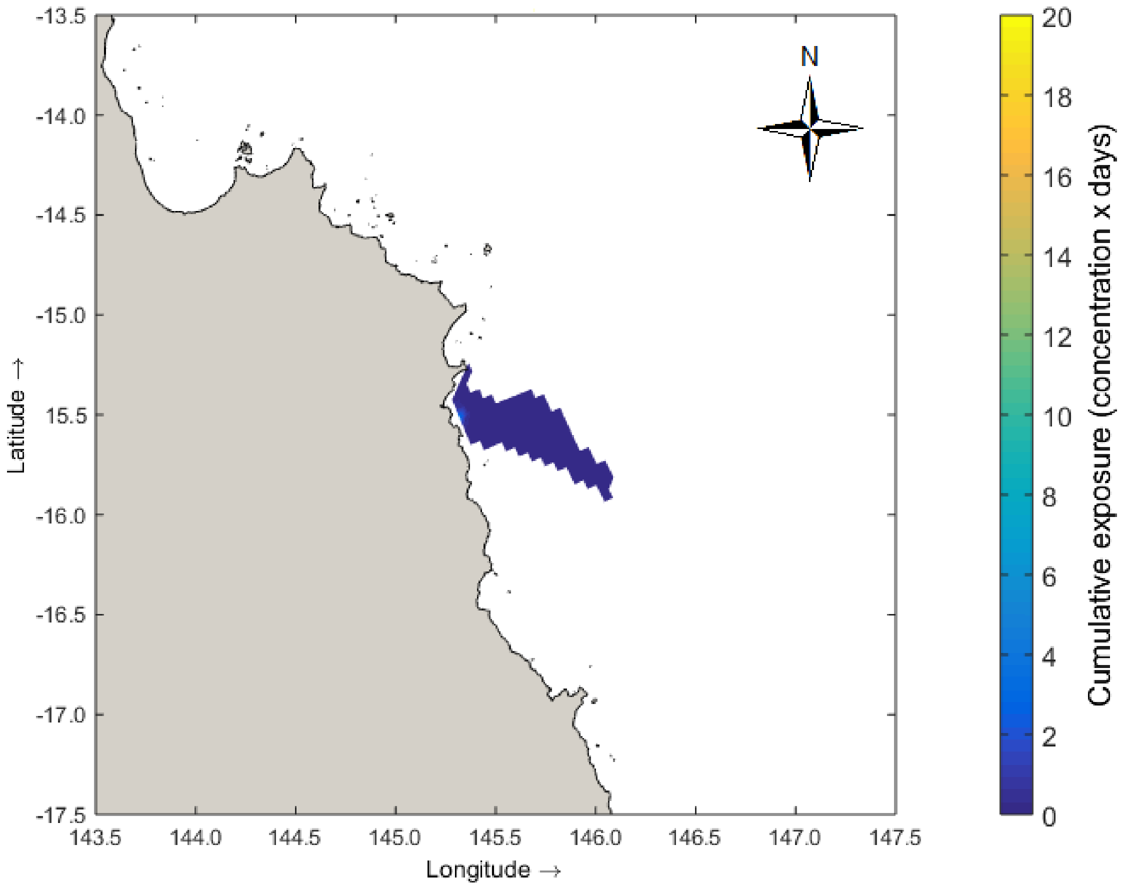

Figure 4-14: Cumulative exposure index for the Annan and Endeavour Rivers from October 2018 to May 2019. The colour bar indicates the calculated three-dimensional cumulative exposure, defined as the concentration of river water (%) * days of exposure (d). Only concentrations of river water >1% are included in these maps. The colour bar is capped at 20 concentration days.

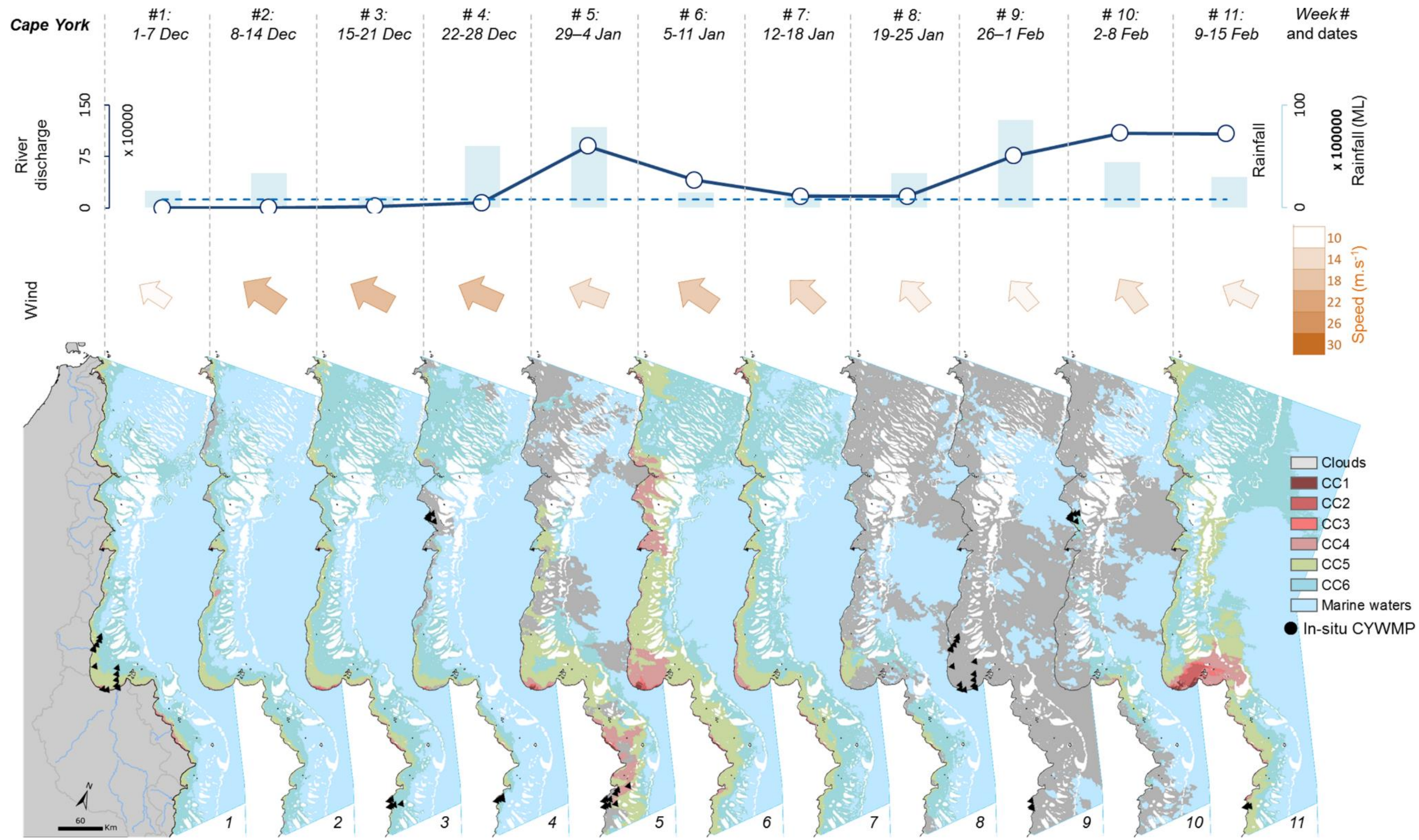

Figure 4-15: Panel of water quality and environmental characteristics in the Cape York region throughout the 2018–19 wet season period: weeks 1 to 11. Includes: 2018-19 weekly river discharge (ML d^{-1}) and rainfall (ML); mean wind speed (m s^{-1}) and direction; and wet season water type maps showing the location of the *in situ* data collected by CYWMP. 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.

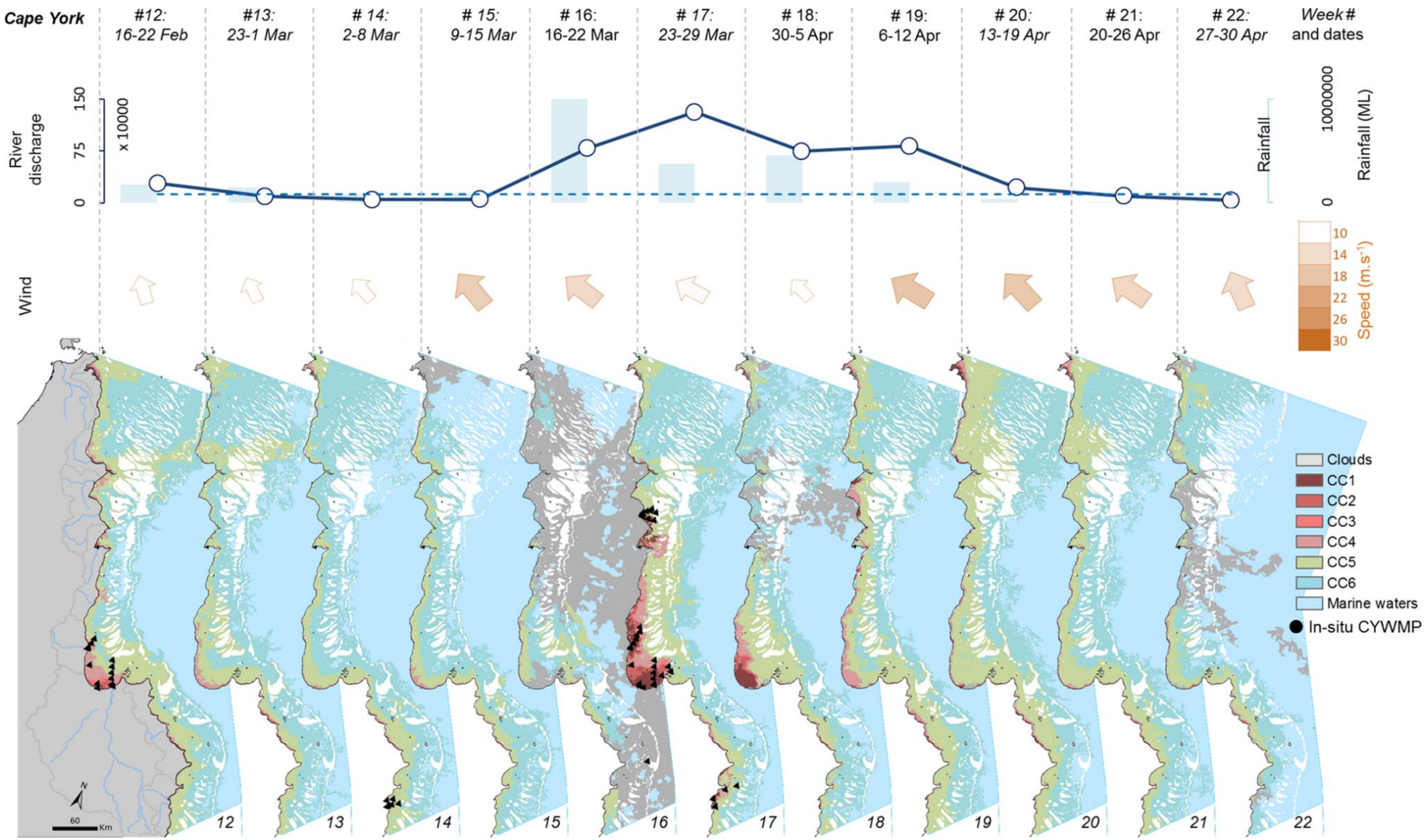

Figure 4-16: Panel of water quality and environmental characteristics in the Cape York region throughout the 2018–19 wet season period: weeks 12 to 22. Includes: 2018-19 weekly river discharge (ML d^{-1}) and rainfall (ML); mean wind speed (m s^{-1}) and direction; and wet season water type maps showing the location of the *in situ* data collected by CYWMP. 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.

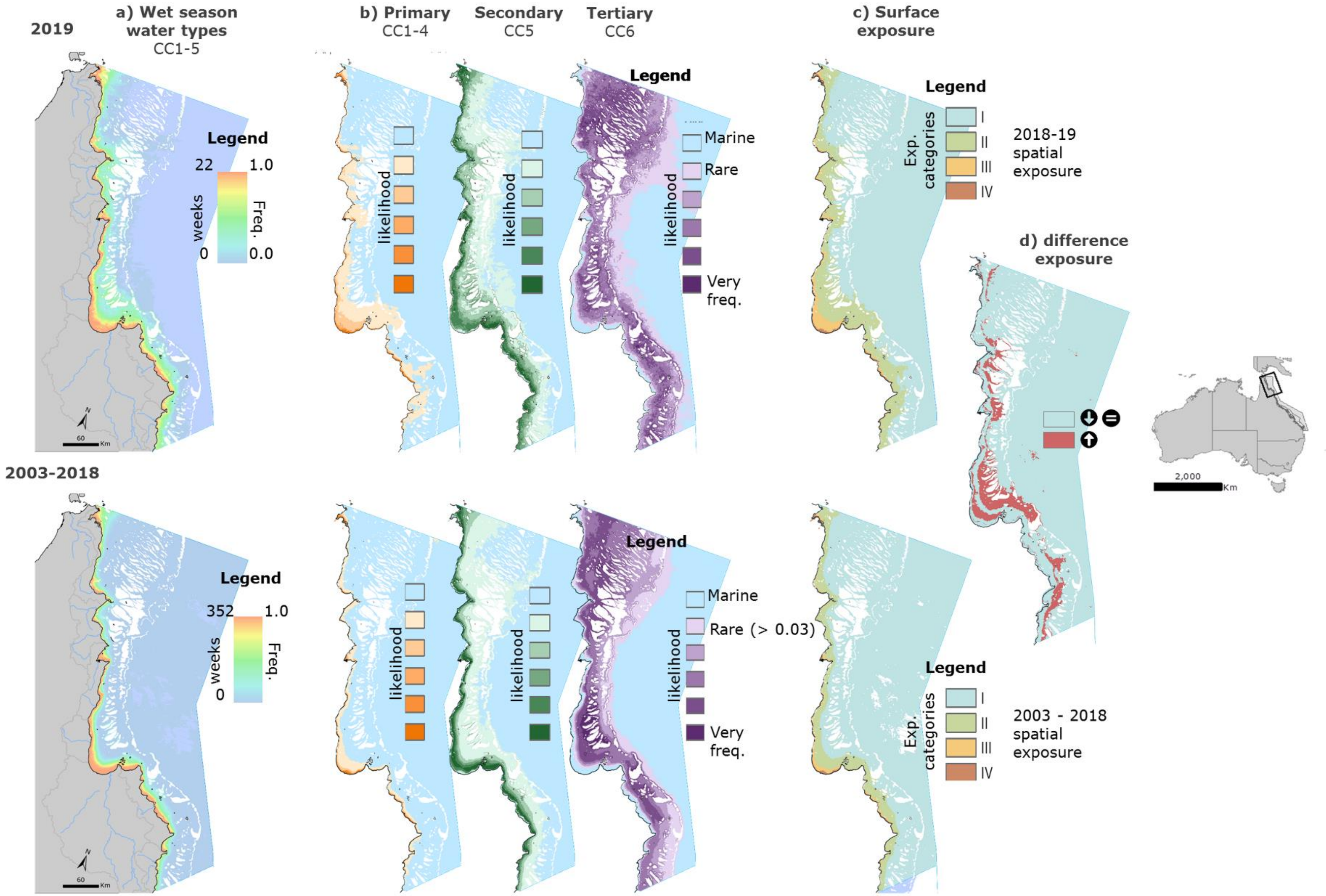

Figure 4-17: Long-term and current year remote sensing results for the Cape York region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), 0.2–0.4, 0.4–0.6, 0.6–0.8 and 0.8–1 (very frequent)]; c) exposure in the long-term (bottom) and 2018–19 wet season (top); and d) a difference map showing areas with an increase in risk category in 2019 (in red, ⬆) against long-term trends [calculated as (c, top) exposure in 2019 minus (c, bottom) 2003–2018].

The MODIS 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 4-15 and Figure 4-16). Discharge in the Cape York region was 2–3 times the long term median (Section 3.2.2) and three major flood events influenced Cape York during the 2018–19 wet season. Major flood events were associated with (i) cyclone Penny in late December 2018–early January 2019, (ii) extensive sustained rainfall in late January–early February 2019 and (iii) cyclone Trevor in mid- to late-March 2019. Multiple large flood plumes were captured with MODIS satellite imagery.

Weekly composites of the Cape York region showed that primary waters were confined next to the Cape York estuary mouths during weeks 1 to 4. Primary waters extended further offshore after cyclone Penny and major flood plumes were observed off the Annan and Endeavour rivers in southeast Cape York between 29 December and 4 January (week 5) as well as off the Normanby River and Pascoe rivers between 5–11 January (weeks 6). Another large flood plume was mapped off the Normanby River following the late January–early February peak discharge. During this event (week 11: 9–15 February), primary plume waters from the Normanby River flowed east, pushed by westerly winds, and inundated reefs in the open coastal, mid-shelf and offshore water bodies (e.g., Warden, Tuydeman, Wilson and south of Corbett reefs). Large flood plumes were also observed off the Annan, Endeavour, Normanby and Pascoe rivers following large rainfall associated with Severe Tropical Cyclone Trevor (week 17 and 18: 23 March–5 April). Sampling of the Cape York flood plumes occurred after the main flood events and across all colour classes (1 to 6). A full description of water quality patterns and flood plumes is available in Section 5.1 of this report.

Figure 4-17 (top) presents: frequency of combined primary and secondary water types; the frequency of primary, secondary, and tertiary water types individually; the Cape York exposure map in the long-term and during the 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. Table 4-3 presents the areas (km^2) 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 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 2018–19, it was estimated that:

- 21% of the Cape York region was exposed to combined potential risk categories II–IV. However, only 1% of the region was in the highest exposure category (IV) and only 2% was in category III.
- 37% of coral reefs in the Cape York region were exposed to combined potential risk categories II–IV. However, less than 1% of corals were in the highest exposure category (IV) and in category III.
- 88% of seagrasses in the Cape York region were exposed to combined potential risk categories II–IV. 9% of seagrasses were in the highest exposure category (IV) and 17% were in category III.
- The coral and seagrass areas in the Cape York region exposed to combined potential risk categories II–IV in 2018–19 were greater than the average long-term areas by +32% and +18%, respectively. These results were logical with the relatively high discharge in Cape York.

Table 4-3: Areas (km^2) and percentages (%) of the Cape York region, coral reefs, and surveyed seagrass affected by different categories of exposure during the 2018–19 wet season and the long-term (2003–2018). The last three rows show the differences between % affected in 2018–19 and the long-term average (: increase, : decrease, : no change, difference <1%). 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	2019	76,493	16,980	2,249	*595*	*19,824*
			LT	86,044	8,649	1,125	498	10,272
	%	*100%*	2019	79%	18%	2%	1%	21%
			LT	89%	9%	1%	1%	11%
Coral reefs	area	10,375	2019	6,554	3,745	61	*15*	*3,821*
			LT	9,837	496	34	8	538
	%	*100%*	2019	63%	36%	1%	<1%	37%
			LT	95%	5%	<1%	<1%	5%
Surveyed seagrass	area	2,655	2019	310	1,675	440	*231*	*2,346*
			LT	777	1,371	319	189	1,878
	%	*100%*	2019	12%	63%	17%	9%	88%
			LT	29%	52%	12%	7%	71%
Difference (2019 – Long Term average)	*Surface area*			-10%	9%	1%	<1%	10%
	Coral Reef			-32%	31%	<1%	<1%	32%
	Surveyed seagrass			-18%	11%	5%	2%	17%

4.4 Wet Tropics region

The three-dimensional cumulative exposure of coastal waters to wet season discharge from several Wet Tropics rivers (Barron, Russell-Mulgrave, and Tully) was estimated using a passive tracer in the eReefs hydrodynamic model. Results from tracer modelling will show smaller extents of river influence than satellite imagery, as tracer modelling is three-dimensional while satellite imagery observes the surface ocean only.

River gauge data for the Barron River showed that its 2018–19 discharge was roughly three times greater than its long-term median discharge (Table 3-1). As a result, the three-dimensional extent of Barron River discharge in 2018–19 was greater than the 2017–18 wet season. Moderate exposure to river discharge occurred in enclosed and open coastal waters offshore of Cairns during the 2018–19 wet season (Figure 4-18), with exposures ~10 near the Barron mouth. Open coastal, mid-shelf, and offshore water bodies near Cairns were also exposed to Barron River discharge but had exposures ~1. Extent of exposure was high in all directions. Tracers >1% concentration travelled ~100 km north (to Cape Tribulation), which is the typical direction of transport. Periods of high discharge in January and February 2019 corresponded with offshore winds, which affected coastal circulation patterns causing river discharge to be transported ~80 km southeast into offshore waters, although at very low concentrations.

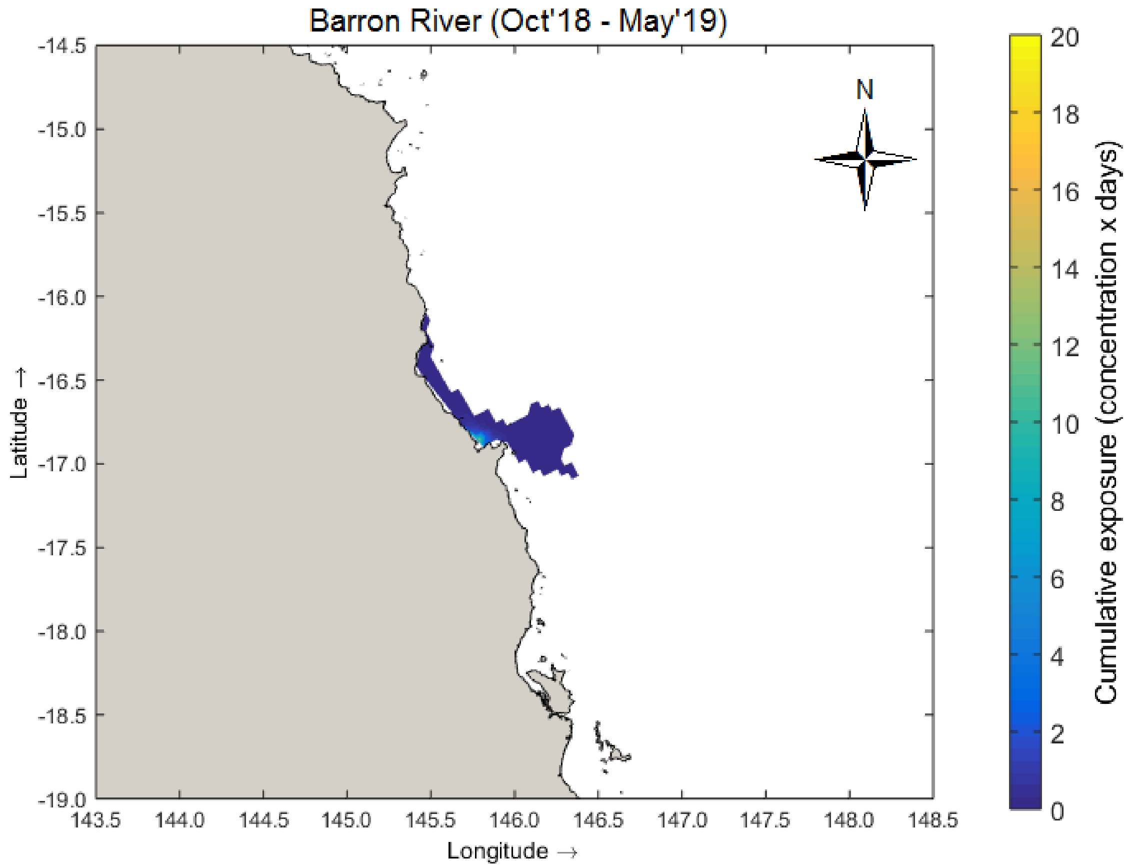

Figure 4-18: Cumulative exposure index for the Barron River from October 2018 to May 2019. The colour bar indicates the calculated three-dimensional cumulative exposure, defined as the concentration of river water (%) * days of exposure (d). Only concentrations of river water >1% are included in these maps. The colour bar is capped at 20 concentration days.

River gauge data for the Russell-Mulgrave River showed that its 2018–19 discharge was slightly elevated above (~30%) but similar to its long-term median discharge (Table 3-1). As a result, the three-dimensional extent of Russell-Mulgrave River discharge in 2018–19 was similar to the 2017–18 wet season (Figure 4-19). Moderate exposure to river discharge occurred in enclosed coastal waters near the river mouth, where exposures were ~16. Open coastal waters near the Russell-Mulgrave (e.g., High Island) had moderate exposures ~4–10 during the 2018–19 wet season. Open coastal and mid-shelf water bodies from the Daintree River mouth to offshore of South Mission Beach were also exposed to Russell-Mulgrave River discharge but had exposures ~1. Extent of exposure was similar to 2017–18, but discharge travelled much further to the southeast. Tracers >1% concentration travelled ~120 km north (near Cape Tribulation), which is the typical direction of transport. Periods of high discharge in January and February 2019 corresponded with offshore winds, which affected coastal circulation patterns causing river discharge to be transported ~100 km southeast to mid-shelf reefs offshore of South Mission Beach.

River gauge data for the Tully River showed that its 2018–19 discharge was slightly elevated above (~25%) but similar to its long-term median discharge (Table 3-1). As a result, the three-dimensional extent of Tully River discharge in 2018–19 was similar to the 2017–18 wet season (Figure 4-20). High exposure to river discharge occurred in enclosed coastal waters near the river mouth, where exposures were ~20. Open coastal waters near the Tully (e.g., Dunk and Bedarra Islands) had moderate exposures ~4–12 during the 2018–19 wet season. Open coastal and mid-shelf water bodies from Fitzroy Island (south of Cairns) to northern Hinchinbrook Island were also exposed to Tully River discharge but had exposures ~1.

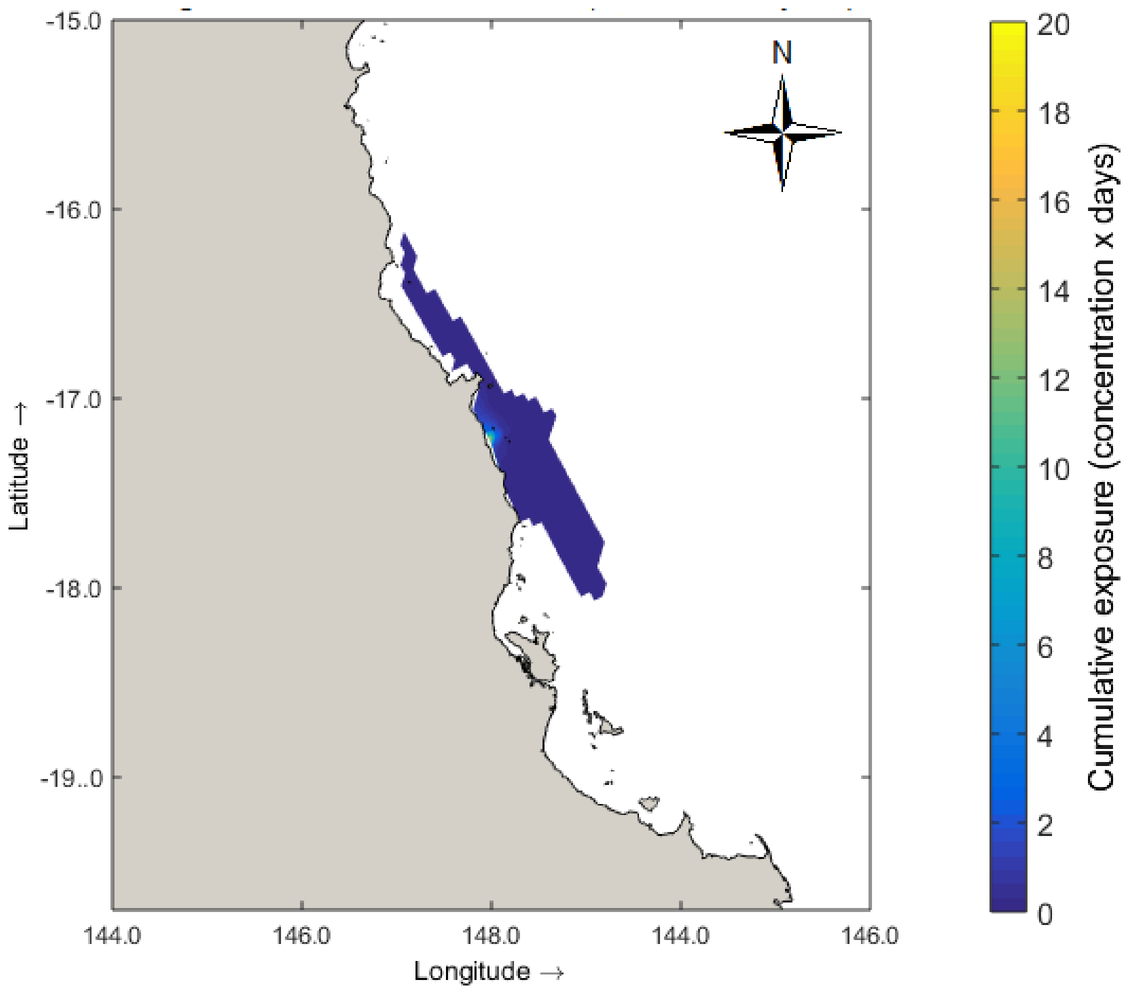

Figure 4-19: Cumulative exposure index for the Russell-Mulgrave River from October 2018 to May 2019. The colour bar indicates the calculated three-dimensional cumulative exposure, defined as the concentration of river water (%) * days of exposure (d). Only concentrations of river water >1% are included in these maps. The colour bar is capped at 20 concentration days.

Extent of exposure was similar to 2017–18. Tracers >1% concentration travelled ~120 km north (near Fitzroy Island), which is the typical direction of transport. Periods of high discharge in January and February 2019 corresponded with offshore winds, which affected coastal circulation patterns causing river discharge to be transported ~35 km southeast to the northern side of Hinchinbrook Island.

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 4-21 and Figure 4-22) and in Figure 4-23, 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 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. 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.

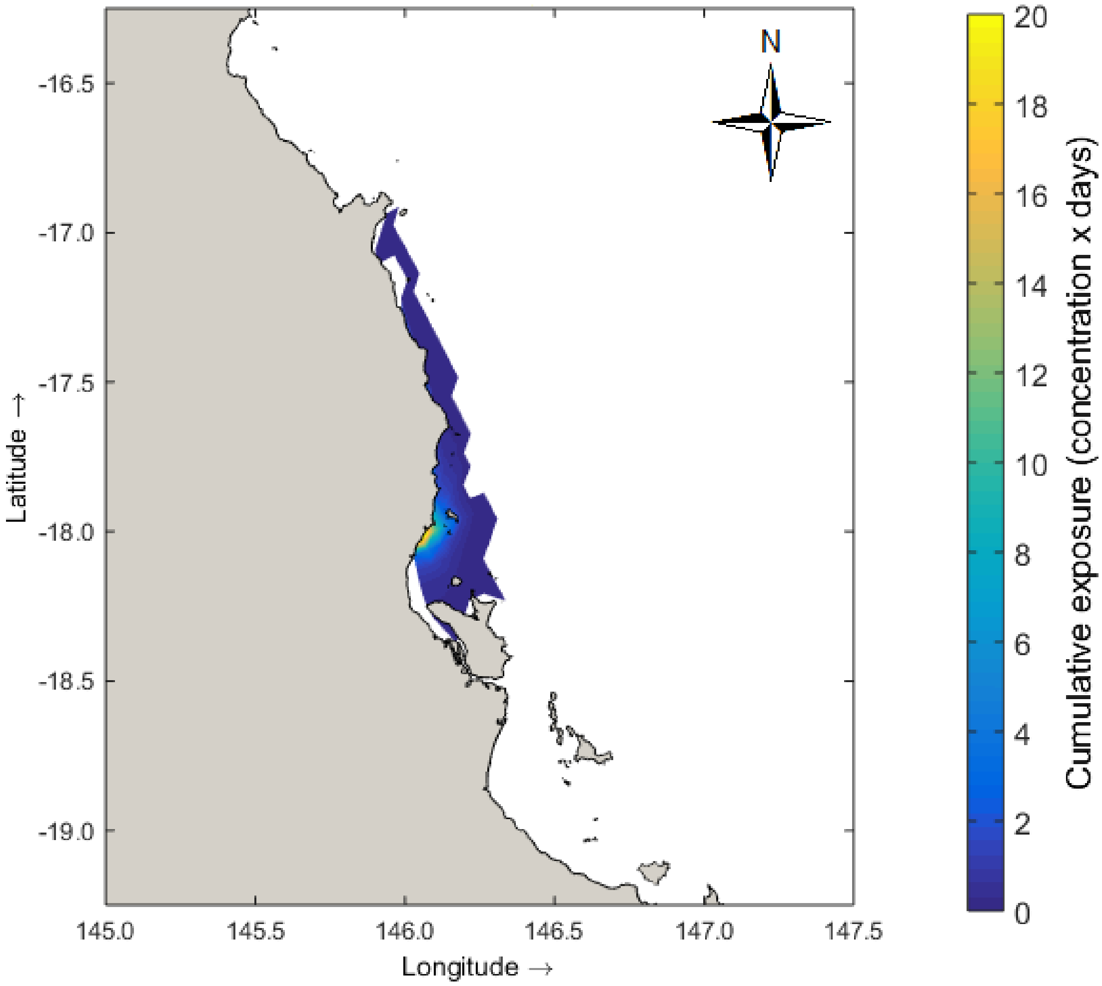

Figure 4-20: Cumulative exposure index for the Tully River from October 2018 to May 2019. The colour bar indicates the calculated three-dimensional cumulative exposure, defined as the concentration of river water (%) * days of exposure (d). Only concentrations of river water >1% are included in these maps. The colour bar is capped at 20 concentration days.

The MODIS monitoring products (when not obstructed by cloud cover) 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 4-21 and Figure 4-22). Discharge in the Wet Tropics region was slightly above the long term median (Section 3.2.2) and two major flood events influenced the Wet Tropics during the 2018–19 wet season. Major flood events were associated with (i) cyclone Penny in late December 2018–early January 2019 and (ii) extensive sustained rainfall in late January–early February 2019. Multiple large flood plumes were captured with MODIS satellite imagery.

Weekly composites of the Wet Tropics region showed that primary waters were confined next to the Wet Tropics estuary mouths during weeks 1 to 2. Primary waters extended further offshore from mid-December and large flood plumes were observed off the Tully and Herbert rivers from 15–21 December 2018 (week 3) and off the Herbert River from 29 December–4 January (week 5).

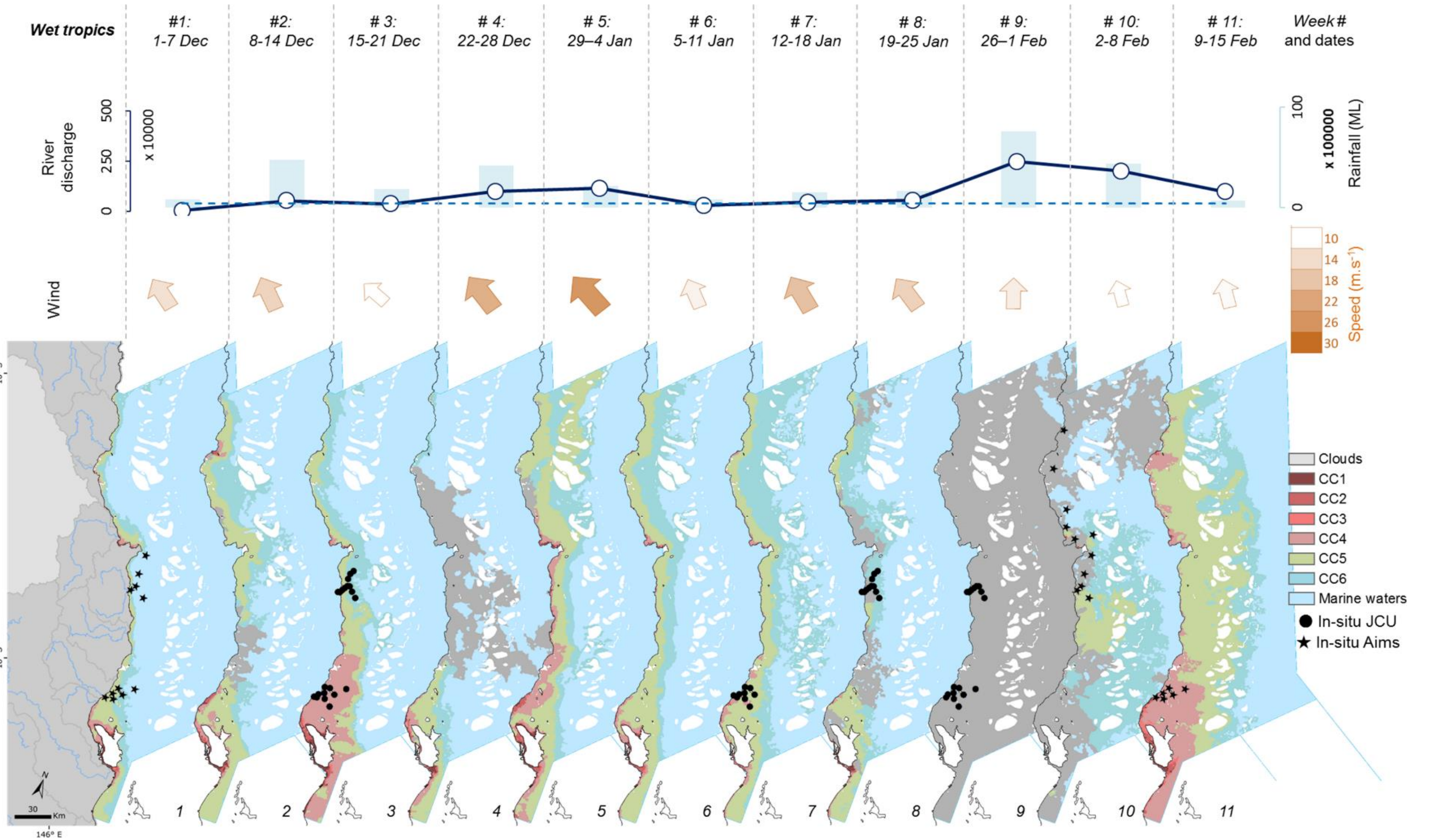

Figure 4-21: Panel of water quality and environmental characteristics in the Wet Tropics region throughout the 2018–19 wet season period: weeks 1 to 11. Includes: 2018–19 weekly river discharge (ML d^{-1}) and rainfall (ML); mean wind speed (m s^{-1}) and direction; and wet season water type maps showing the location of the *in situ* data collected by JCU and AIMS. 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.

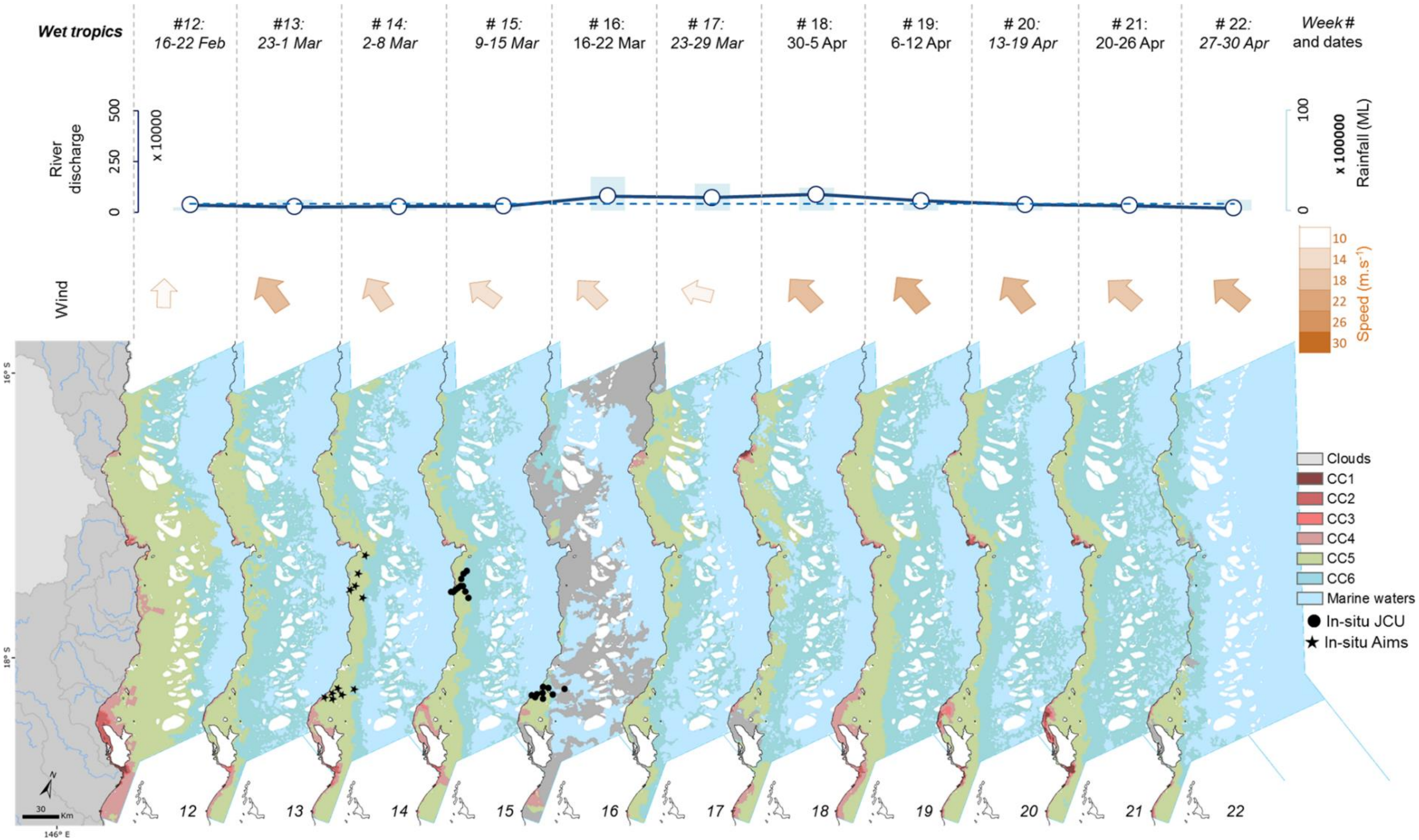

Figure 4-22: Panel of water quality and environmental characteristics in the Wet Tropics region throughout the 2018–19 wet season period: weeks 12 to 22. Includes: 2018–19 weekly river discharge (ML d-1) and rainfall (ML); mean wind speed (m s-1) and direction; and wet season water type maps showing the location of the *in situ* data collected by JCU and AIMS. 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.

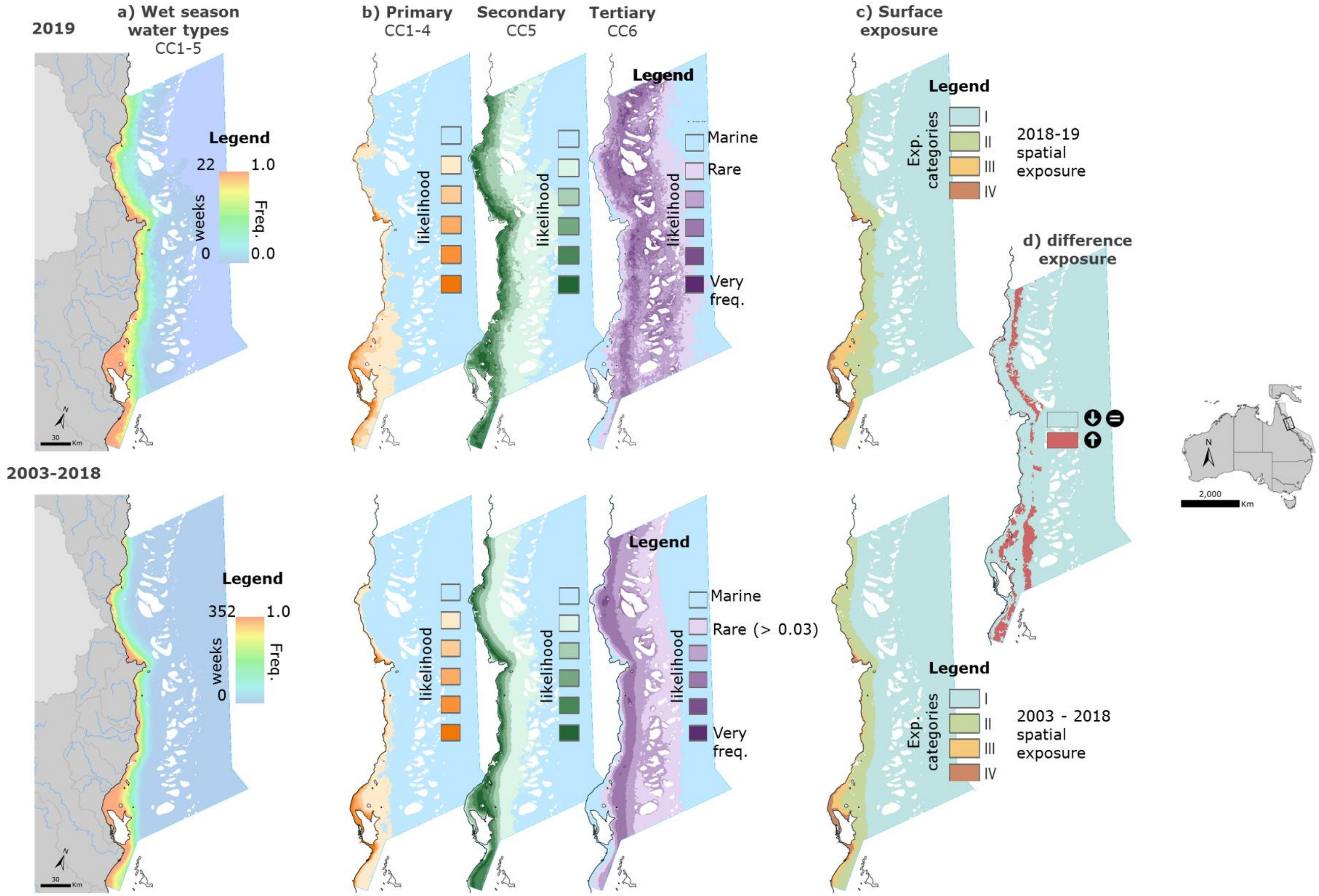

Figure 4-23: Long-term and current year remote sensing results for the Wet Tropics region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), 0.2–0.4, 0.4–0.6, 0.6–0.8 and 0.8–1 (very frequent)]; c) exposure in the long-term (bottom) and 2018–19 wet season (top); and d) a difference map showing areas with an increase in risk category in 2019 (in red, ⬆) against long-term trends [calculated as (c, top) exposure in 2019 minus (c, bottom) 2003–2018].

Another large flood plume was mapped off the Tully and Herbert Rivers following the late January–early February peak discharge (week 11 and 12: 9–22 February). Mid-shelf and offshore Wet Tropics reefs were exposed to secondary and tertiary waters during both weeks (11 and 12). A smaller flood event occurred following cyclone Trevor, but flood plumes from the Tully and Herbert Rivers were less developed (week 16–18: 16 March–5 April).

Sampling of the Wet Tropics flood plumes occurred after the main flood events and across all colour classes (CC1 and CC3-6), except colour class 2. A full description of water quality patterns and flood plumes is available in Section 5.2 of this report.

Figure 4-23 (top) presents: the frequency of combined primary and secondary water types; the frequency of primary, secondary and tertiary water types individually; the Wet Tropics exposure map in the long-term and during the 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. Table 4-4 presents the areas (km^2) 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 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.

Table 4-4: Areas (km^2) and percentages (%) of the Wet Tropics region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2018–19 wet season and the long-term (2003–2018). The last three rows show the differences between % affected in 2018–19 and the long-term average (red: increase, blue: decrease, green: no change, difference <1%). 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**	**IV**	
Surface area	area	31,976	2019	25,657	4,528	1,362	*429*	6,318
			LT	26,928	3,919	710	419	5,048
	%	*100%*	2019	80%	14%	4%	1%	20%
			LT	84%	12%	2%	1%	16%
Coral reefs	area	2,425	2019	2,338	57	28	*3*	87
			LT	2,380	34	10	2	46
	%	*100%*	2019	96%	2%	1%	<1%	4%
			LT	98%	1%	<1%	<1%	2%
Surveyed seagrass	area	232	2019	10	12	131	*79*	222
			LT	14	40	79	99	219
	%	*100%*	2019	4%	5%	56%	34%	96%
			LT	6%	17%	34%	43%	94%
Difference (2019 – Long term average)	*Surface area*			-4%	2%	2%	<1%	4%
	Coral Reef			-2%	1%	1%	<1%	2%
	Surveyed seagrass			-2%	-12%	22%	-9%	2%

In 2018–19, it was estimated that:

- 20% of the Wet Tropics region was exposed to combined potential risk categories II–IV. However, only 1% of the region was in the highest exposure category (IV) and only 4% was in category III.
- 4% of coral reefs in the Wet Tropics region were exposed to combined potential risk categories II–IV. However, less than 1% of coral were in the highest exposure category (IV) and only 1% of corals were in category III.
- 96% of seagrasses in the Wet Tropics region were exposed to combined potential risk categories II–IV. 34% of seagrasses were in the highest exposure category (IV) and 56% were in category III.
- The coral and seagrass areas in the Wet Tropics region exposed to combined potential risk categories II–IV in 2018-19 were both greater than the average long-term areas by +2%. These characteristics were logical given the Wet Tropics wet season discharge was similar to the long-term median.

4.5 Burdekin region

The three-dimensional cumulative exposure of coastal waters to wet season discharge from the Burdekin River was estimated using a passive tracer in the eReefs hydrodynamic model. Tracer modelling will show smaller extents of river influence than satellite imagery, as tracer modelling is three-dimensional while satellite imagery observes the surface ocean only.

River gauge data for the Burdekin River showed that its 2018–19 discharge was roughly four times greater than its long-term median discharge (Table 3-1). As a result, the three-dimensional extent of Burdekin River discharge in 2018–19 was greater than the 2017–18 wet season (Figure 4-24). High exposure to river discharge occurred in enclosed coastal waters of Upstart Bay, especially near the Burdekin mouth where exposures were >20. Open coastal and mid-shelf waters from Cape Upstart to Cape Cleveland had moderate exposures ~2–12. Open coastal and mid-shelf waters in the broader region were also exposed to Burdekin River discharge but had exposures ~1. Extent of exposure was high in all directions. Tracers >1% concentration travelled ~200 km northwest (to Hinchinbrook Island), which is the typical direction of transport. Periods of high discharge in January and February 2019 corresponded with offshore winds, which affected coastal circulation patterns causing river discharge to be transported ~80 km east into mid-shelf (and a small amount of offshore) waters.

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 4-25 and Figure 4-26) and in Figure 4-27, 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 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. 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 MODIS monitoring products (when not obstructed by cloud cover as in weeks 9 and 10) 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 4-25 and Figure 4-26). The remnants of cyclones Owen and Penny and an intense tropical low coupled with a very active and stationary monsoonal trough resulted in heavy rainfall occurring across the Burdekin region during periods from late December to mid-February 2019. Discharge in the Burdekin region was four times the long term median (Section 3.2.2) and multiple large flood plumes were captured with MODIS satellite imagery during the wet season, including plumes off the Burdekin, Haughton, Black, and Ross rivers.

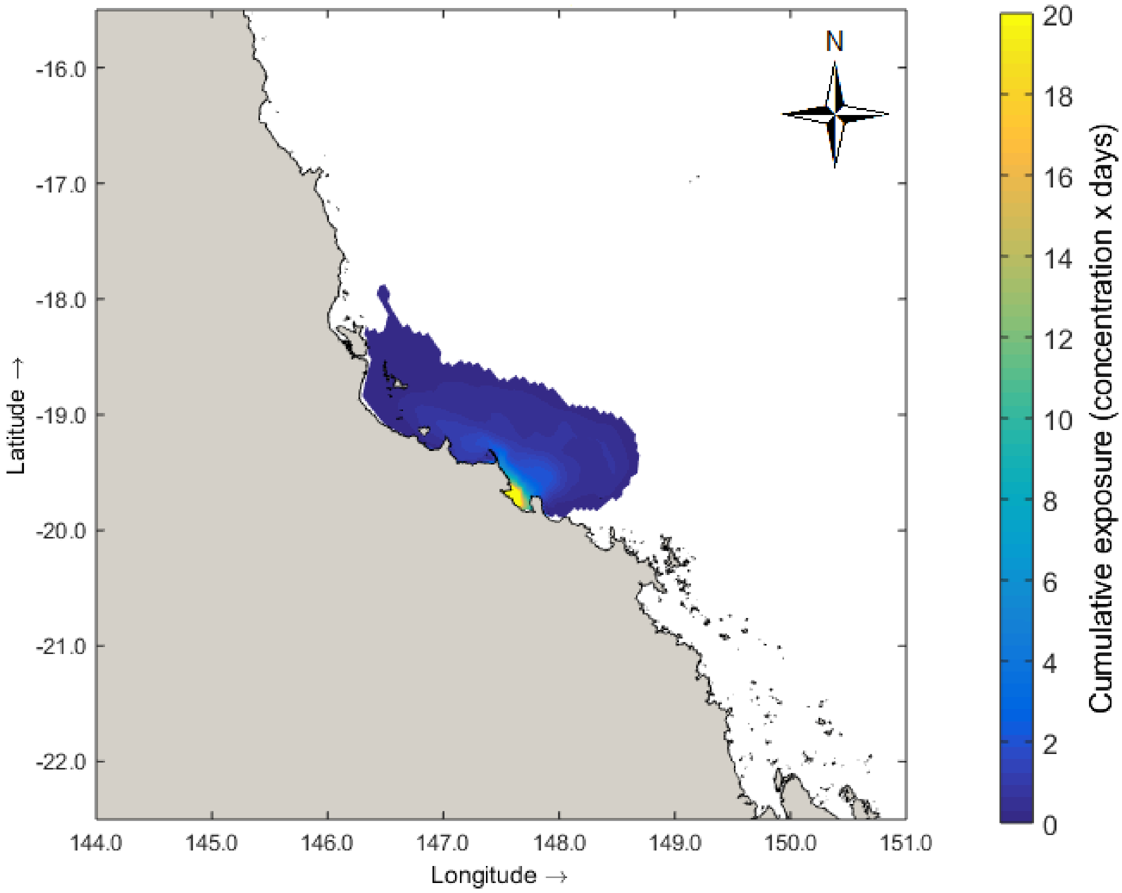

Figure 4-24: Cumulative exposure index for the Burdekin River from October 2018 to May 2019. The colour bar indicates the calculated three-dimensional cumulative exposure, defined as the concentration of river water (%) * days of exposure (d). Only concentrations of river water >1% are included in these maps. The colour bar is capped at 20 concentration days.

The Burdekin River peaked in the week of 2–8 of February (week 10) and the weekly composite for this week captured the primary waters of the Burdekin plume moving offshore and reaching mid-shelf at Old Reef. This was an unusual event, as Burdekin plumes typically move northwards along the coast, and can be attributed to a combination of heavy flow and offshore winds from 11–13 Feb 2019. Sediment settled (primary areas reduced in size) from 23 March (week 13) but secondary and tertiary waters stayed well-developed and impinged upon the open coastal and mid-shelf areas of the Burdekin until the end of the wet season.

Sampling of the Burdekin and Ross River flood plumes targeted plume waters along the MMP-defined 'event' sites on weeks 11, 12, 14, and 15 (9 February–15 March). Water samples were collected across all colour classes (1 to 6). Other rounds of sampling were undertaken on weeks 2, 6, 8, and on the last week of the wet season. A full description of water quality patterns and flood plumes is available in Section 5.3 of this report.

Figure 4-27 (top) presents: the frequency of combined primary and secondary water types; the frequency of primary, secondary and tertiary water types individually; the Burdekin exposure map in the long-term and during the 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. 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.

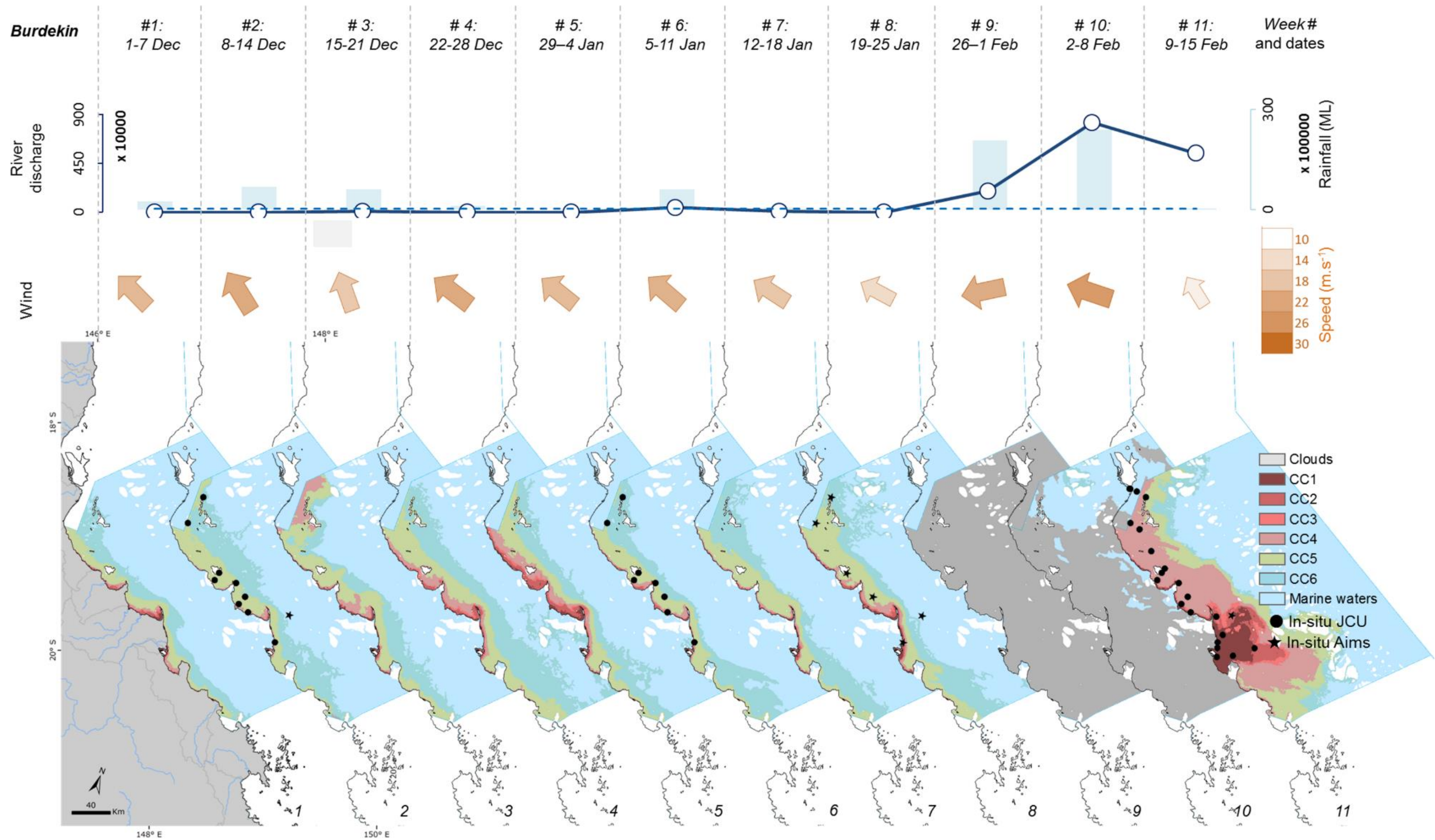

Figure 4-25: Panel of water quality and environmental characteristics in the Burdekin region throughout the 2018–18 wet season period: weeks 1 to 11. Includes: 2018–19 weekly river discharge (ML d^{-1}) and rainfall (ML); mean wind speed (m s^{-1}) and direction; and wet season water type maps showing the location of the *in situ* data collected by JCU and AIMS. 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.

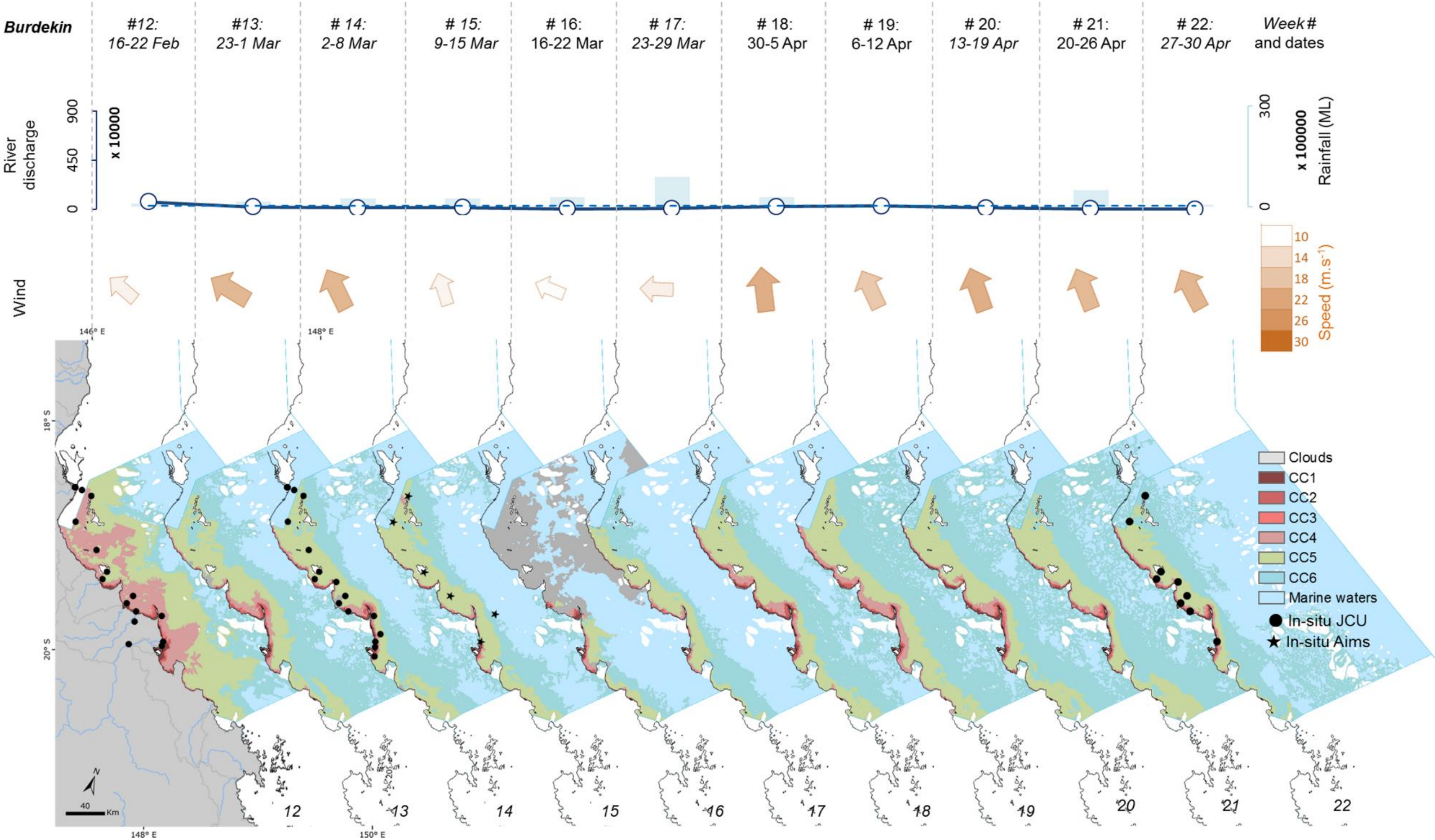

Figure 4-26: Panel of water quality and environmental characteristics in the Burdekin region throughout the 2018–18 wet season period: weeks 12 to 22. Includes: 2018–19 weekly river discharge (ML d^{-1}) and rainfall (ML); mean wind speed (m s^{-1}) and direction; and wet season water type maps showing the location of the *in situ* data collected by JCU and AIMS. 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.

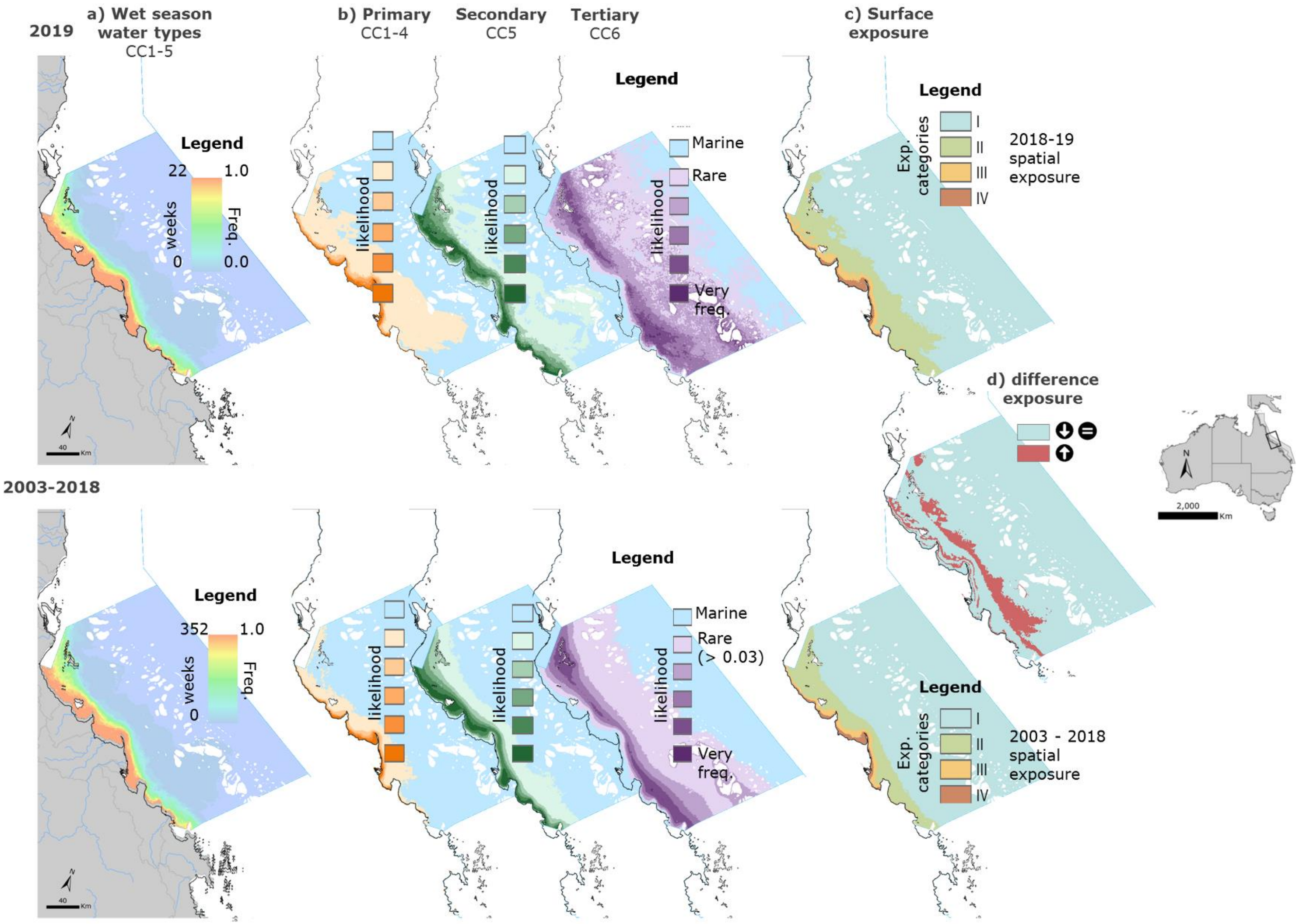

Figure 4-27: Long-term and current year remote sensing results for the Burdekin region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), 0.2–0.4, 0.4–0.6, 0.6–0.8 and 0.8–1 (very frequent)]; c) exposure in the long-term (bottom) and 2018–19 wet season (top); and d) a difference map showing areas with an increase in risk category in 2019 (in red, ⬆) against long-term trends [calculated as (c, top) exposure in 2019 minus (c, bottom) 2003–2018].

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 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 2018–19, it was estimated that:

- 21% of the Burdekin region was exposed to combined potential risk categories II–IV. However, only 2% of the region was in the highest exposure category (IV) and 3% was in category III.
- 5% 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 category (IV) and in category III.
- 98% of seagrasses in the Burdekin region were exposed to combined potential risk categories II–IV. 25% of seagrasses were in the highest exposure category (IV) and 32% were in category III.
- The coral and seagrass areas in the Burdekin region exposed to combined potential risk categories II–IV in 2018-19 were both greater than the average long-term areas by +3%. These results were logical with the high discharge in the Burdekin region.

Table 4-5: Areas (km^2) and percentages (%) of the Burdekin region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2018–19 wet season and the long-term (2003–2018). The last three rows show the differences between % affected in 2019 and the long-term average (: increase, : decrease, : no change, difference <1%). 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	IV	
Surface area	area	47,009	2019	37,327	7,527	1,345	*811*	9,682
			LT	40,627	4,867	914	602	6,382
	%	*100%*	2019	79%	16%	3%	2%	21%
			LT	86%	10%	2%	1%	14%
Coral reefs	area	2,966	2019	2,834	117	13	*2*	132
			LT	2,916	36	13	1	50
	%	*100%*	2019	96%	4%	<1%	<1%	5%
			LT	98%	1%	<1%	<1%	2%
Surveyed seagrass	area	708	2019	14	295	226	*173*	695
			LT	32	346	184	146	676
	%	*100%*	2019	2%	42%	32%	25%	98%
			LT	5%	49%	26%	21%	95%
Difference (2019 – Long Term average)	*Surface area*			-7%	6%	1%	1%	7%
	Coral Reef			-2%	3%	<1%	<1%	3%
	Surveyed seagrass			-3%	-7%	6%	4%	3%

4.6 Mackay-Whitsunday region

The three-dimensional cumulative exposure of coastal waters to wet season discharge from the O'Connell River was estimated using a passive tracer in the eReefs hydrodynamic model. Results from tracer modelling will show smaller extents of river influence than satellite imagery, as tracer modelling is three-dimensional while satellite imagery observes the surface ocean only.

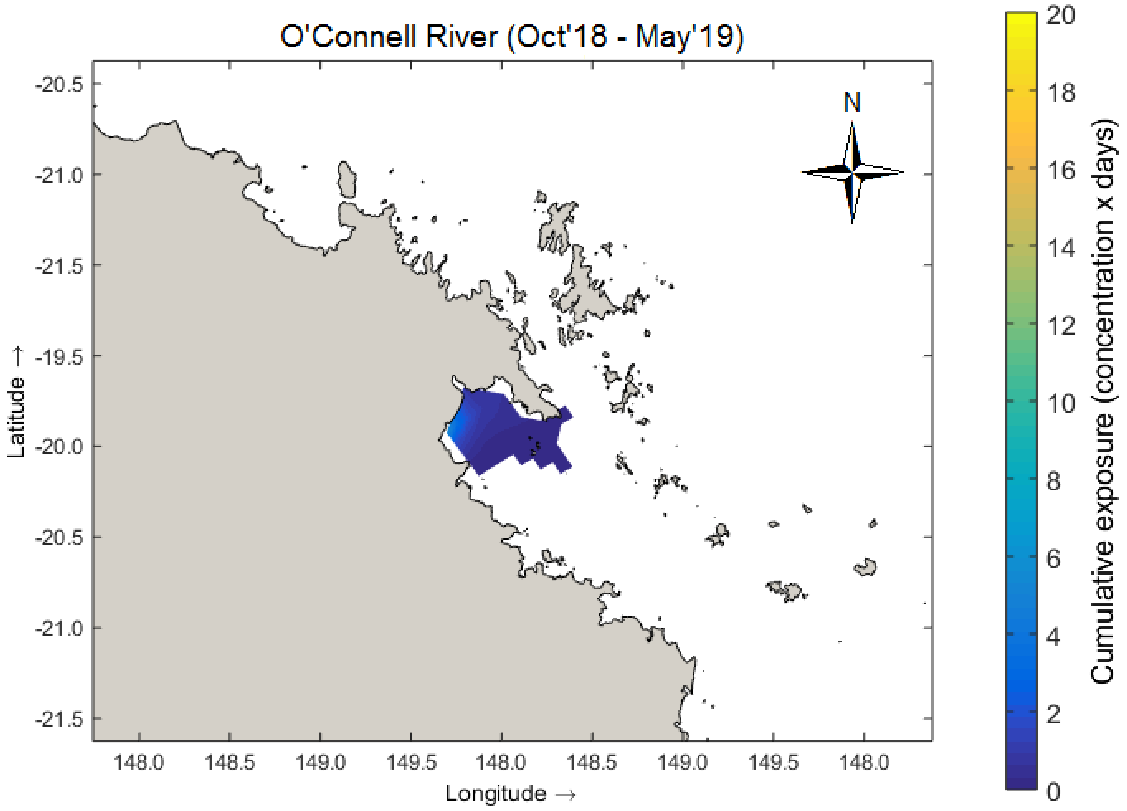

Figure 4-28: Cumulative exposure index for the O'Connell River from October 2018 to May 2019. The colour bar indicates the calculated three-dimensional cumulative exposure, defined as the concentration of river water (%) * days of exposure (d). Only concentrations of river water >1% are included in these maps. The colour bar is capped at 20 concentration days.

River gauge data for the O'Connell River showed that its 2018–19 discharge was roughly 2.5 times greater than its long-term median discharge (Table 3-1). Moderate exposure to river discharge occurred in enclosed coastal waters of Repulse Bay, especially near the O'Connell mouth where exposures were ~4–6 (Figure 4-28). Open coastal waters near Repulse Bay had low exposures ~1. Mid-shelf waters were not affected by O'Connell River discharge. Extent of exposure was relatively low compared to other modelled rivers. Tracers >1% concentration travelled ~30 km east (to Cape Conway), which is the typical direction of transport.

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 4-29 and Figure 4-30) and in Figure 4-31, 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 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. 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.

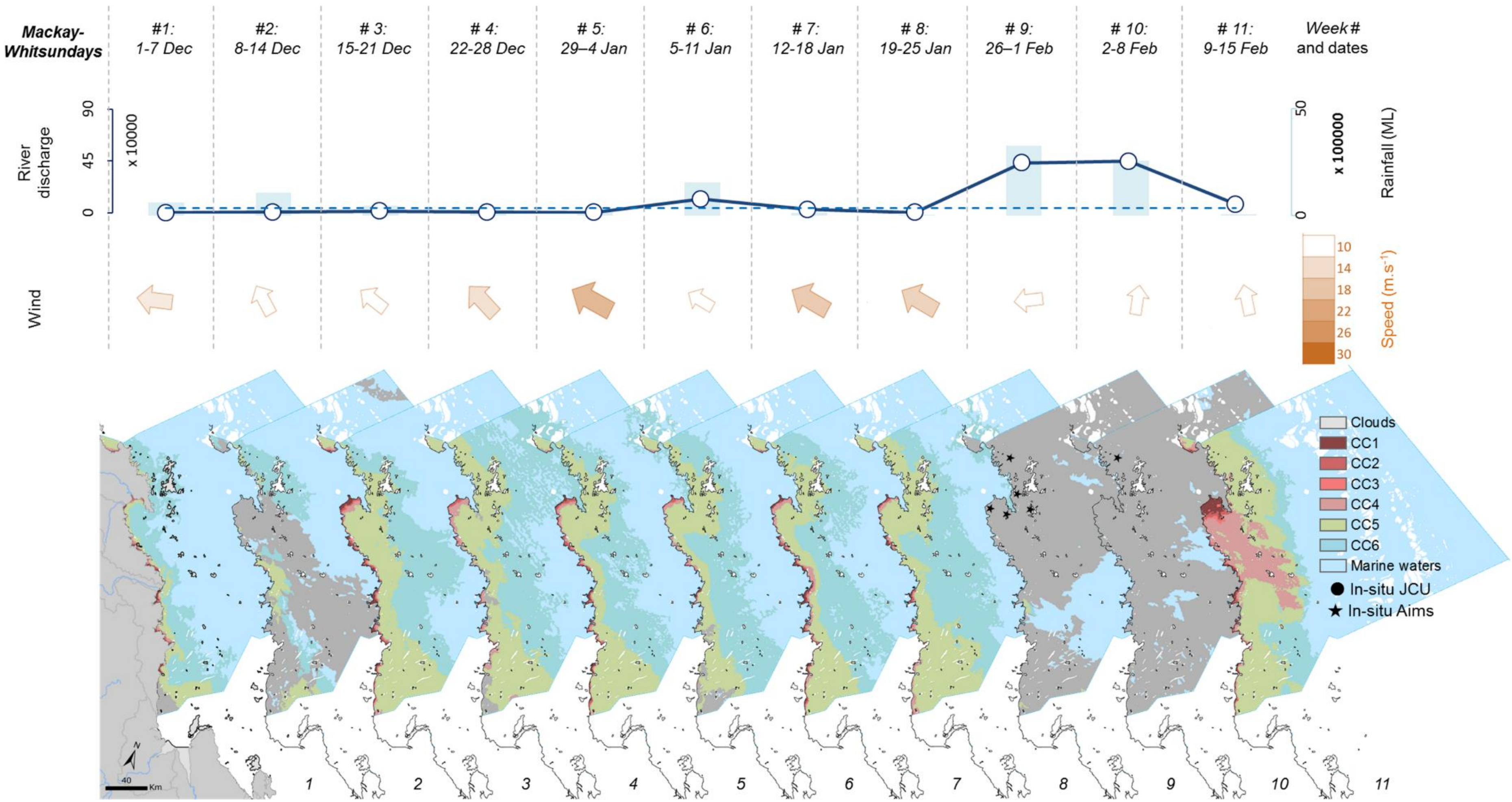

Figure 4-29: Panel of water quality and environmental characteristics in the Mackay-Whitsunday region throughout the 2018–19 wet season period: weeks 1 to 11. Includes: 2018–19 weekly river discharge (ML d^{-1}) and rainfall (ML); mean wind speed (m s^{-1}) and direction; and wet season water type maps showing the location of the *in situ* data collected by AIMS. 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, Pioneer and Sandy Creek Rivers.

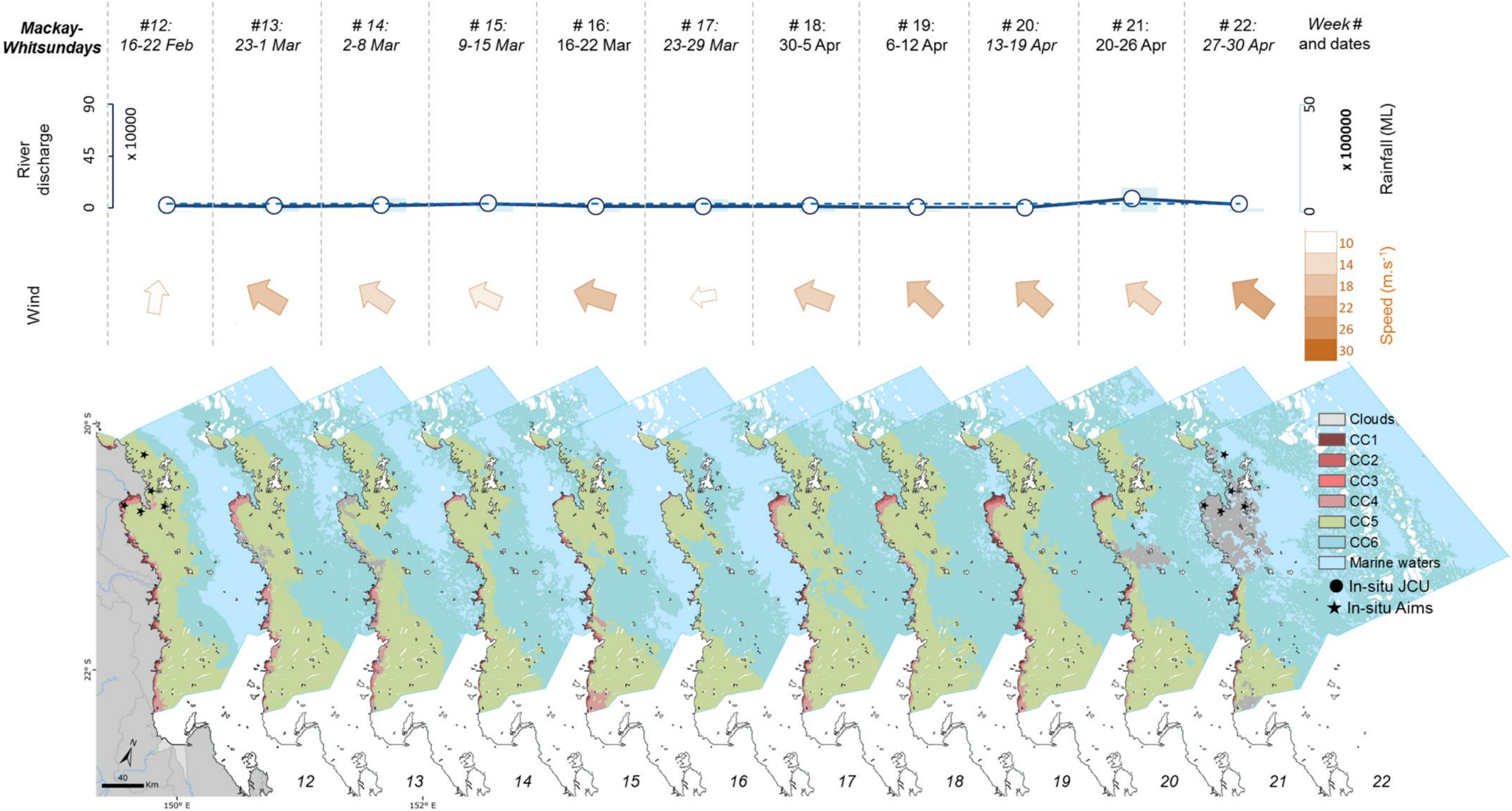

Figure 4-30: Panel of water quality and environmental characteristics in the Mackay-Whitsunday region throughout the 2018–19 wet season period: weeks 12 to 22. Includes: 2018–19 weekly river discharge (ML d^{-1}) and rainfall (ML); mean wind speed (m s^{-1}) and direction; and wet season water type maps showing the location of the *in situ* data collected by AIMS. 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, Pioneer, and Sandy Creek Rivers.

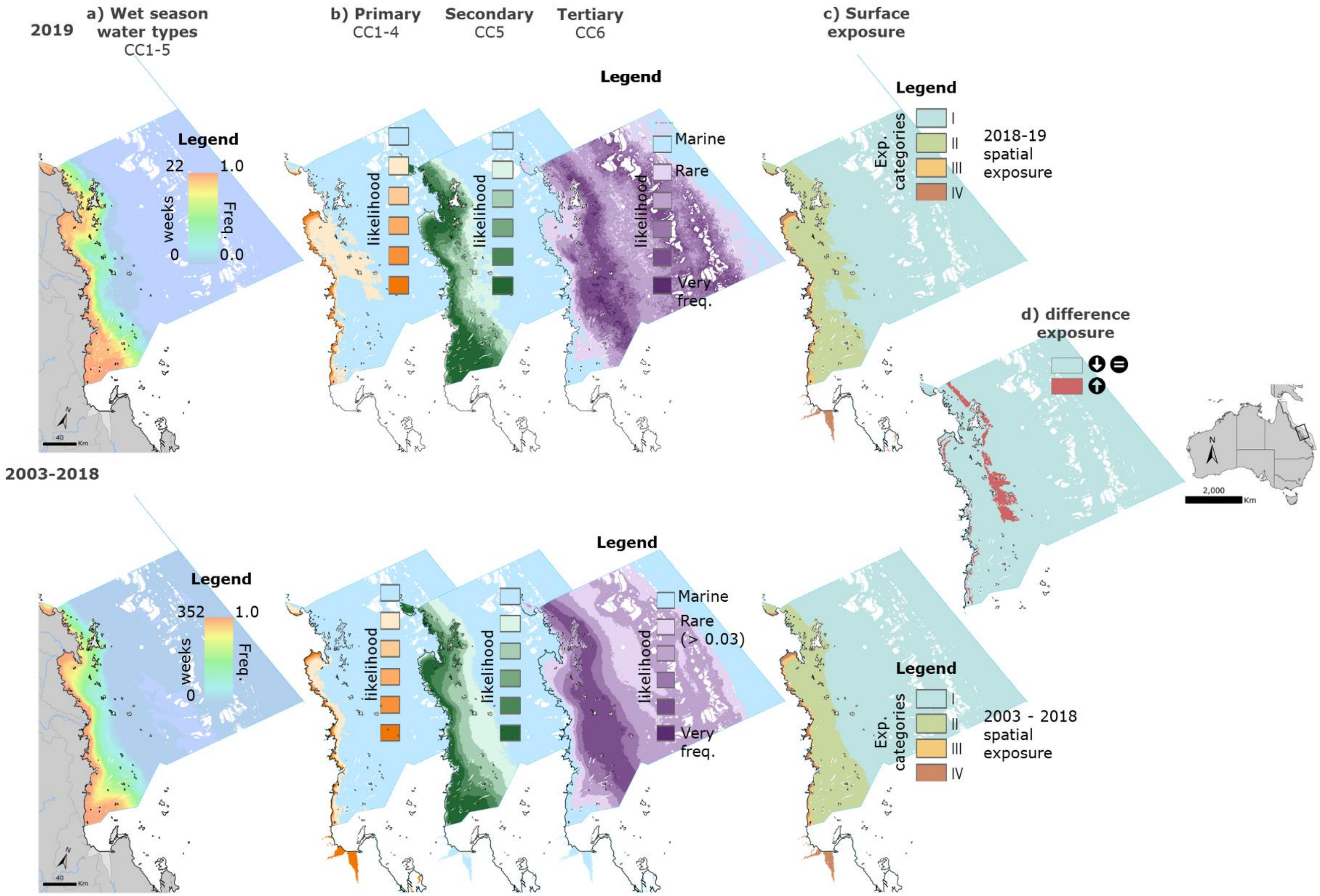

Figure 4-31: Long-term and current year remote sensing results for the Mackay-Whitsunday region showing the a) frequency of combined primary and secondary water types; b) the frequency of primary, secondary and tertiary wet season water types regrouped into five likelihood categories [<0.2 (Rare), 0.2–0.4, 0.4–0.6, 0.6–0.8 and 0.8–1 (very frequent)]; c) exposure in the long-term (bottom) and 2018–19 wet season (top); and d) a difference map showing areas with an increase in risk category in 2019 (in red, 🡅) against long-term trends [calculated as (c, top) exposure in 2019 minus (c, bottom) 2003–2018] .

The MODIS monitoring products (when not obstructed by cloud cover as in weeks 9 and 10) 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 4-29 and Figure 4-30). One major flood event influenced the Mackay-Whitsunday region during the 2018–19 wet season and was associated with extensive rainfall in late January–early February 2019. Weekly composites at the time of the peak discharge (26 January–8 February period, weeks 9–10) were cloudy, but a large flood plume was visible off the Pioneer River on the MODIS weekly composite of 9–15 February (week 11). Overall discharge was above the long-term median. The next weekly composites (weeks 12–22, Figure 4-30) showed less extended areas of primary waters until the end of the wet season. Sampling of wet season waters was conducted by AIMS during the main flood event (26 January–22 February period: weeks 9, 10, and 12), and during the last week of the wet season. No water quality samples were collected in colour classes 1, 2, or 3.

Figure 4-31 (top) presents: frequency of combined primary and secondary water types; the frequency of primary, secondary and tertiary water types individually; the Mackay-Whitsunday exposure map in the long-term and during the 2018–19 wet season; and a difference map showing areas exposed to an increased risk in 2019. Table 4-6Table 4-4 presents the areas (km^2) 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/Very low risk) represents waters with detectable but 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.

Table 4-6: Areas (km^2) and percentages (%) of the Mackay-Whitsunday region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2018–19 wet season and the long-term (2003-2018). The last three rows show the differences between % affected in 2019 and the long-term average (red: increase, blue: decrease, green: no change, difference ≤0.1%). Areas south of the Marine Park (Hervey Bay) not included.

Mackay-Whitsunday		Total		Potential Risk category				Total area exposed II-IV
				No / very low	Lowest Highest			
				I	II	III	IV	
Surface area	area	48,957	2019	38,199	9,657	623	*478*	10,758
			LT	38,701	9,320	515	419	10,255
	%	*100%*	2019	78%	20%	1%	1%	22%
			LT	79%	19%	1%	1%	21%
Coral reefs	area	3,216	2019	3,000	192	21	*4*	217
			LT	3,004	194	16	2	212
	%	*100%*	2019	93%	6%	1%	<1%	7%
			LT	93%	6%	<1%	<1%	7%
Surveyed seagrass	area	307	2019	23	174	36	*75*	284
			LT	19	169	42	77	288
	%	*100%*	2019	7%	57%	12%	25%	93%
			LT	6%	55%	14%	25%	94%
Difference (2019 – Long Term average)	*Surface area*			-1%	1%	<1%	<1%	1%
	Coral Reef			<1%	<1%	<1%	<1%	<1%
	Surveyed seagrass			1%	2%	-2%	0%	-1%

In 2018–19, it was estimated that:

- 22% of the Mackay-Whitsunday region was exposed to combined potential risk categories II–IV. However, only 1% of the region was in the highest exposure category (IV) and in category III.
- 7% of coral reefs in the Mackay-Whitsunday region were exposed to combined potential risk categories II–IV. However, less than 1% of coral were in the highest exposure category (IV) and in category III.
- 93% of seagrasses in the Mackay-Whitsunday region were exposed to combined potential risk categories II–IV. 25% of seagrasses were in the highest exposure category (IV) and 12% were in category III.
- The coral and seagrass areas in the Mackay-Whitsunday region exposed to combined potential risk categories II–IV in 2018-19 were both similar to or slightly less than the long-term areas.

4.7 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, this year, 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. It should be noted that exposure maps have a higher degree of uncertainty in these 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 detectable but low water quality concentrations and therefore low risk of any detrimental ecological effect. Area exposed to category I are presentedTable 4-3 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 2018–19 was below the long-term median, and there were no large flood plumes captured in satellite imagery in the Fitzroy region during the wet season. Moderate exposure to primary waters occurred mainly in enclosed coastal waters south and north of Curtis Island, especially near the Fitzroy and Calliope River mouths.

Table 4-7 presents the areas (km^2) 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 2018–19, it was estimated that:

- 10% of the Fitzroy region was exposed to combined potential risk categories II–IV. However, only 2% of the region was in the highest exposure category (IV) and 1% in category III.
- 3% of coral reefs in the Fitzroy region were exposed to combined potential risk categories II–IV. However, less than 1% of coral were in both the highest exposure category (IV) and category III.
- 70% of seagrasses in the Fitzroy region were exposed to combined potential risk categories II–IV. 28% of seagrasses were in the highest exposure category (IV) and 8% were in category III.

- The coral areas in the Fitzroy region exposed to combined potential risk categories II–IV in 2018-19 were very similar to the average long-term areas. However, the area of seagrass exposed to combined potential risk categories II–IV in 2018-19 were 26% lower than the long-term average which is consistent with the relatively dry conditions in the Fitzroy region in 2018–19.

Table 4-7: Areas (km^2) and percentages (%) of the Fitzroy region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2018–19 wet season and the long-term (2003–2018). The last three rows show the differences between % affected in 2018–19 and the long-term average (red: increase, blue: decrease, green: no change, difference <1%). 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**	**IV**	
Surface area	area	86,869	2019	78,527	5,672	1,148	*1,521*	8,342
			LT	76,616	7,457	1,322	1,475	10,253
	%	*100%*	2019	90%	7%	1%	2%	10%
			LT	88%	9%	2%	2%	12%
Coral reefs	area	4,881	2019	4,730	97	24	*29*	151
			LT	4,729	100	22	30	152
	%	*100%*	2019	97%	2%	<1%	<1%	3%
			LT	97%	2%	<1%	<1%	3%
Surveyed seagrass	area	478	2019	146	160	37	*135*	332
			LT	20	286	34	137	457
	%	*100%*	2019	30%	34%	8%	28%	70%
			LT	4%	60%	7%	29%	96%
Difference (2019 – Long term average)	*Surface area*			2%	-2%	-1%	<1%	-2%
	Coral Reef			0%	0%	0%	<1%	0%
	Surveyed seagrass			26%	-26%	1%	-1%	-26%

Burnett-Mary

The river discharge from the Burnett-Mary region in 2018–19 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. Minor exposure to primary waters occurred in enclosed coastal waters off Hummock Hill Island in early January 2019 but this may also be linked to resuspension of sediments in the shallow waters.

Table 4-8 presents the areas (km^2) 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.

Table 4-8: Areas (km^2) and percentages (%) of the Burnett-Mary region, coral reefs, and surveyed seagrass affected by different risk categories of exposure during the 2018–19 wet season and the long-term (2003–2018). The last three rows show the differences between % affected in 2018–19 and the long-term average (red: increase, blue: decrease, green: no change, difference <1%). 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	IV	
Surface area	area	37,713	2019	36,847	632	113	*120*	866
			LT	35,748	1,556	267	142	1,965
	%	*100%*	2019	98%	2%	<1%	<1%	2%
			LT	95%	4%	<1%	<1%	5%
Coral reefs	area	285	2019	9	1	3	*0*	4
			LT	281	0	3	0	4
	%	*100%*	2019	3%	0%	<1%	0%	<1%
			LT	99%	0%	<1%	0%	<1%
Surveyed seagrass	area	259	2019	101	95	29	*35*	159
			LT	9	170	39	42	251
	%	*100%*	2019	39%	20%	6%	7%	33%
			LT	3%	36%	8%	9%	53%
Difference (2019 – Long term average)	*Surface area*			3%	-2%	<1%	<1%	-3%
	Coral Reef			-96%	0%	<1%	0%	<1%
	Surveyed seagrass			36%	-16%	-2%	-2%	-20%

In 2018–19, it was estimated that:

- 2% of the Burnett-Mary region was exposed to combined potential risk categories II–IV, with less than 1% in both the highest exposure category (IV) and category III.
- Less than 1% of coral reefs in the Burnett-Mary region were exposed to combined potential risk categories II–IV.
- 33% of seagrasses in the Burnett-Mary region were exposed to combined potential risk categories II–IV. However, only 7% of seagrasses were in the highest exposure category (IV) and 6% were in category III.
- The coral areas in the Burnett-Mary region exposed to combined potential risk categories II–IV in 2018-19 were very similar to the average long-term areas. However, the area of seagrass exposed to combined potential risk categories II–IV in 2018-19 were 20% lower than the long-term average which is consistent with the relatively dry conditions in the Burnett-Mary region in 2018–19.

4.8 Modelling and mapping summary

Main results:

- Tracer simulations (eReefs hydrodynamic model)

Simulations of three-dimensional tracer dispersal showed river exposure in open coastal waters was high this year, especially near the Normanby, Barron, Russell-Mulgrave, Tully, and Burdekin Rivers. Discharge from all modelled rivers (with the exception of the O'Connell) reached mid-shelf waters, and some river discharge reached well into offshore waters (Normanby River), although river-derived material was fairly dilute in the offshore water body.

River discharge generally travelled in a northerly direction along the coastline, but extended periods of offshore winds during the 2018–19 wet season caused discharge to be transported in an easterly or offshore direction as well. River discharge could extend far from the source for short periods, as was observed for the Normanby and Burdekin Rivers, where discharge reached >200 km north of the river mouth.

- Water type frequency maps (MODIS data)

Maps showed a well-documented inshore-to-offshore spatial pattern, with the highest frequency of the primary water type (typically enriched in sediment and dissolved organic matter, brownish turbid waters) in the coastal areas and mid-shelf to offshore areas most frequently exposed only to the tertiary water type (typically detectable water quality concentrations but with a low risk of any detrimental ecological effect). The extent and frequency of the water types were variable across regions and across the shelf, reflecting the constituent concentrations, river discharge volumes and resuspension events. Generally, though typical of an above average wet season year.

- Exposure maps (MODIS and field water quality data)

Exposure maps showed that approximately 16% of the total area of the Reef was exposed to a potential risk in 2018–19, which was higher than the long-term average area of 12.7%. The areas of coral reef and seagrass exposed to potential risk categories were also greater than the average long-term areas (+14.1% and +5.9 % of Reef coral and seagrasses, respectively), with a majority of the increases occurring in the Cape York, Wet Tropics, Burdekin and, to a lesser extent, Mackay-Whitsunday regions. These characteristics are consistent with the relatively wet conditions in the northern and central regions of the Reef in 2018–19.

Regional exposure results were:

- Cape York: Approximately 21% of the total area of the Cape York region, including 37% of the region's coral reefs and 88% of the seagrasses were exposed to a potential risk. These areas were much higher than the long-term average areas, particularly for coral reefs (37% compared to 5%), although little exposure was in the higher risk classes III and IV (3% and <1%, respectively).

- Wet Tropics: Approximately 20% of the total area of the Wet Tropics region, including 4% of the region's coral reefs and 96% of the seagrasses were exposed to a potential risk. The areas were similar to the long-term average areas (within 2–4%).

- Burdekin: Approximately 21% of the total area of the Burdekin region, including 5% of the region's coral reefs and 98% of the seagrasses were exposed to a potential risk. The region area was greater than the long-term average area (7%) and the coral and seagrass areas were similar (3% difference).

- Mackay-Whitsunday: Approximately 22% of the total area of the Mackay-Whitsunday region, including 7% of the region's coral reefs and 93% of the seagrasses were exposed to a potential risk. These areas were similar to the long-term average areas (within 1%).

- Fitzroy: Approximately 10% of the total area of the Fitzroy region, including 3% of the region's coral reefs and 70% of the seagrasses were exposed to a potential risk. The total area and area of coral reefs exposed were similar to the long-term average, but the area of seagrass exposed was less than the long-term average area (70% compared to 96%) which is consistent with the relatively low discharge in the region.

- Burnett-Mary: Approximately 2% of the total area of the Burnett-Mary region, including less than 1% of the region's coral reefs and 33% of the region's seagrasses were exposed to a potential risk. The total area and area of coral reefs exposed were similar to the long-term average, but the area of seagrass exposed was less than the long-term average area (33% compared to 53%) which is consistent with the relatively low discharge in the region.

Of the area exposed, the Category 1 or No/Very Low risk were the most prevalent, in agreement with long-term trends. Similar to the long-term average, there was a small proportion of areas in the highest potential risk exposure Category IV.

The panels showing the pressures combined with the wet season water types and frequency maps for each NRM region highlight the need to distinguish the influence of river discharge, as opposed to other processes such as resuspension, in driving water quality as well as the need to keep integrating spatial and temporal information obtained from the wet season water type maps with the *in situ* water quality measurements. This method will be explored further to establish a metric specific to river plumes, distinct from overall wet season conditions.

- River-derived DIN, TSS and PN loading maps

A new approach to modelling the dispersion of DIN, TSS and PN loads was adopted to improve the predicted distribution of the estimated end-of-catchment pollutant loads across the Reef lagoon. The outputs were produced using the eReefs marine model for 2018–19 and back to 2002–03 using tracer maps and end-of-catchment load estimates.

The estimated wet season river-derived DIN loading in the Reef lagoon for the 2019 water year highlighted that the area between Cooktown and Bowen (in addition to Repulse Bay) had the highest loading. The 'anthropogenic' influence was emphasised in the area between Cairns and Bowen and further south near Proserpine which receives inputs from the Wet Tropics and Burdekin region rivers, and the Proserpine and O'Connell rivers respectively. The areas of influence in 2018–19 are comparable to those years with river discharge above the long-term median, e.g. 2008–09.

For TSS, the highest loadings occurred in the area of Princess Charlotte Bay (receiving the Normanby River discharge) and the area between Cairns and Bowling Green Bay (receiving the discharge from the Wet Tropics and Burdekin region rivers), with the greatest intensity around the Burdekin River mouth. The areas of influence in 2018–19 were comparable to those years with river discharge above the long-term median, e.g. 2008–09 and 2009–10.

Model assessment of the anthropogenic influence emphasises the intensity of the influence from the Burdekin River, and de-emphasizes the area of high loading in Princess Charlotte Bay. However, the pre-development loads for Cape York and the Normanby River are highly uncertain. They are based on limited historical data and model assumptions about land use impacts. The current load modelling assumptions do not fully account for the widespread impact of grazing land use (cattle, fences, roads, fires, weeds) on the initiation and acceleration of gully erosion post-European settlement (Brooks et al. 2013; Shellberg and Brooks 2013; Spencer et al. 2016). Historic moderate-intensity grazing land use cannot be assumed to have minimal impacts on anthropogenic sediment yields on Cape York or elsewhere (e.g., Shellberg et al. 2016b). The Normanby catchment is modelled to have relatively high anthropogenic loading compared to other Cape York rivers (McCloskey et al., 2014) despite historic impacts in other rivers (e.g., Annan River, Shellberg et al. 2016a). Further investigation of the pre-development load estimates for Cape York rivers is necessary.

PN showed similar patterns to TSS for 2018–19. The predicted anthropogenic influence was reasonably similar to the total loads, suggesting that the PN may be linked to anthropogenic sources, although further validation of this is necessary.

Caveats

It should be noted there are several caveats to the modelling and mapping products.

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 with *in situ* data varies between regions, with limited current water quality data in the Fitzroy and Burnett-Mary regions.

Loading maps

The limitations of the previous model which was driven by average wind conditions that are typically represented in a south-easterly direction has been addressed 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 recommended. 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.

5. Focus area water quality and Water Quality Index

The following sections provide detailed analysis of key water quality variables in focus areas 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 are still under development):

- 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 2019
- 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 E and may be referred to for detail. These appendices include:

- Figure E-1: Time-series of chlorophyll and turbidity measured by moored FLNTUSB instruments
- Figure E-2: Time-series of temperature and salinity measured by moored Sea-Bird Electronics instruments
- Table E-1 Cape York: Summary statistics for each water quality variable from each monitoring location, June 2018 to Sept 2019
- Table E-2 Wet Tropics, Burdekin and Mackay-Whitsunday: Summary statistics for each water quality variable from each monitoring location, June 2018 to Sept 2019
- Table E-3: Annual summaries of moored FLNTUSB turbidity measurements for each monitoring location, including percentage exceedances of GVs
- Table E-4 to Table E-8: 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: Endeavour Basin, Normanby Basin, Stewart River and Pascoe River. The monitoring results are presented separately for each.

Water quality monitoring by the MMP commenced in the Cape York region in January 2017. Twenty-nine primary sites throughout 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. Ambient sampling primarily occurs between October to June due to strong winds (>25 kph) preventing access during the winter months.

As the 2018–19 water year is only the third year of sampling for the Cape York region, long-term trends cannot yet be analysed. The small number of ambient surveys completed each year per transect also limits the ability to statistically analyse changes over time. Water quality results within each focus region have been assessed relative to distance from river mouths and compared against the draft Eastern Cape York Water Quality Guidelines for the enclosed coastal, open coastal, mid-shelf and offshore water bodies (Honchin et al., 2017). The draft Cape York guidelines for the open coastal water body have been updated since the previous annual MMP report (Gruber et al., 2019) and some values have been revised. 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.

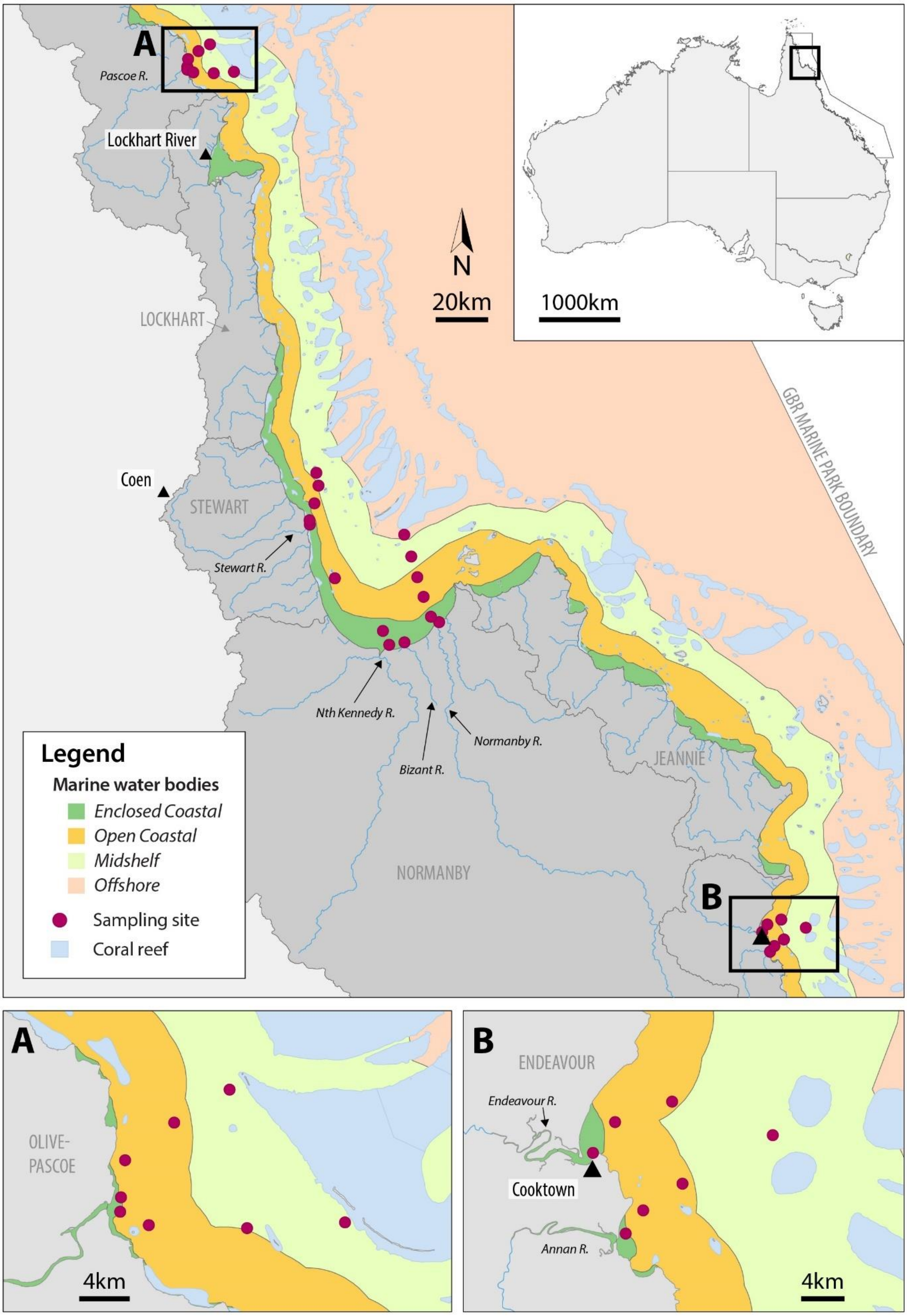

Figure 5-1: Water quality sampling sites in the Cape York region shown with water body boundaries.

Multiple large flood events influenced Cape York marine waters during the 2018–19 wet season, and all four monitored focus regions experienced annual discharges from adjacent rivers that were at least two to three times greater than the 10-year median annual discharges. Major flood events were associated with cyclone Penny in late December 2018, extensive sustained rainfall in late January and cyclone Trevor in mid- to late March.

5.1.1 Annan-Endeavour

The Annan-Endeavour focus area is influenced primarily by discharge from the Endeavour and Annan Rivers. Seven sampling sites are located along transects from the two river mouths to mid-shelf waters, representing a gradient in water quality (Figure 5-2).

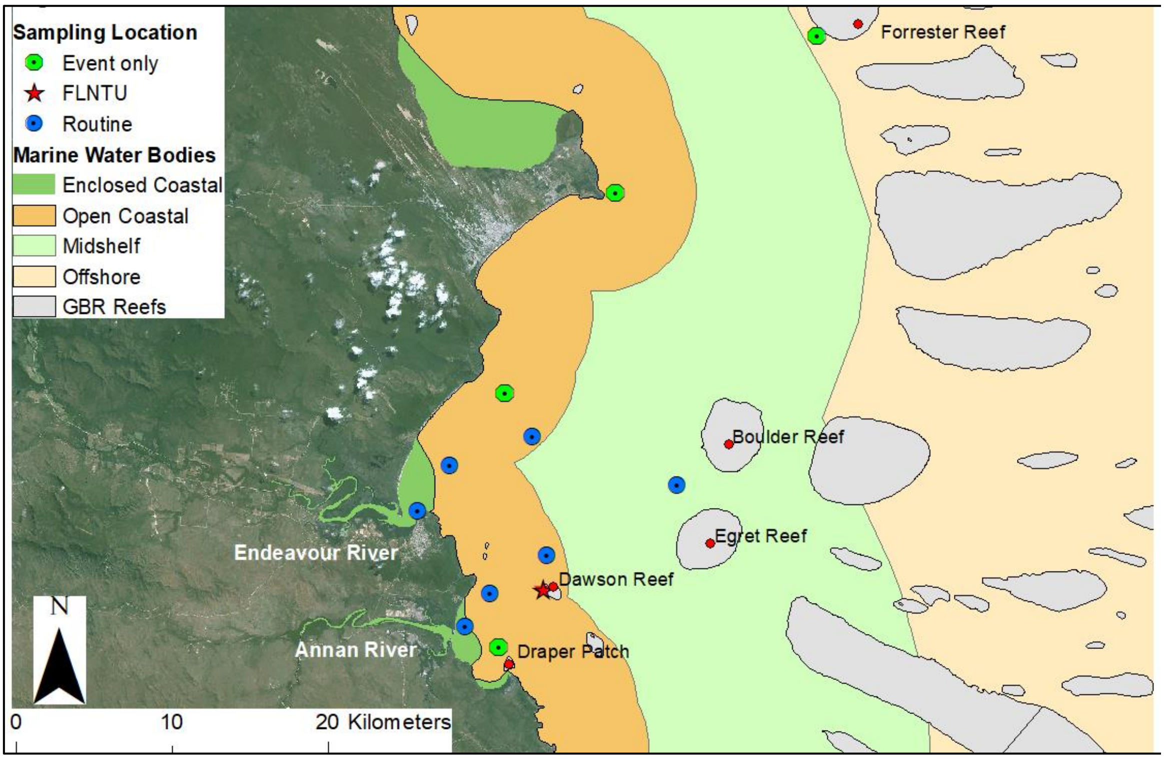

Figure 5-2: Water sampling sites in the Endeavour Basin focus area with water body boundaries.

During the 2018–19 wet season, a total of 46 surface and subsurface samples were collected from the Annan and Endeavour transect over four days during ambient conditions (between October 2018–March 2019). An additional 25 event samples were collected over nine days (Figure 5-3). In addition to manual sampling, a Wetlabs FLNTU sensor and *in situ* conductivity datalogger were installed at Dawson Reef, six kilometres from the mouth of the Annan River (Figure 5-2), in January 2019. The FLNTU measured Chl-*a* fluorescence and turbidity every 10 minutes over the wet season, including during two major flood events.

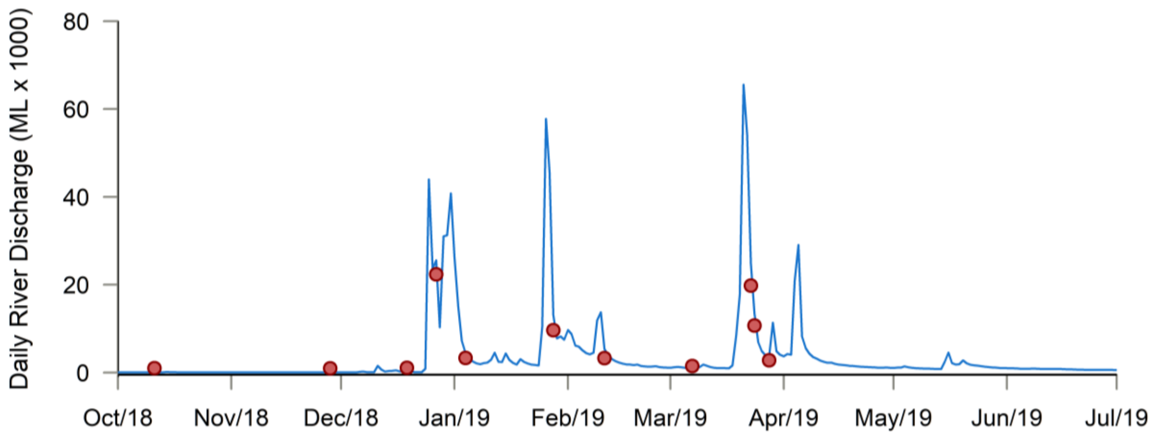

Figure 5-3: Daily discharge for the Endeavour Basin, combined values from the Annan River (gauge 107003A) and Endeavour River gauge (107001B) for the 2018–19 wet season. Red dots represent ambient and event sampling dates.

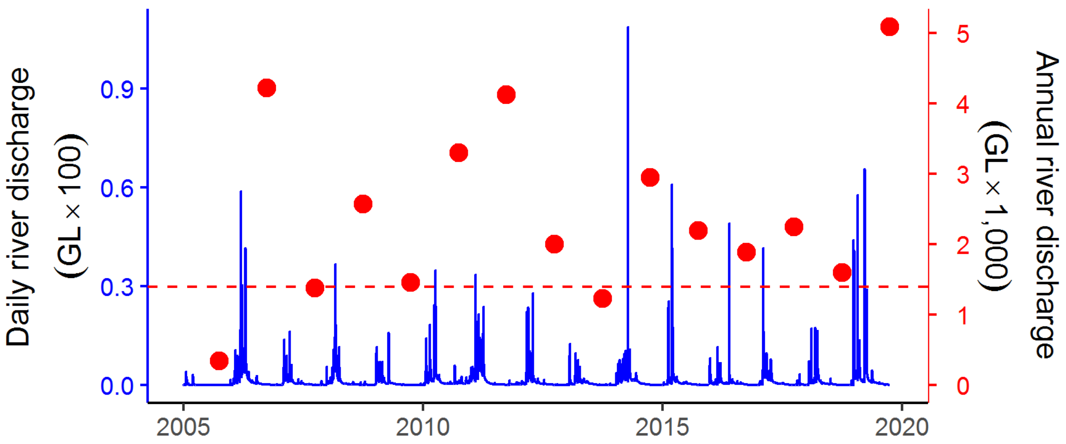

Figure 5-4: Long-term discharge for the Endeavour Basin, combined values from the Annan River (gauge 107003A) and Endeavour River (gauge 107001B). Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge. Method for estimation is described in Table 2-2.

The estimated total discharge from the Endeavour Basin for the 2018–19 water year is almost three times above the long-term median discharge and the highest recorded over the previous decade (Table 3-1, Figure 5-4 and Figure 5-5). The combined discharge and modelled loads estimated for the 2018–19 water year from the Endeavour Basin are shown in Figure 5-5. Over the 13-year period from 2006:

- discharge has varied from 984 GL (2012–13) to 3,847 GL (2018–19)
- TSS loads have ranged from 49 kt (2012–13) to 192 kt (2018–19)
- DIN loads from 49 t (2012–13) to 192 t (2018–19)
- PN loads from 79 t (2012–13) to 308 t (2018–19).

These load calculations, derived using annual mean concentrations from the Source Catchments model, may significantly underestimate total Endeavour Basin loads when compared with empirical load calculations (Shellberg et al. 2016b). For example, the model does not accurately incorporate loads from Oaky Creek, which is a significant anthropogenic sediment source to the Annan River and coastal zone (Howley, 2016; J. Shellberg unpublished data).

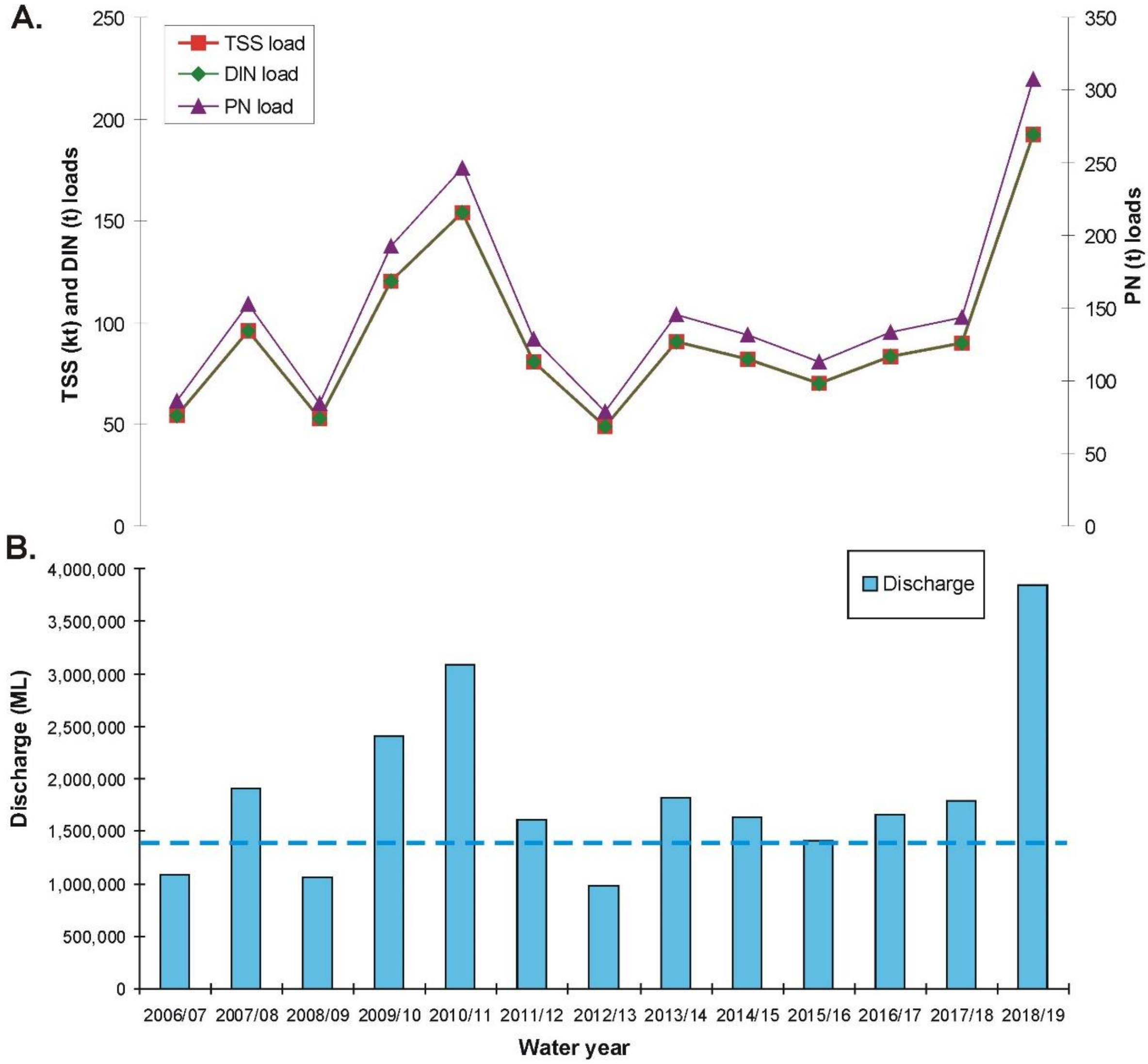

Figure 5-5. Loads of (A) total suspended solids, dissolved inorganic (DIN) and particulate nitrogen (PN) and (B) discharge for the Endeavour Basin from 2006 to 2019. The loads reported here are based on the annual mean concentration reported in the Source Catchments modelling data and applied to each 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 5-6). Ambient mean, median, 20th and 80th percentile values for each analyte are compared against the draft Eastern Cape York regional guidelines for the enclosed coastal (sites ER-01 and AR-01), open coastal (ER02, ER03, AR02, and AR03) and mid-shelf (AE04) water bodies in Table E-1.

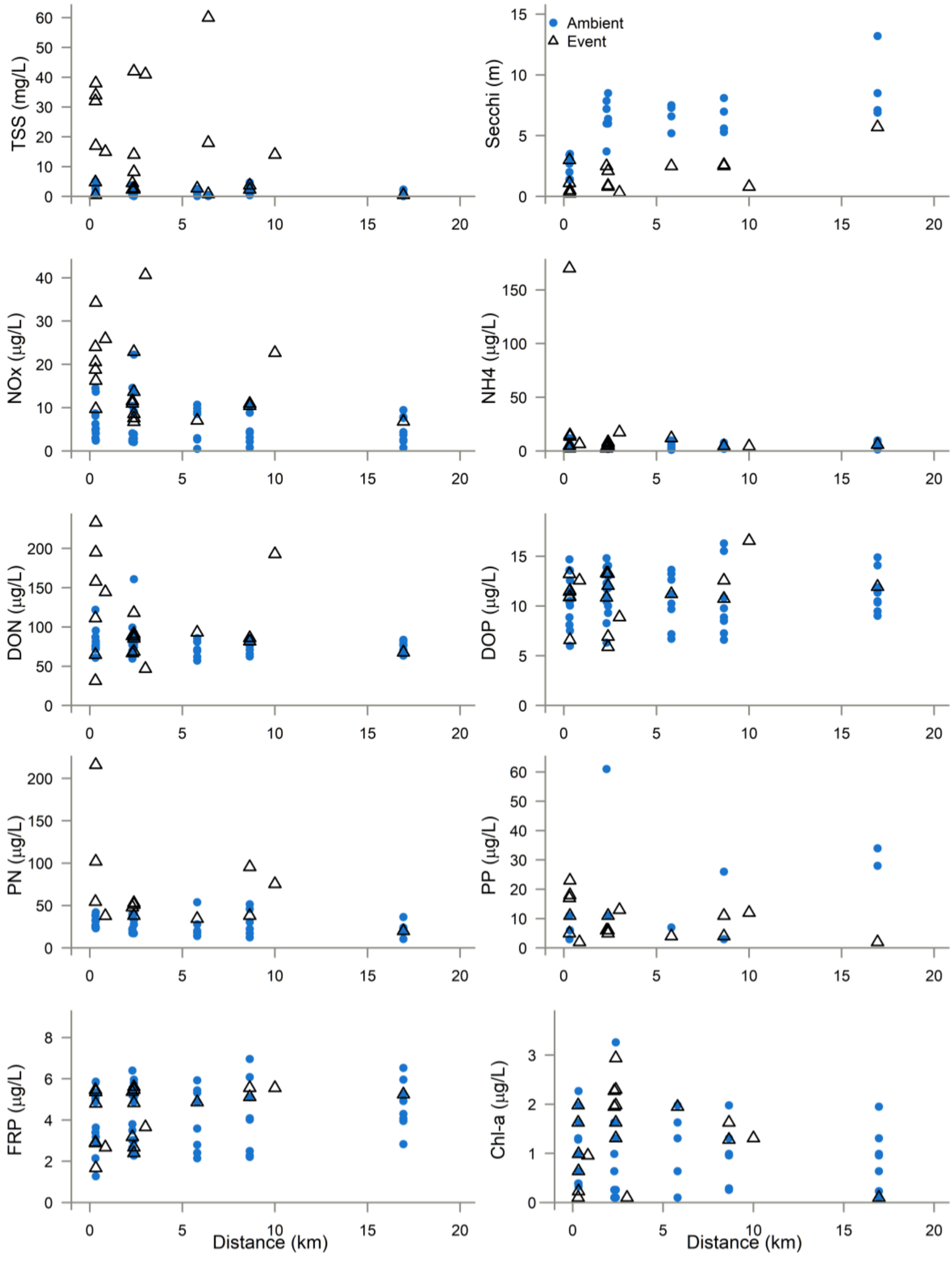

Figure 5-6: Water quality concentrations (surface and subsurface samples) and Secchi depth over distance from river mouth (km) for the Endeavour Basin focus region during ambient (blue circles) and event (black triangles) conditions (2018–19 water year).

The comparison of the 2018–19 ambient results with previous years and the water quality guidelines include the following findings:

- Ambient TSS concentrations remained below 5 mg L^{-1} and were at or below guideline values, with ambient means of 2.4, 1.5, and 1.0 mg L^{-1} for the enclosed coastal, open coastal, and mid-shelf water bodies, respectively (Table E-1).
- Mean Secchi depths in the open coastal (6.5 m) and mid-shelf (8.1 m) water bodies were less than the guideline of ≥10 m for both water bodies (Figure 5-6). This was consistent with the 2017–18 ambient wet season results.
- PN and PP concentrations increased significantly compared to previous years, however this is at least partly due to a change in laboratory analytical methodology. PN in the mid-shelf water body exceeded the annual GV.
- NO_x, NH_3 and PO_4 concentrations exceeded the annual GVs in the open coastal and mid-shelf water bodies (NO_x by an order of magnitude). NO_x and PO_4 concentrations also exceeded the dry season GVs in the open coastal water body, and wet season GVs in the enclosed coastal and open coastal water bodies.
- Chl-*a* concentrations in the open coastal water body exceeded the dry season and wet season GVs, and the median mid-shelf concentration (1.0 µg L^{-1}) exceeded the annual GVs. Dry season and wet season mean concentrations doubled and tripled, respectively, compared to the 2017–18 wet season.

Exceedances of wet season water quality GVs and increased mean Chl-*a* concentrations compared to previous years are likely due to the high frequency and magnitude of flooding during the 2018–19 wet season. Figure 5-8 shows the extended periods of indicative Chl-*a* guideline exceedances at Dawson Reef (open coastal water body) following local flooding. However, this does not explain dry season increases in Chl-*a*.

Event water quality

Average and above-average magnitude flood events occurred in the Endeavour Basin from 25 December–5 January (estimated discharge 974 GL), 24 January–12 February (estimated discharge 874 GL), and 18 March–7 April 2019 (estimated discharge 1125 GL) (Figure 5-3). Twenty-five event samples were collected at both regular transect sites and extra sites within the flood plumes over nine days (Figure 5-2). Satellite images (Figure 5-7) and sampling showed that turbid plume waters reached open coastal and mid-shelf reefs over multiple days during each event.

The first event of the wet season flowed primarily to the north due to south-easterly winds. Sampling on 27 December (falling limb) measured:

- a TSS maximum of 34 mg L^{-1} in the enclosed coastal water body
- TSS of 14 mg L^{-1} reaching fringing reefs at Cape Bedford 26 km to the north, and
- a Chl-*a* maximum of 2.94 µg L^{-1} in the open coastal water body during post-flood sampling.

Event sampling during the falling stage of the second flood event (28 January) and two weeks later after sustained flooding (11 February) showed:

- seagrass meadows and fringing coral at Walker Bay (>3 km south of the Annan River mouth) were exposed to high TSS concentrations (32 mg L^{-1} to 41 mg L^{-1}) several days after the flood peak, and
- Chl-*a* concentrations were low (<0.25 µg L^{-1}) despite high DIN (191 µg L^{-1}).
- Two weeks later after continued flooding, a maximum TSS of 15 mg L^{-1} was measured near the Annan river mouth and Chl-*a* increased to a maximum of 2.27 µg L^{-1} in the open coastal water body.

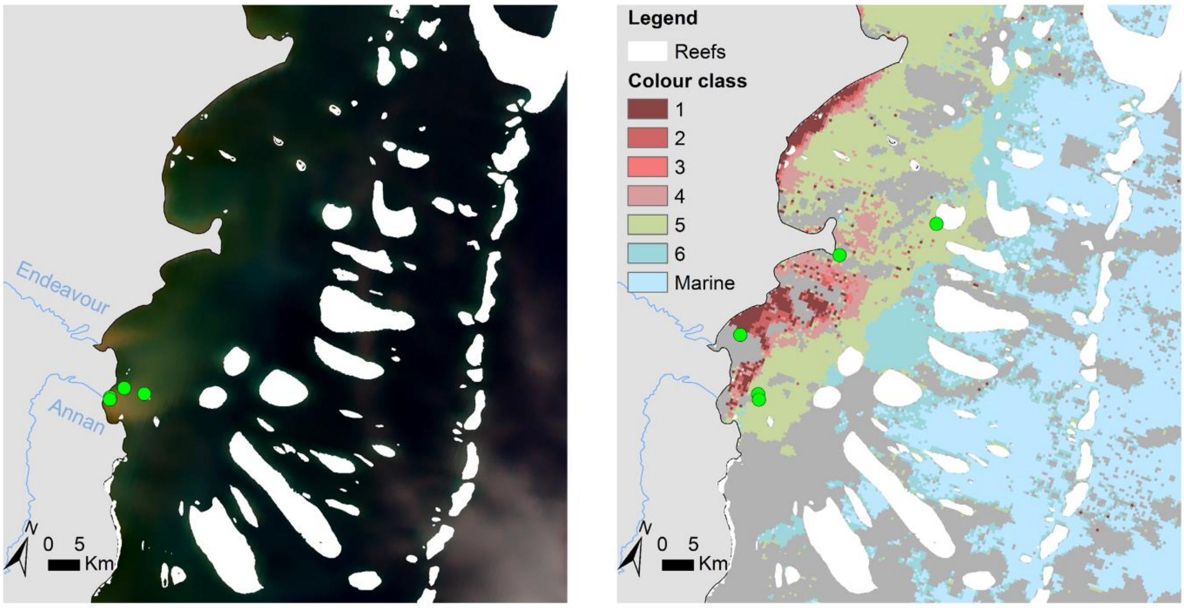

Figure 5-7: Annan and Endeavour River flood plumes extending out to mid-shelf reefs on 10 February 2019. (left: Source: NASA MODIS image) and 24 March 2019 (right: C. Petus JCU colour class map).

The largest magnitude event of the year occurred in late March 2019. Samples collected on 23 March (two days after the flood peak upstream) recorded:

- TSS of 60 mg L^{-1} in surface waters and 18 mg L^{-1} at a depth of 1.2 m at Dawson Reef (6 km east from the mouth of the Annan River; Figure 5-2) and
- 10 mg L^{-1} TSS and 1.63 µg L^{-1} Chl-*a* at Forrester Reef (40 km northeast from the Endeavour river mouth; Figure 5-2).

The FLNTU at Dawson Reef monitored turbidity and Chl-*a* fluorescence over the late January-February and late March events. The results clearly show the connection between flood water from the Annan and Endeavour River and resulting increases in turbidity and Chl-a at Dawson. Over both events, turbidity peaks above 20 NTU at Dawson Reef correlated with peaks in river discharge and turbidity peaks around 400 NTU at the river mouths (Figure 5-8).

Manual surface and sub-surface water quality sampling at the Dawson Reef FLNTU sonde showed that TSS concentrations were significantly higher in surface waters (at least 60 NTU) than what was recorded 1 m to 3 m beneath the surface at the sonde. Prolonged periods of elevated turbidity and Chl-*a* (indicated by Chl-*a* fluorescence) were recorded at Dawson Reef during and after flood events (Figure 5-8). A delayed Chl-*a* peak at Dawson in February following the late January flood event may be driven by discharge from Wet Tropics rivers. The median Chl-*a* concentration (0.35 µg L^{-1}) measured on the FLNTU met the wet season GV (0.46 µg L^{-1}). The median wet season turbidity (2.1 NTU) exceeded the GV (0.8 NTU). Limited sampling means the results may not be representative of ambient condition.

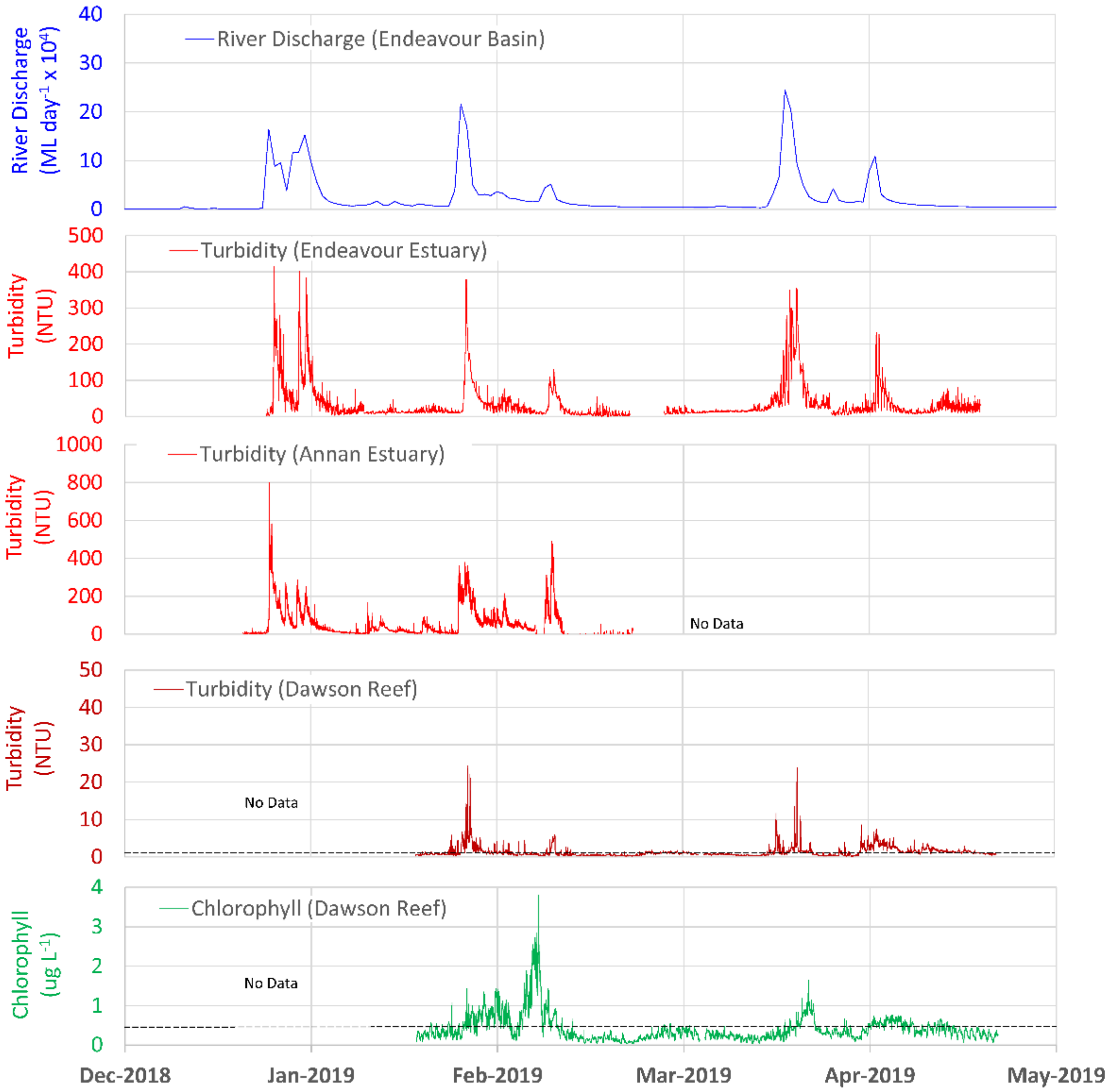

Figure 5-8: River discharge (combined Annan and Endeavour Rivers), turbidity measured on YSI EXO2s at the mouth of the Annan and Endeavour River, and turbidity and Chl-*a* fluorescence measured on the Wetlabs FLNTU at Dawson Reef over the 2018–19 wet season. Estuary turbidity (EXO2) data provided by CYWMP and CSIRO. Dotted lines show wet season water quality GVs.

5.1.2 Normanby

The Normanby focus area is influenced by discharge from the Normanby, Laura, Kennedy, Hann, Mossman, Morehead and Annie Rivers, plus three distributaries—the North Kennedy, Normanby and Bizant. Six of ten sampling sites for the Normanby Basin are located along a transect from the Normanby River mouth to open coastal waters and Corbett Reef (Figure 5-9). Two additional sample sites are located near the Kennedy River and one near the Bizant River mouth in the enclosed coastal water body. An additional site (CI01) is located near the Cliff Isles ('Marrpa' in traditional Lama Lama language).

A total of 71 surface and sub-surface samples were collected over six sampling periods (four ambient and two event) from December 2018 to June 2019 (Figure 5-10). Due to the distances between sample locations and tidal restrictions getting into and out of local rivers to access the sites, it is not possible to sample all sites in any one day. Therefore, some sites have been sampled more frequently than others. River mouth and Cliff Island sites were each sampled five times, while other ambient sites were sampled three to four times each. Sub-surface samples were collected at sites where water depths were greater than 3 m.

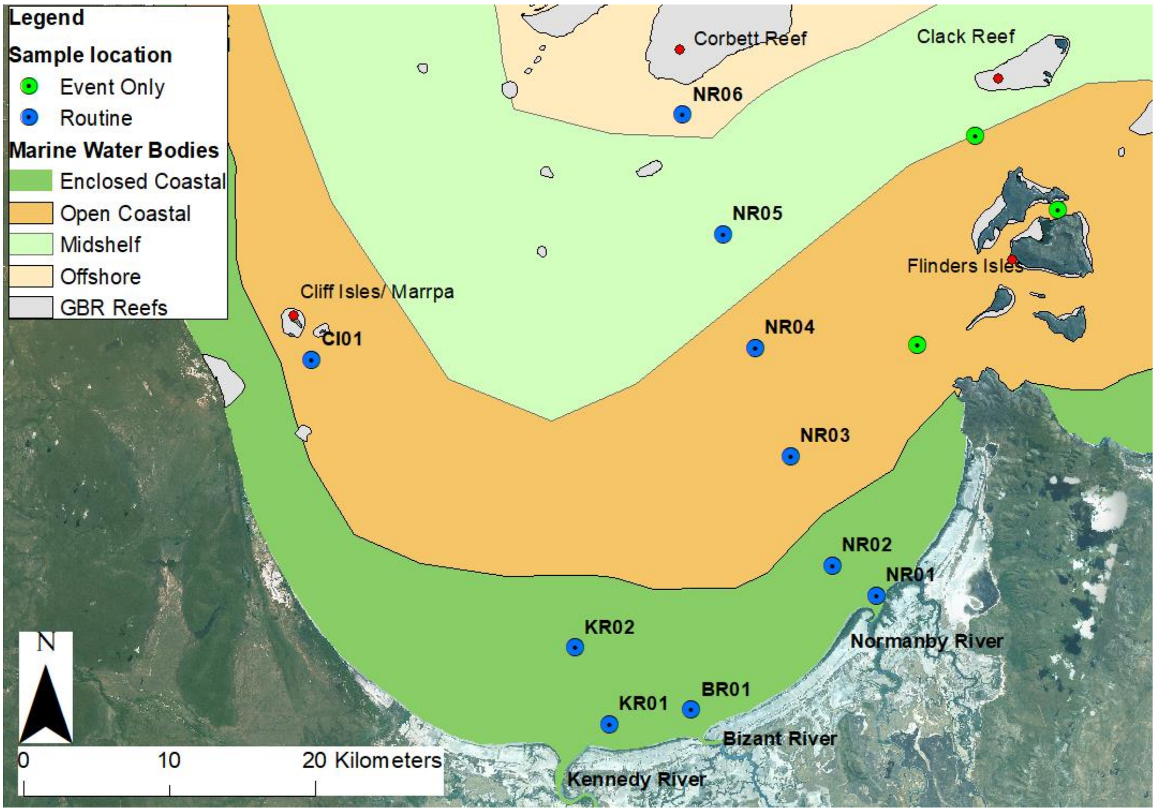

Figure 5-9: Water quality sampling sites in the Normanby Basin focus area with water body boundaries.

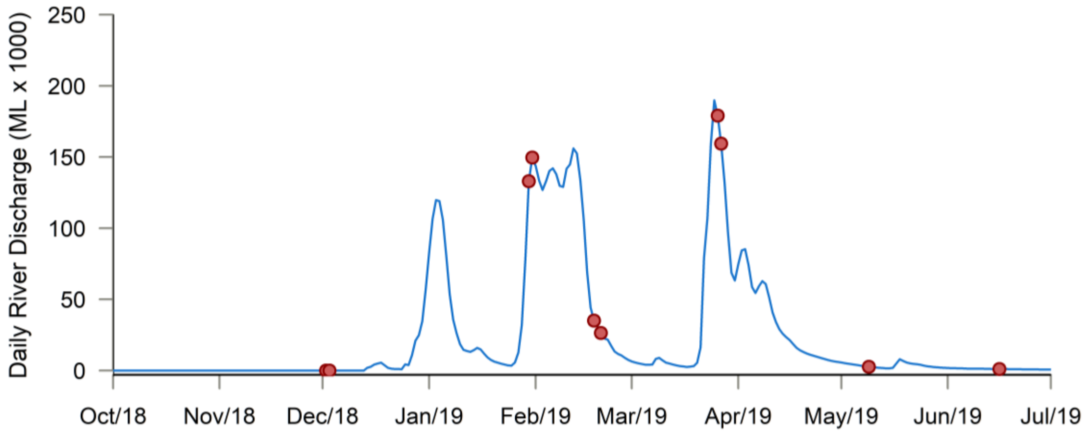

Figure 5-10: Daily discharge for the Normanby River (gauge 105107A) for the 2018–19 wet season. Red dot represents sampling date.

Estimated discharge from the Normanby Basin for the 2018–19 water year (12,102 GL) was 2.9 times greater than the long-term median (Table 3-1) and was the highest annual discharge since at least 2005 (Figure 5-11). 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 has been estimated using the method described in Table 2-2.

The discharge and modelled load estimates (Source Catchments) for the 2018–19 water year from the Normanby Basin were the highest calculated for the past decade. Over the 13-year period from 2006:

- discharge has varied from 2,182 GL (2011–12) to 12,102 GL (2018–19)
- TSS loads ranged from 55 kt (2014–15) to 535 kt (2018–19)
- DIN loads ranged from 42 t (2011–12) to 396 t (2018–19)
- PN loads ranged from 124 t (2009–10) to 1,608 t (2018–19).

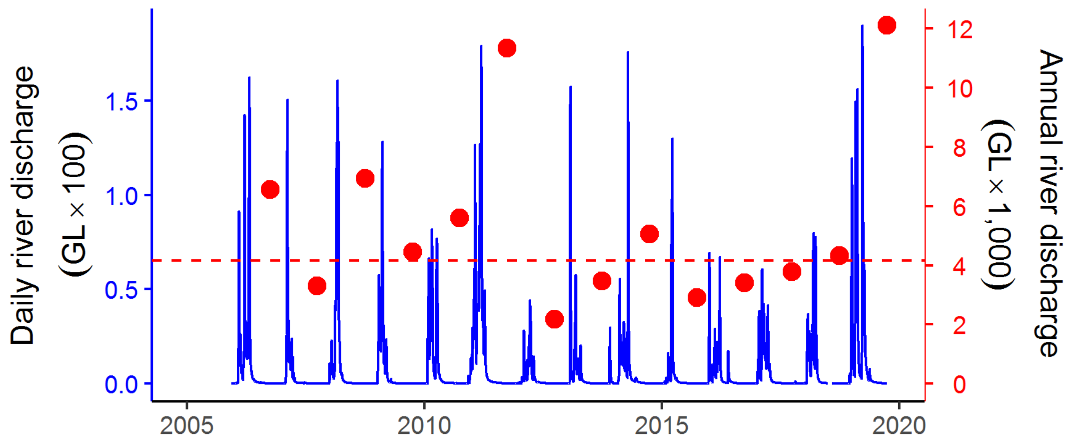

Figure 5-11: Long-term discharge for the Normanby River at gauge 105107A (Kalpowar Crossing). Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge. Method for estimation is described in Table 2-2.

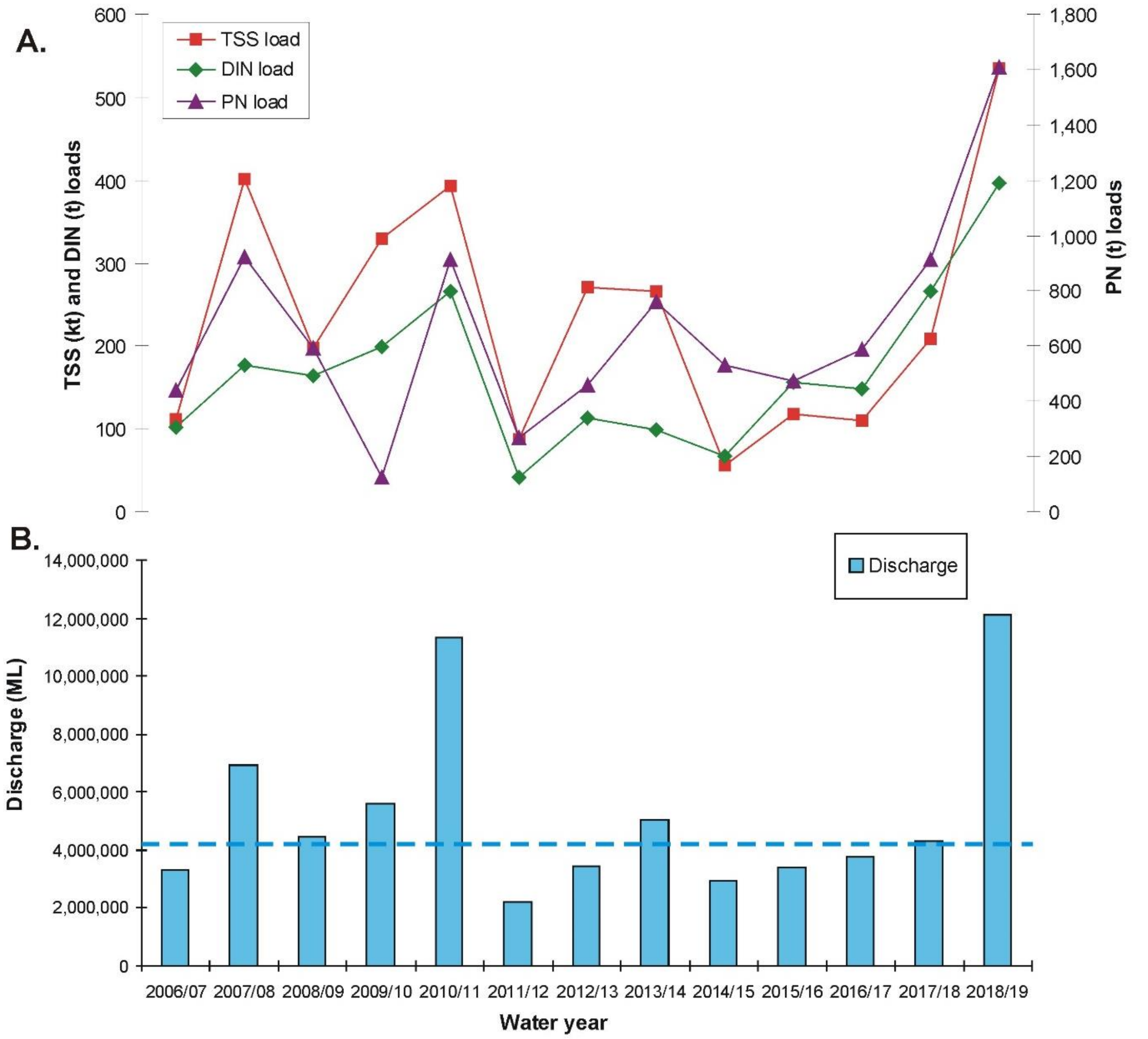

Figure 5-12: Modelled loads of (A) total suspended solids, dissolved inorganic (DIN) and particulate nitrogen (PN) and (B) discharge for the Normanby Basin. The loads reported here are a combination of 'best estimates' based on 'up-scaled' discharge and monitoring data from the Normanby River at Kalpowar 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 two ambient sampling events over the dry season and two sampling trips (over four days) during the wet season (Figure 5-10). Both ambient and event water quality results are plotted against distance from the closest river mouth (Normanby, Bizant, or Kennedy) in Figure 5-13. Ambient results are compared against the water quality guidelines for each water body in Table E-1.

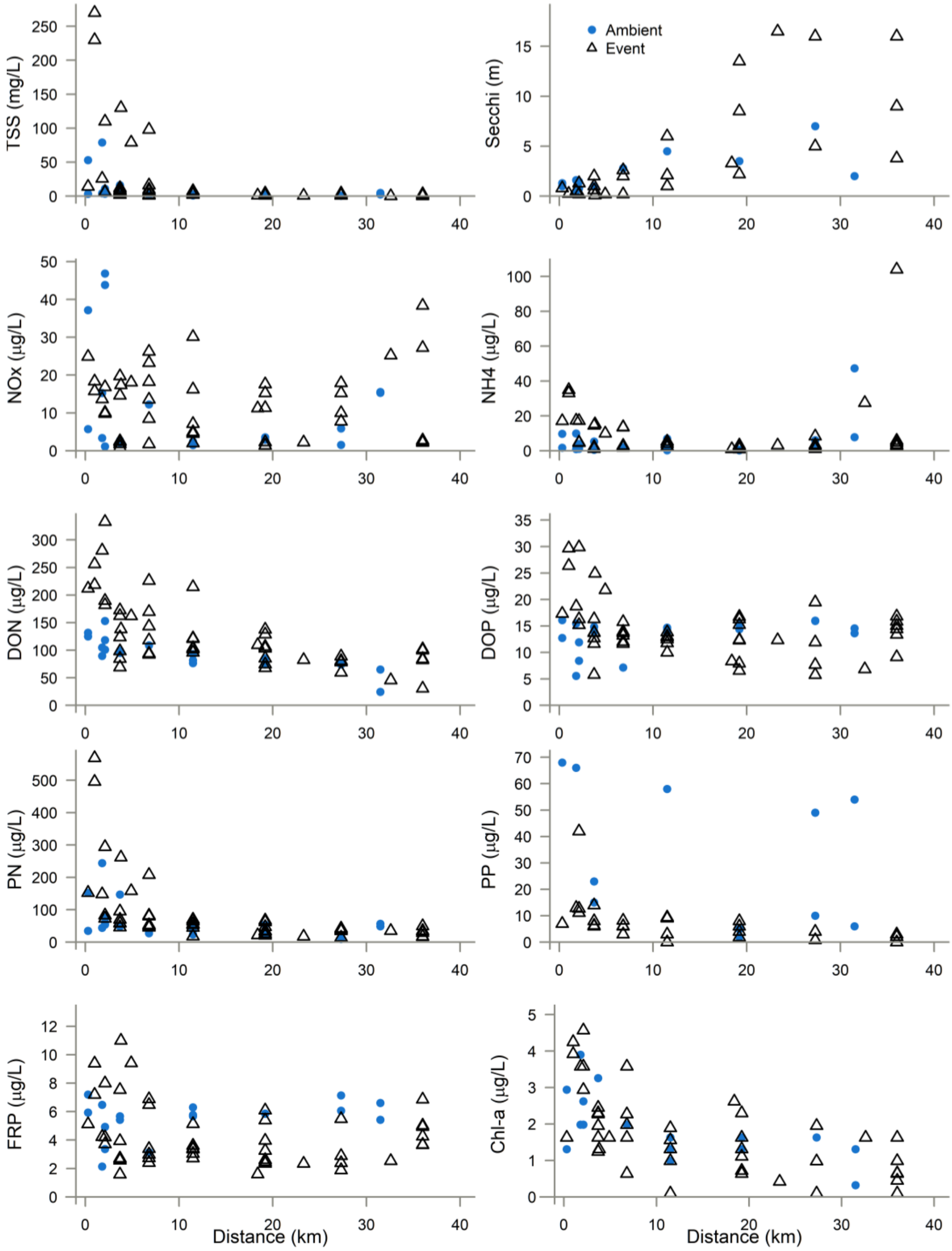

Figure 5-13: Water quality concentrations (surface and subsurface) and Secchi depth over distance (km) from river mouth for the Normanby Basin focus region, all 2018—19 ambient (blue circles) and event (black triangles) sampling dates.

The comparison of the 2018-19 ambient results with previous years and the water quality guidelines include the following findings:

- High TSS in the enclosed coastal water body, particularly during the wet season when the median value (16 mg L^{-1}) exceeded the wet season GV. The enclosed coastal annual mean (19 mg L^{-1}) was double the 2017–18 annual mean (7 mg L^{-1}). TSS was below GVs in the open coastal and mid-shelf water bodies (Figure 5-13, Table E-1).
- Mean Secchi depth was 1.3 m in the enclosed coastal water body, 5.2 m in the open coastal water body (not meeting the ≥10 m GV) and 13.2 m in the mid-shelf water body.
- NO_x concentrations exceeded the annual, wet season, and dry season GVs across all water bodies, with median concentrations of 2.8, 5.4, and 4.1 µg L^{-1} from the enclosed coastal to mid-shelf water bodies, respectively. Concentrations of NH_3 and PO_4 in the open coastal and mid-shelf also exceeded the relevant GVs, and PO_4 increased significantly compared to the previous year.
- Elevated Chl-*a* concentrations in the enclosed coastal water body (median 2.3 µg L^{-1}), decreasing to 1.3 and 1.0 in the open coastal and mid-shelf water bodies, respectively. These concentrations exceeded the guidelines for all water bodies and were two to three times higher than median concentrations during the 2017–18 sampling period.
- PN and PP concentrations also showed a notable increase above previous years, most likely due to changes in analytical methodology. PN and PP exceeded the wet season GVs for the enclosed coastal and open coastal water bodies, and PP (but not PN) exceeded the mid-shelf annual GV (although limited sampling means the results may not be representative of ambient condition*)*.

In terms of aquatic habitat exposure, seagrass meadows near the river mouths (enclosed coastal water body) were subject to high TSS concentrations during both ambient and event conditions (Figure 5-13). Other studies have measured high (>1000 mg L^{-1}) ambient suspended sediment concentrations in Normanby Basin estuaries due to sediment re-suspension by tidal currents, particularly during spring tides (Howley et al. 2018,Howley and Shellberg 2019; Crosswell et al. 2020). Seagrass meadows in the southern bay are largely limited to shallow coastal strips, most likely due to these conditions. Seagrass meadows in the open coastal water body near Cliff Island (Marrpa) were exposed to lower levels of suspended sediments (ambient mean 2.3 mg L^{-1} over three visits) but still had relatively low light availability at depth, with a mean Secchi depth of 3.2 m at CL01.

During the ambient sampling periods, coral reefs in the open coastal (Flinders Island) and mid-shelf (Edith, Wharton, Clack) water bodies were also exposed to low levels of suspended sediments (<5 mg L^{-1}) and increased light availability (up to 16.5 m Secchi depth), but higher levels of dissolved nutrients and Chl-*a* were measured in these areas compared to previous years. Flood events contributed high concentrations of nutrients to Princess Charlotte Bay waters; however, dissolved inorganic nutrient concentrations were above GVs during both wet season and dry season periods, indicating that the immediate influence of floodwater was not the only factor associated with the high concentrations.

Event water quality

Three major flood events influenced water quality in Princess Charlotte Bay over the 2018–19 wet season. The first flood event of the year occurred from late December to early January with a peak river discharge of 1405 $m^3 s^{-1}$ (Figure 5-10). No marine water quality samples were collected during this event.

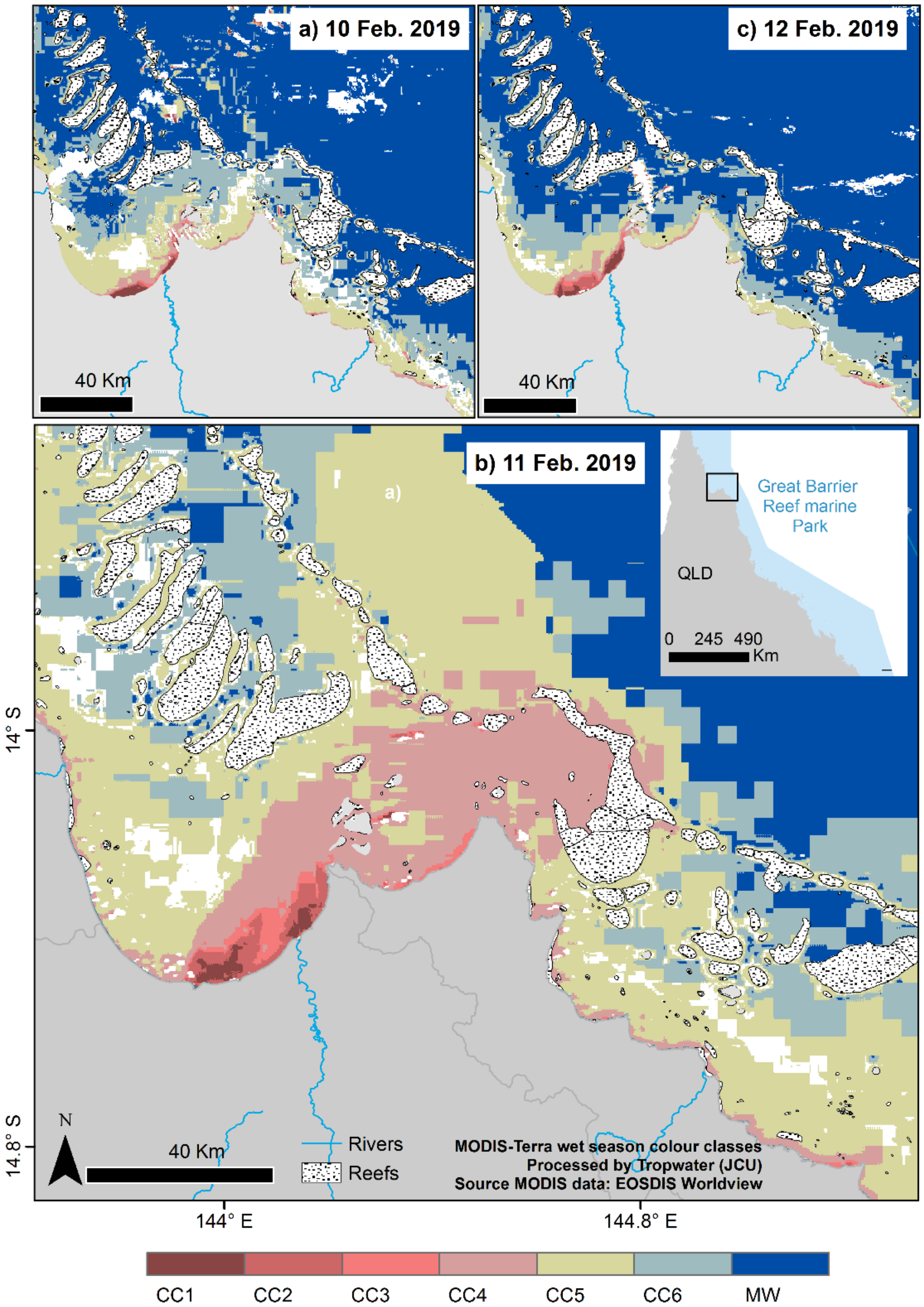

Figure 5-14: NASA Modis-Terra satellite images showing flood plume area of influence and colour classes during the February 2019 flood event in the Normanby Basin and surrounding area.

From 28 January–21 February, a second larger event [peak discharge 1840 $m^3 s^{-1}$ (Figure 5-10) on 2 December] discharged over 5000 GL water from the Basin into Princess Charlotte Bay. Satellite images over this period show primary and secondary plume water reaching beyond outer shelf reefs, over 70 km from the mouth of the Normanby River (Figure 5-14). Open coastal and mid-shelf reefs, such as fringing reefs around the Flinders Isles, were exposed to high turbidity and nutrient concentrations for over two weeks. Sampling across Princess Charlotte Bay occurred early in the event (30–31 January) and two weeks after the peak river discharge (18–20 February).

A third large magnitude event (peak discharge 2217 $m^3 s^{-1}$) occurred from 2 March–14 April following extensive rainfall associated with cyclone Trevor. River discharge in the Normanby reached historic highs and total estimated discharge to PCB was 3887 GL. Satellite images and field sampling close to the flood peak (27 March) showed that plume waters flowed north, mixed with discharge from the Stewart and other rivers, and inundated reefs in the open coastal, mid-shelf, and offshore water bodies (Figure 4-13).

Event sampling over the course of the January–February and March–April events found:

- Seagrass meadows in the EC water body were frequently exposed to high concentrations of suspended sediments (>100 mg L^{-1}). TSS concentrations >100mg L^{-1} (max 270 mg L^{-1}) were common over extended periods near river mouths during both events. TSS concentrations remained < 5.5 mg L^{-1} (mean 2.8 mg L^{-1}) in the open coastal and mid-shelf during event sampling periods, and
- Cliff Isles (Marrpa) in the open coastal water body was inundated with floodwaters over both events, with salinity ranging from 13–33 and Secchi depth ranging from 2.5–3.5 m. Secchi depth was 2.5 m at Cliff Isles (CL01) in the open coastal water body during both events.
- In the mid-shelf and open coastal water bodies, Secchi depth ranged from 9–16.5 m during the January–February event (at the time of sampling), but was ≤5 m in all water bodies near the peak of the March event (27 March)
- Highly elevated (above ambient) NO_x concentrations were measured in the open coastal and mid-shelf water bodies during both events (Figure 5-13). Maximum event DIN concentrations were measured at Cliff Isles (23.3 µg L^{-1}, 31 January) in the open coastal water body and Corbett Reef (131.3 µg L^{-1}, 27 March) in the offshore. FRP, DON, DOP, PN and PP peaked in the enclosed coastal water body during events.
- Maximum Chl-*a* concentrations also occurred in the enclosed coastal water body during events (maximum 4.52 µg L^{-1}), but concentrations as high as 4.25 µg L^{-1} were measured at Cliff Isles in the open coastal water body near the peak of the March flood event.

5.1.3 Stewart

The Stewart focus area 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.

Five sampling sites for the Stewart River are located in a transect from the river mouth to mid-shelf waters, representing a gradient in water quality (Figure 5-15). The transect (surface and subsurface) was sampled five times between December 2018 and June 2019, including four ambient periods and one flood event in late March (Figure 5-16). Additional samples were collected within floodwaters south and north of Magpie Reef (beyond the usual transect sites) during the March flood event. After the March 2019 Cyclone Trevor event, roads to the Stewart River region were damaged and the sampling team was unable to return until June via boat.

The total annual discharge for 2018–19 water year is estimated at 3109 GL based on the measurements from the upper Stewart River gauge 104001A (Figure 5-17) corrected for catchment area. This is 4.6 times greater than the long-term median annual discharge (Table 3-1).

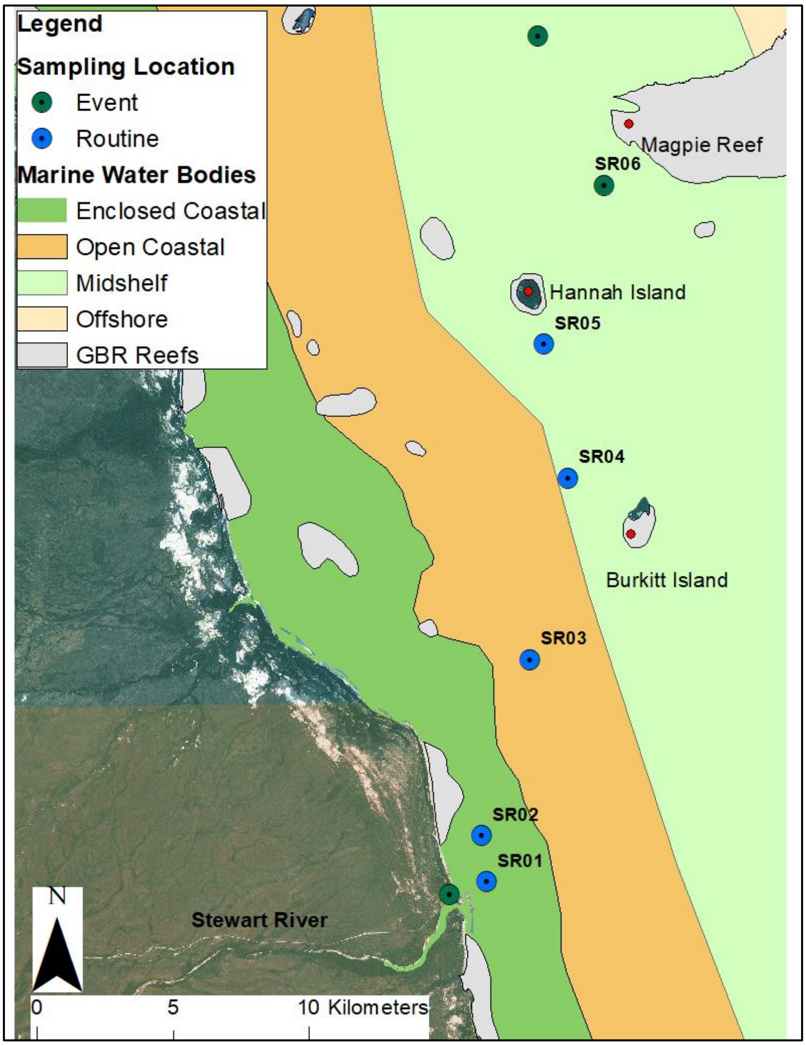

Figure 5-15: Water quality sampling sites in the Stewart River transect with water body boundaries.

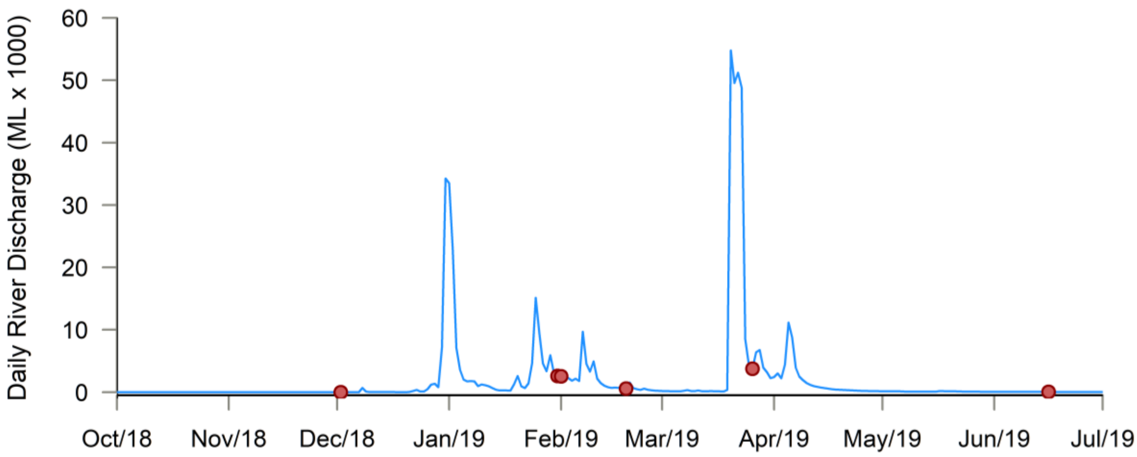

Figure 5-16: Daily discharge for the Stewart River (gauge 104001A) for the 2018–19 wet season. Red dot represents sampling date.

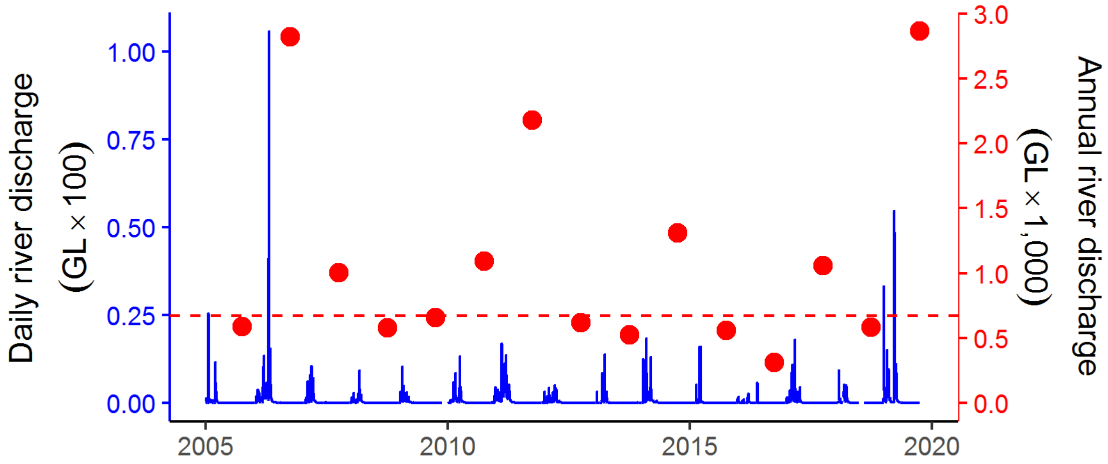

Figure 5-17: Long-term discharge for the Stewart River (gauge 104001A). Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge.

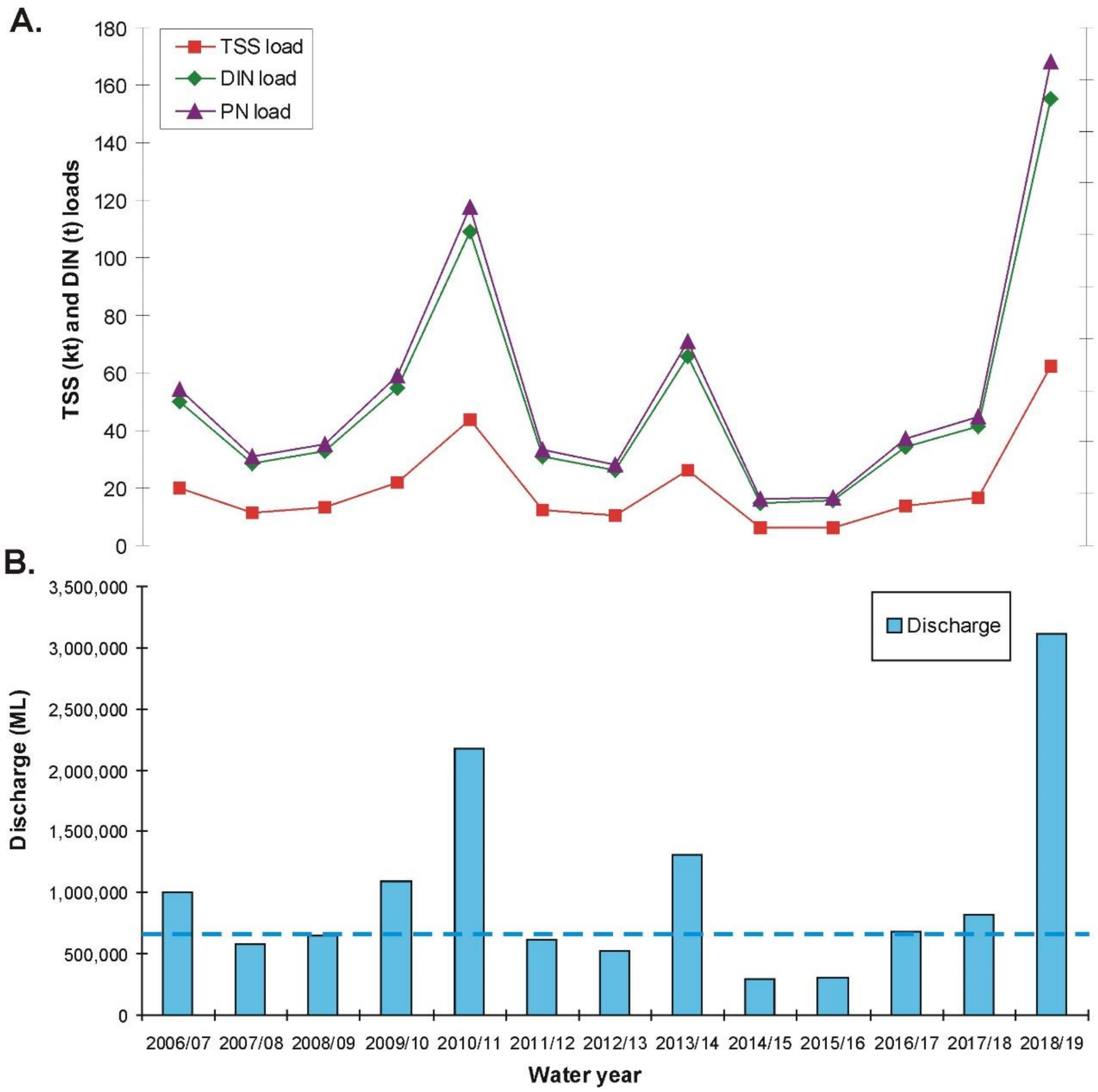

Figure 5-18. Loads of (A) TSS, DIN and PN, and (B) discharge for the Stewart Basin from 2006 to 2019. The loads reported here are based on the annual mean concentration reported in the Source Catchments modelling data and applied to each water year. Dotted line represents the long-term median for basin discharge. Note the different scales on the two y-axes.

The combined discharge and modelled loads estimated for the 2018–19 water year from the Stewart Basin are shown in Figure 5-18. The discharge and loads calculated for the 2018–19 water year from the Stewart Basin were the highest estimated over the previous decade. Over the 13-year period from 2006:

- discharge has varied from 299 GL (2014–15) to 3,109 GL (2018–19)
- TSS loads ranged from 6 kt (2014–15) to 62 kt (2018–19)
- DIN loads ranged from 15 t (2014–15) to 155 t (2010–11)
- PN loads ranged from 18 t (2015–16) to 187 t (2018–19).

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

Ambient water quality

During the 2018–19 water year, ambient water quality samples were collected along the Stewart River transect two times each under dry season and wet season conditions. The ambient and event sampling results are plotted against distance from the river mouth in Figure 5-20. Ambient results from the enclosed coastal, open coastal and mid-shelf water bodies are compared against the relevant annual, dry season and wet season GVs (Table E-1); however, it is noted that the small number of sampling trips may not be representative of conditions. A summary of the results is:

- Secchi depth increased from an annual mean of 2.5 m in the enclosed coastal to 4.7 m in the mid-shelf water body. Mean and median Secchi depths in all water bodies did not meet the minimum guideline values.
- Annual mean TSS was 8.2, 2.7, and 2.1 mg L^{-1} in the enclosed coastal, open coastal and mid-shelf water bodies respectively. Wet season median concentrations exceeded the water quality GVs in the open coastal zone.
- NO_x and PO_4 concentrations exceeded the relevant guidelines (annual, wet season, and dry season) for all water bodies. Median NH_3 concentrations exceeded the annual guidelines for the open coastal and mid-shelf.
- Annual median Chl-*a* concentrations increased substantially from the previous year in the enclosed coastal (0.45 µg L^{-1} in 2017–18 compared to 1.7 µg L^{-1} in 2018–19) and open coastal (0.29 µg L^{-1} in 2017–18 to 0.7 µg L^{-1}) water bodies. Chl-*a* concentrations exceeded the relevant wet season and dry season GVs in these water bodies. Median annual mid-shelf concentrations remained the same over both years (0.4 µg L^{-1}). This value exceeds the annual GV, but limited sampling means the results may not be representative of ambient condition.
- During the ambient sampling periods, fringing coral reefs to the north of the Stewart river mouth (Figure 5-15) were exposed to relatively high suspended sediment concentrations (as high as 26 mg L^{-1} at SR02). This is due to both the discharge of sediment to the coastal zone over multiple flood events and sediment resuspension. Reefs and seagrass meadows at Burkitt Island and Hannah Reef in the mid-shelf water body experienced low TSS concentrations (mean 1.0 mg L^{-1} at SR04 and SR05), but poor light availability at depth (mean Secchi depth 5.6 m).

Event water quality

Multiple flood events in both the Stewart River and Normanby Basin influenced water quality along the Stewart River transect over the 2018–19 wet season. This included two events (late December–early January and mid-March) with the highest instantaneous discharge rates measured over the past decade (Figure 5-17). Satellite images from mid-February (Figure 5-

14) and late March show flood plumes extending beyond coral reefs in the mid-shelf water body over multiple days.

Stewart River transect sampling on 31 January and 1 February coincided with minor flooding in the Stewart River and major flooding to the south in the Normanby Basin. TSS concentrations were between 18 to 26 mg L^{-1} in the enclosed coastal water body and <3 mg L^{-1} in the open coastal and mid-shelf water bodies. Secchi depths were low (compared to ambient) across the transect, with a maximum Secchi depth of 5.0 m in the mid-shelf. Mean Chl-*a* concentrations were 2.46 µg L^{-1} and 1.65 µg L^{-1} in the enclosed coastal and combined open coastal and mid-shelf water bodies, respectively. Two weeks later (19 February) some freshwater influence remained across the transect, most likely due to flooding in the Normanby Basin, however surface TSS concentrations dropped below 4 mg L^{-1} and Secchi depth increased to 10 m in the open coastal water body.

The largest Stewart river flood was associated with cyclone Trevor in mid-March (Figure 5-16). River discharge at the upper catchment gauge peaked at 1203 m^3 s^{-1} on 22 March and an estimated 1235 GL of water was discharged to the marine environment over five days. Field sampling occurred on 26 March, when satellite images showed turbid plume water across the whole region extending beyond the mid-shelf water body from the Stewart River, Normanby Basin, and possibly from flooded coastal wetlands and mud flats (Figure 5-19). The sampling results on this day showed:

- Freshwater influence reached beyond Hannah Reef (salinity 17.7) and Magpie Reef (salinity 20.2);
- A maximum TSS of 9.0 mg L^{-1} near the mouth of the Stewart River, decreasing to ≤3 mg L^{-1} in the open coastal and mid-shelf water bodies;
- Significantly elevated (above ambient) NO_x concentrations across all water bodies (Figure 5-20);
- Mean Chl-*a* concentration 1.34 µg L^{-1} in the open coastal and mid-shelf water bodies, maximum 2.94 µg L^{-1} in mid-shelf waters off Magpie Reef; and
- Mean Secchi depth 2.8 m in open coastal and mid-shelf water bodies, maximum 4.2 m at SR06 near Magpie Reef.

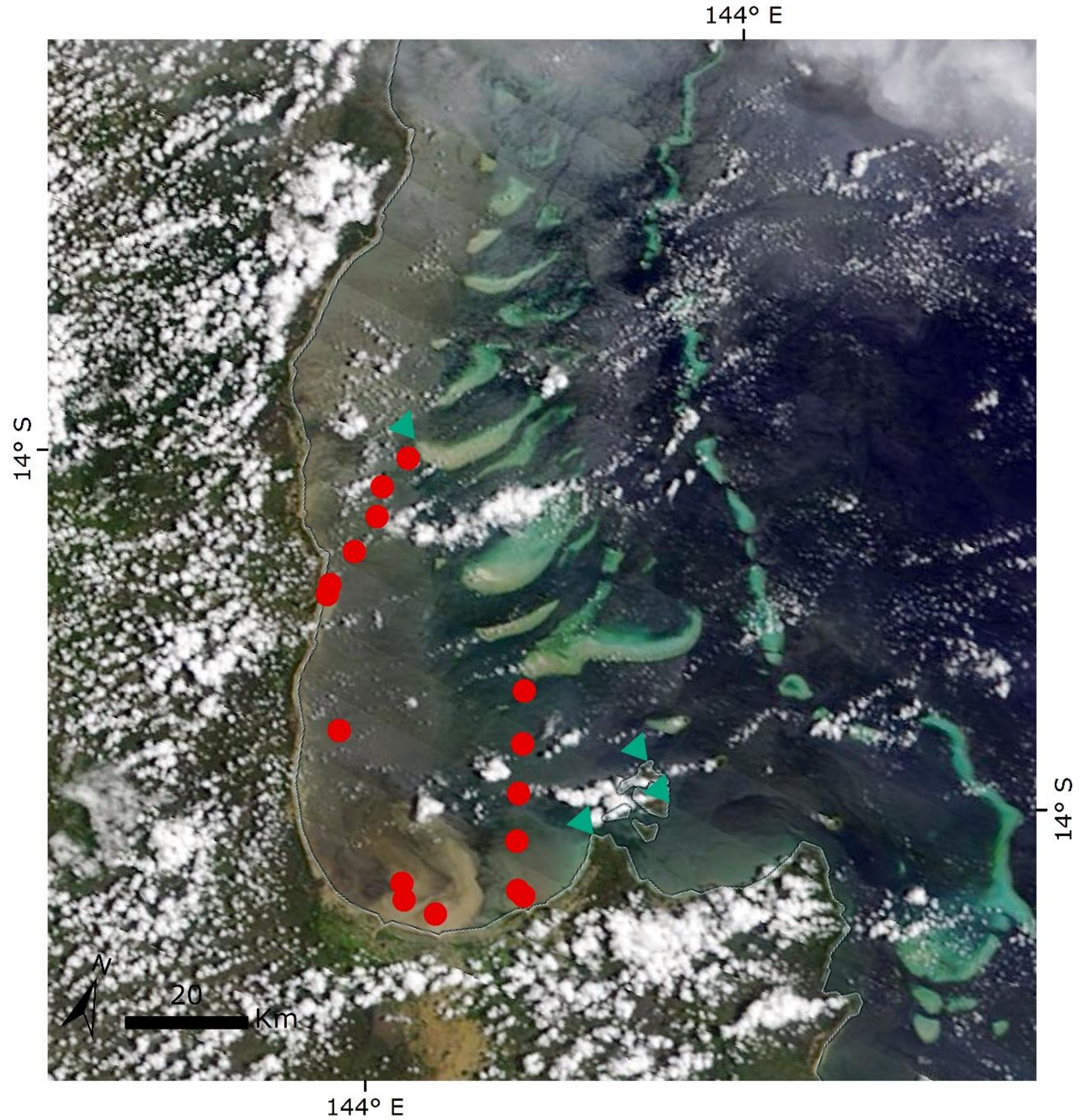

Figure 5-19: NASA MODIS Terra satellite image of Princess Charlotte Bay region on 26 March 2019 during flooding associated with severe tropical cyclone Trevor. Map shows Normanby/Kennedy and Stewart transect ambient (red circle) and event (blue triangle) sampling locations from 26 and 27 March.

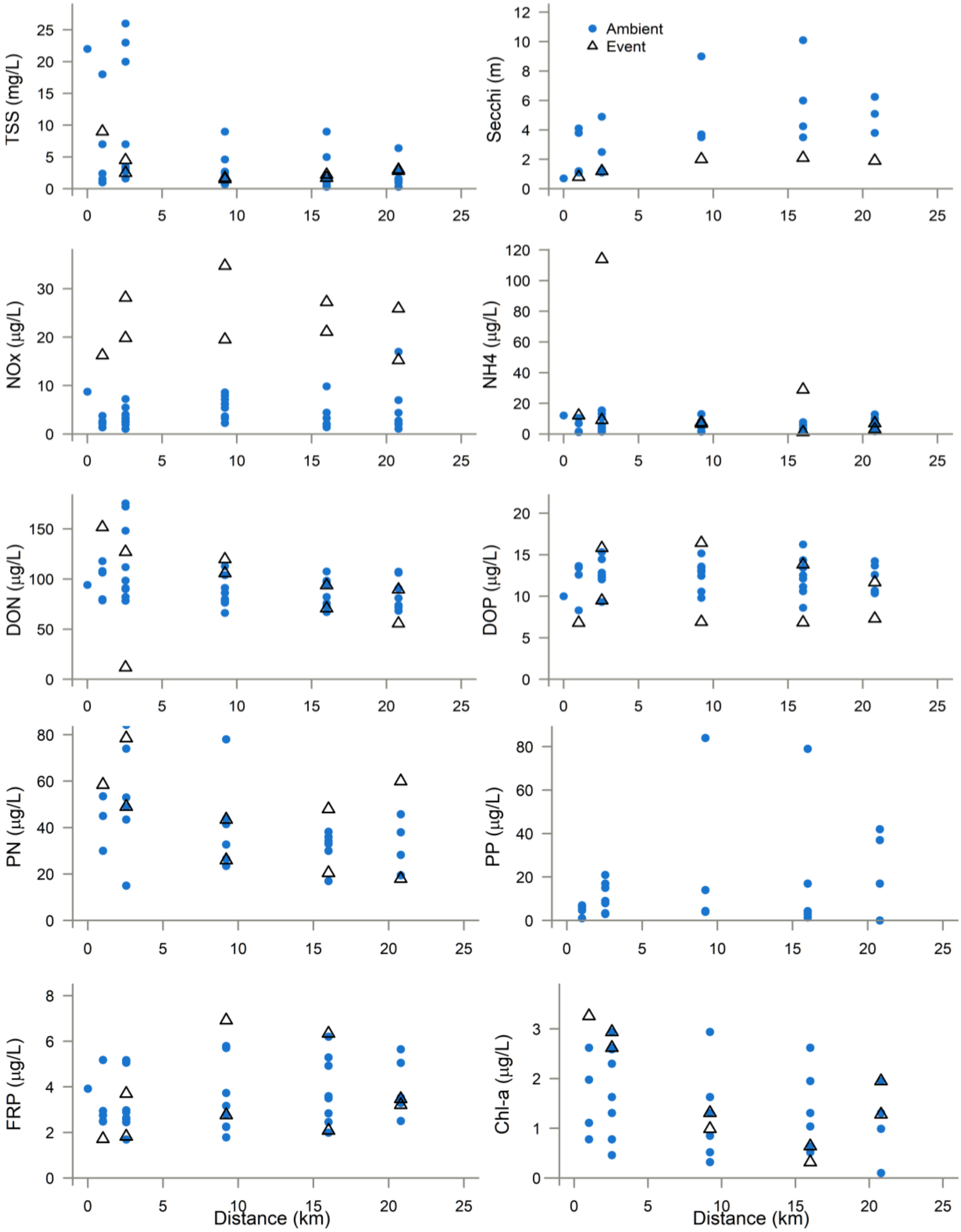

Figure 5-20: Water quality concentrations (surface and subsurface samples) and Secchi depth over distance (km) from river mouth for the Stewart River focus region, during ambient (blue circles) and flood (black triangles) conditions. The Water Quality Index has not been calculated for Cape York due to the lack of long-term data.

5.1.4Pascoe

The Pascoe focus area is influenced primarily by discharge from the Pascoe and Olive Rivers. During the first year of sampling (2016–17), five sampling sites (PRN1 to PRN5) were located along a transect from the mouth of the Pascoe River north to open coastal waters, and two additional sites were located to the south: PRS01 (south of the river mouth) and PRBB located at Middle Reef (locally known as Blue Bells). Due to the observance of floodwaters flowing to the southeast during the 2017–18 wet season, additional sites (PRS02, PRS03 and PRS05) were added along the southern transect at the end of the 2018 sampling season. During the 2018–19 sampling season, new site PRS2.5 replaced PRS2 and PRS03 (Figure 5-21), and site PRN5 was only sampled during major flood events that reached Eel Reef.

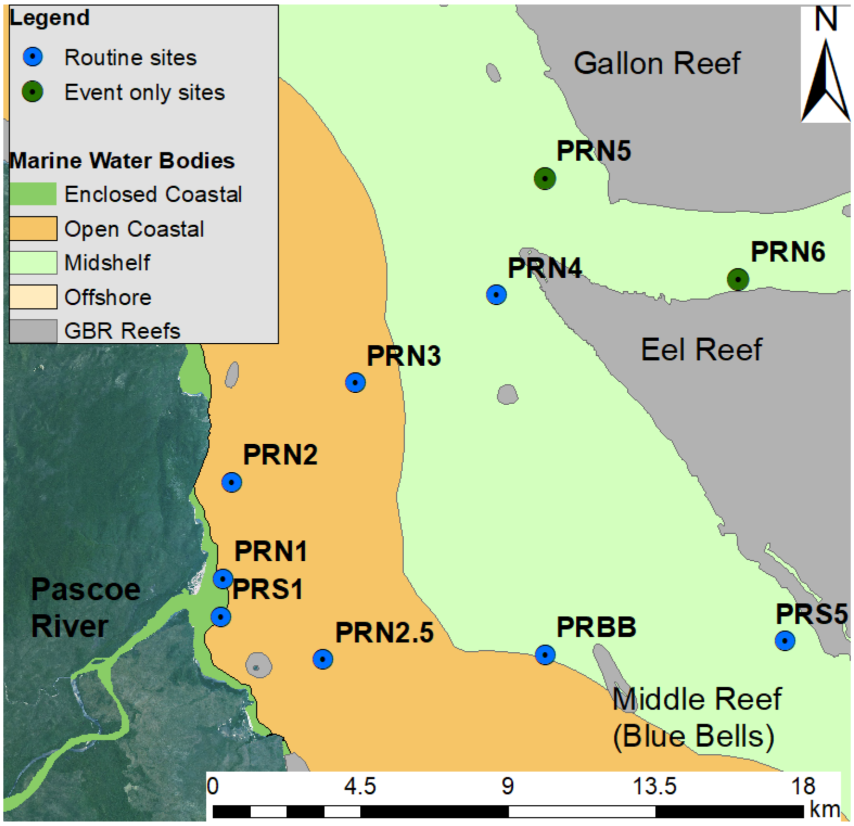

Figure 5-21: Water quality sampling sites in the Pascoe River transect with water body boundaries.

The Pascoe River transect was sampled four times from October 2018–March 2019 (Figure 5-22), including three ambient periods (40 surface and sub-surface samples) and one falling stage flood event (10 surface samples). Local roads and boat ramps on the Pascoe River were destroyed by cyclone Trevor in March 2019 and additional flooding in early April, and no further sampling was conducted after the 26 March sampling trip.

Annual discharge for the Pascoe River at the Garraway gauge was 2311 GL for the 2018–19 water year, which is approximately double the long term median annual discharge (Figure 5-23). Peak daily discharge (3464 $m^3 s^{-1}$) occurred at the Garraway gauge (located 42 km upstream from the mouth) on 20 March associated with the passing of cyclone Trevor to the south (Figure 5-22). Cyclone Trevor generated a total of 642 GL floodwater measured at the Garraway gauge (1024 GL upscaled to the Pascoe catchment) from 20–28 March, followed by a smaller flood event in early April that peaked at 1708 $m^3 s^{-1}$ with a total discharge of 520 GL (832 GL upscaled).

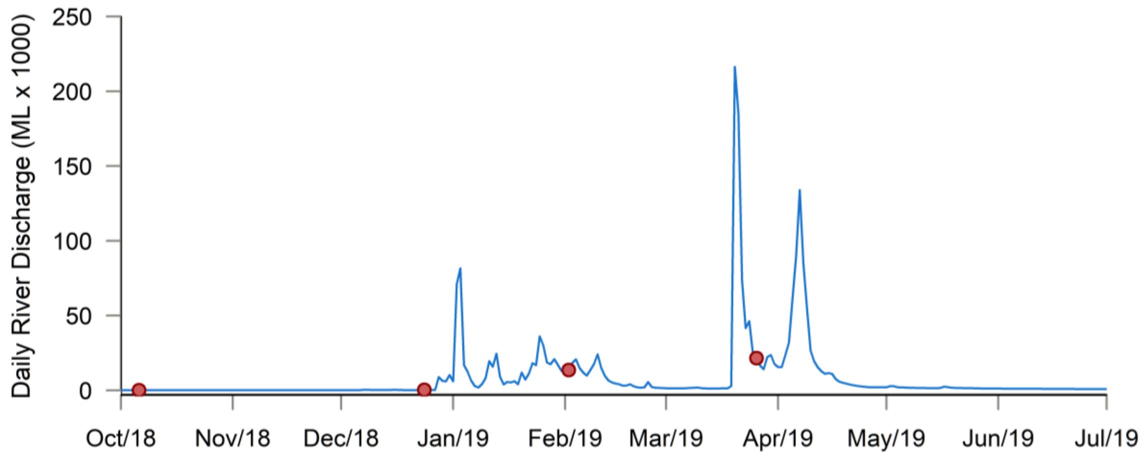

Figure 5-22: Daily discharge for the Pascoe River (gauge 102102A) for the 2018-19 water year. Red dots represent sampling dates.

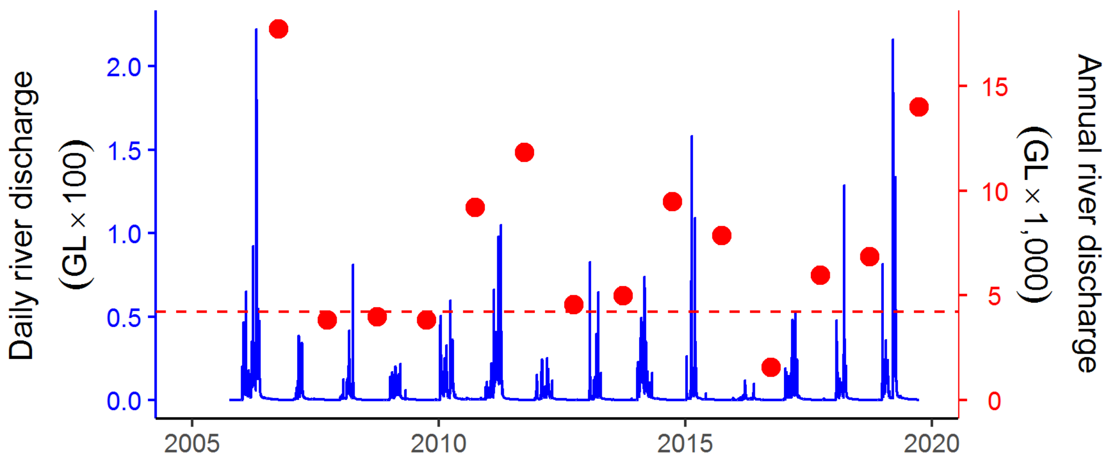

Figure 5-23: Long-term discharge for the Pascoe River (gauge 102102A). Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge.

The total discharge and modelled loads estimated for the 2018–19 water year from the Pascoe catchment (upscaled from the Garraway gauge) are shown in Figure 5-24. The loads calculated for the 2018–19 water year from the Pascoe catchment (not including the Olive catchment) were the highest estimated over the past decade. Over the 13-year period from 2006:

- discharge has varied from 425 GL (2015–16) to 3,770 GL (2018–19)
- modelled TSS loads ranged from 20 kt (2015–16) to 177 kt (2018–19)
- modelled DIN loads ranged from 28 t (2015–16) to 252 t (2018–19)
- modelled PN loads ranged from 59 t (2015–16) to 524 t (2018–19).

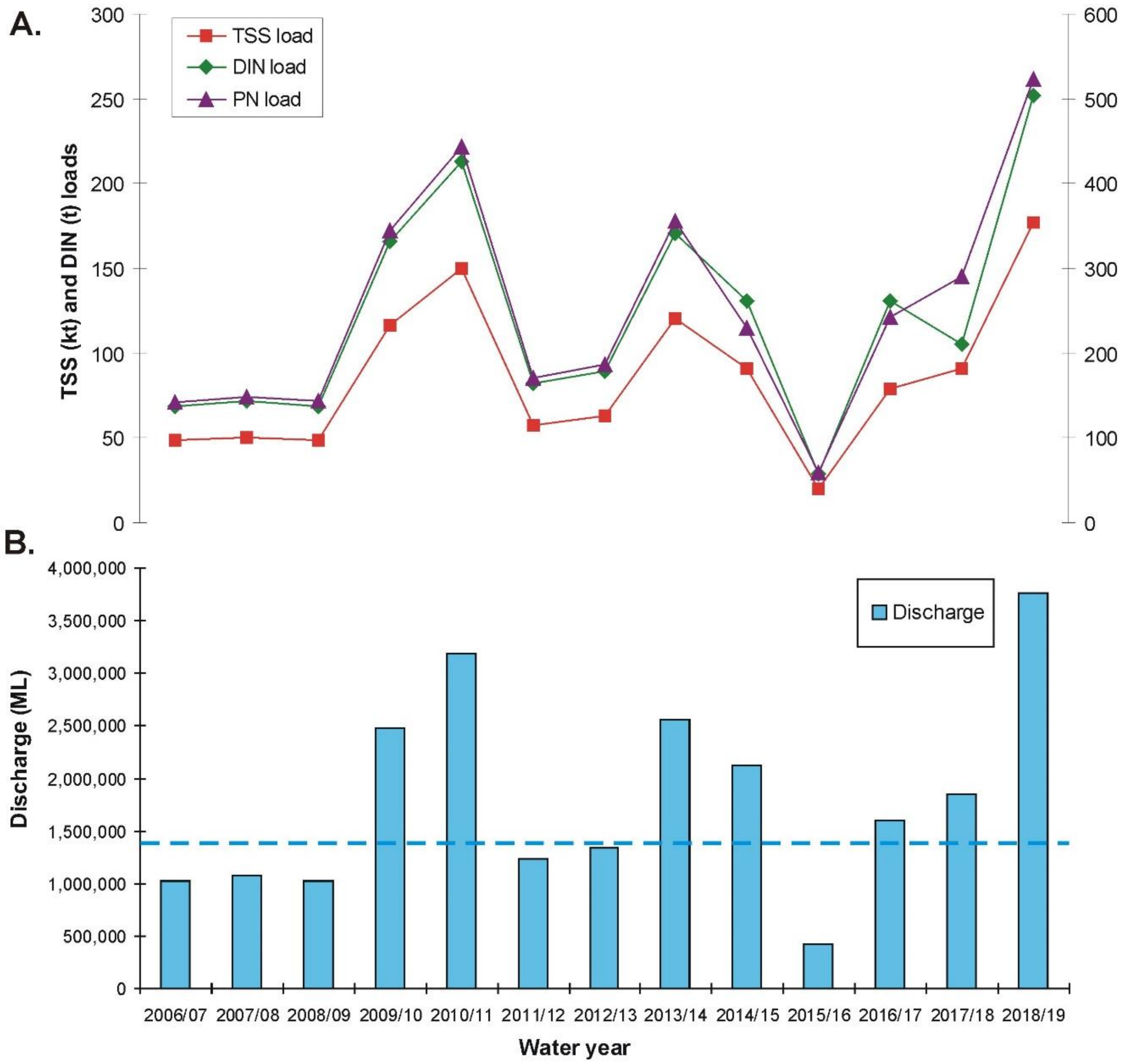

Figure 5-24: Modelled loads of (A) TSS, DIN and PN and (B) discharge for the Pascoe catchment (note Pascoe catchment only, does not include the Olive catchment) from 2006 to 2019. The loads reported here are a combination of 'best estimates' based on 'up-scaled' discharge data from gauging stations and monitoring data for 2014–15, 2016–17 and 2017–18) and an average of the annual mean concentrations for these three 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

During the 2018–19 water year, ambient samples were collected along the Pascoe transect once during the dry season and two times during the wet season. Infrastructure damage associated with cyclone Trevor at the end of March limited any additional sampling for the year. Ambient sampling in February was influenced by minor freshwater flooding. The results of both ambient and event sampling are plotted against distance from the river mouth in Figure 5-25. Ambient results from the enclosed coastal, open coastal and mid-shelf water bodies are compared against the annual, dry season and wet season GVs (Table E-1); however, it is noted that the small number of sampling trips may not be representative of ambient conditions.

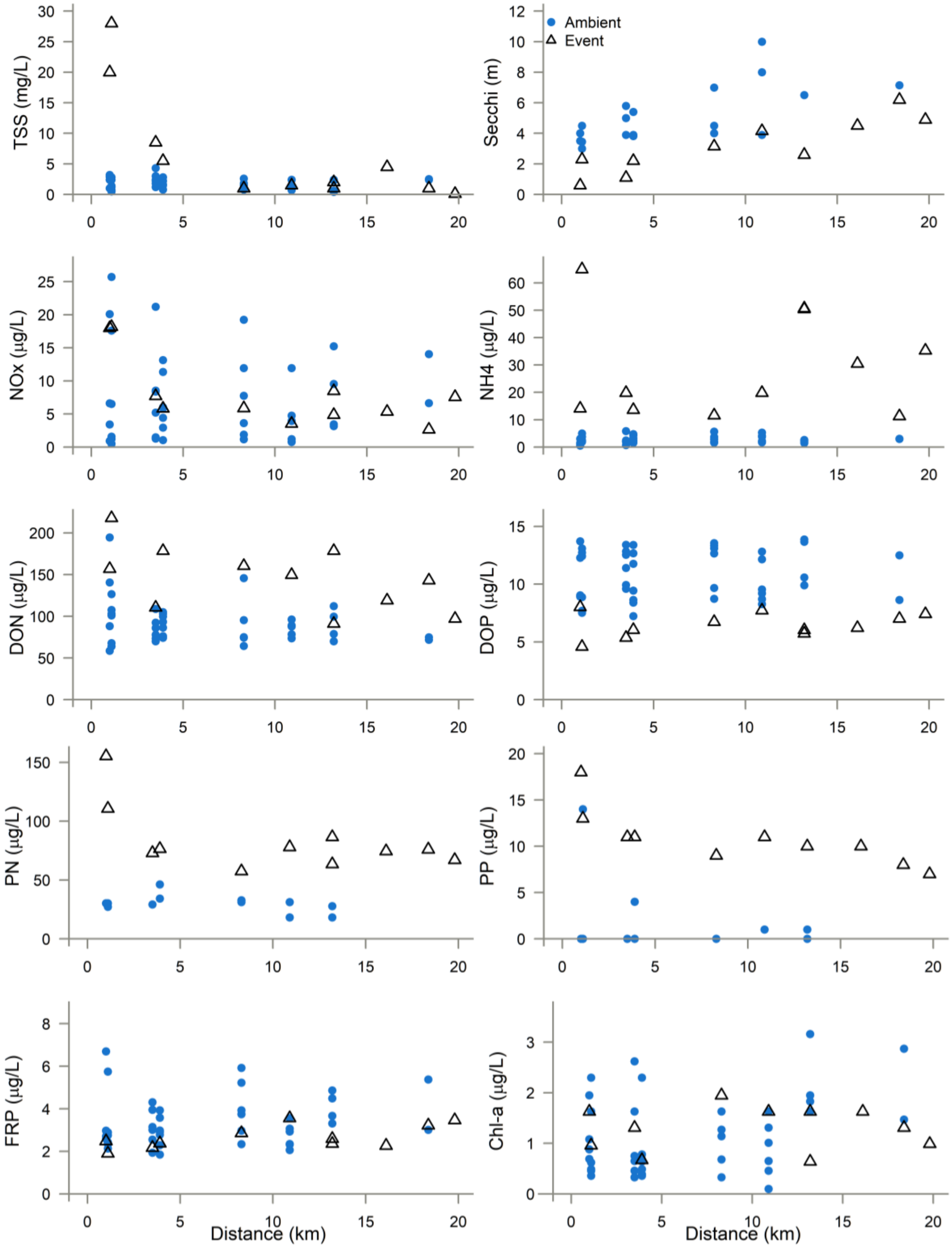

Figure 5-25: Water quality concentrations (surface and subsurface samples) and Secchi depth over distance (km) from river mouth for the Pascoe River focus region (all 2018–19 ambient and event samples).

Key findings from the 2018–19 ambient sampling results include:

- Ambient TSS concentrations generally met the annual (wet and dry season results combined) and wet season GVs in all water bodies.
- Combined wet and dry season mean Secchi depths in the open coastal water body (4.7 m) and mid-shelf water body (7.0 m) were below the annual guideline value (≥10 m; Figure 5-25).
- Combined wet and dry season NO_x, NH_3, and PO_4 concentrations in the open coastal and mid-shelf water bodies exceeded the annual guidelines. NO_x was an order of magnitude greater than guideline values. These analytes also exceeded wet season guidelines for the open coastal water body.
- Enclosed coastal water body wet season Chl-*a* results (median 1.4 µg L^{-1}) exceeded the water quality guidelines. Open coastal dry season and wet season medians (0.6 and 1.0 µg L^{-1} respectively) also exceeded the relevant guidelines. Combined wet and dry season Chl-*a* concentrations in the mid-shelf water body (median 1.6 µg L^{-1}) exceeded the annual water quality guidelines; however these samples were collected between October to January and are therefore not representative of annual concentrations
- The mean Pascoe transect ambient Chl-*a* concentration doubled from 0.6 µg L^{-1} in 2017–18 wet season to 1.2 µg L^{-1} over the 2018–19 wet season. Concentrations were particularly high during the February sampling event.

Event water quality

Water quality surface samples were collected from the Pascoe transect sites and additional sites past Eel Reef (within the flood plume) on 26 March 2019, on the falling limb of the cyclone Trevor flood event. This was the largest event of the year, with the highest discharge measured at the Pascoe River Garraway gauge in its 49-year history and a 1-in-32 year flood return interval (Figure 5-23).

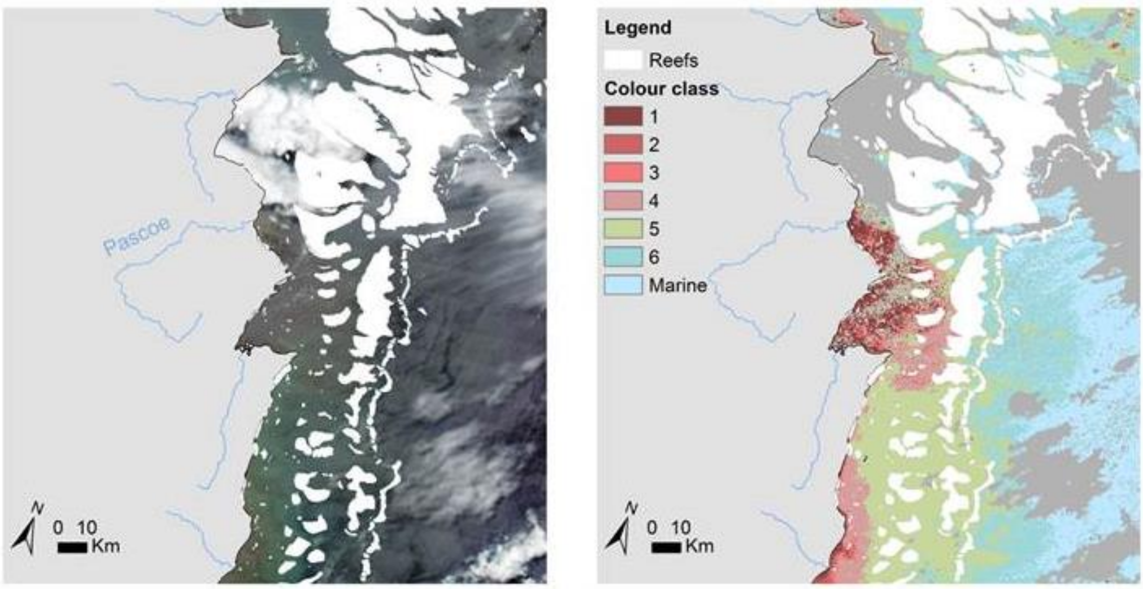

Figure 5-26: NASA Modis-Aqua True colour (left) and colour class (right) satellite images from 24 March 2019 showing flood plume area of influence and colour classes during the Cyclone Trevor flood event in the Pascoe River and surrounding area (images C. Petus, JCU).

Satellite images and field sampling showed that the flood plume extended beyond reefs in the mid-shelf water body (Figure 5-26). Sampling was conducted six days after the peak of the event, yet still showed freshwater influence at Eel Reef 19 km east of the river mouth (salinity 16–22). TSS ranged from 20–28 mg L^{-1} at the mouth of the river with a mean of 5.0 mg L^{-1} in the open coastal water body and 1.8 mg L^{-1} in the vicinity of mid-shelf reefs. Chl-*a* peaked at 1.95 µg L^{-1} in the open coastal water body on the day of sampling.

As an indication of event peak end-of-system concentrations, turbidity measured continuously on a YSI EXO2 in the estuary peaked around 279 NTU on 20 March (rising stage of the event), remained elevated above 50 NTU through 22 March, and decreased to 32 NTU at the time of coastal sampling on 26 March (Figure 5-27) (CYWMP and CSIRO unpublished data), coinciding with the lab measurement of 28 mg L^{-1} TSS at MMP site PR-N1. Chl-*a* in the estuary peaked at 6.93 µg L^{-1} during the event based on EXO2 measurements.

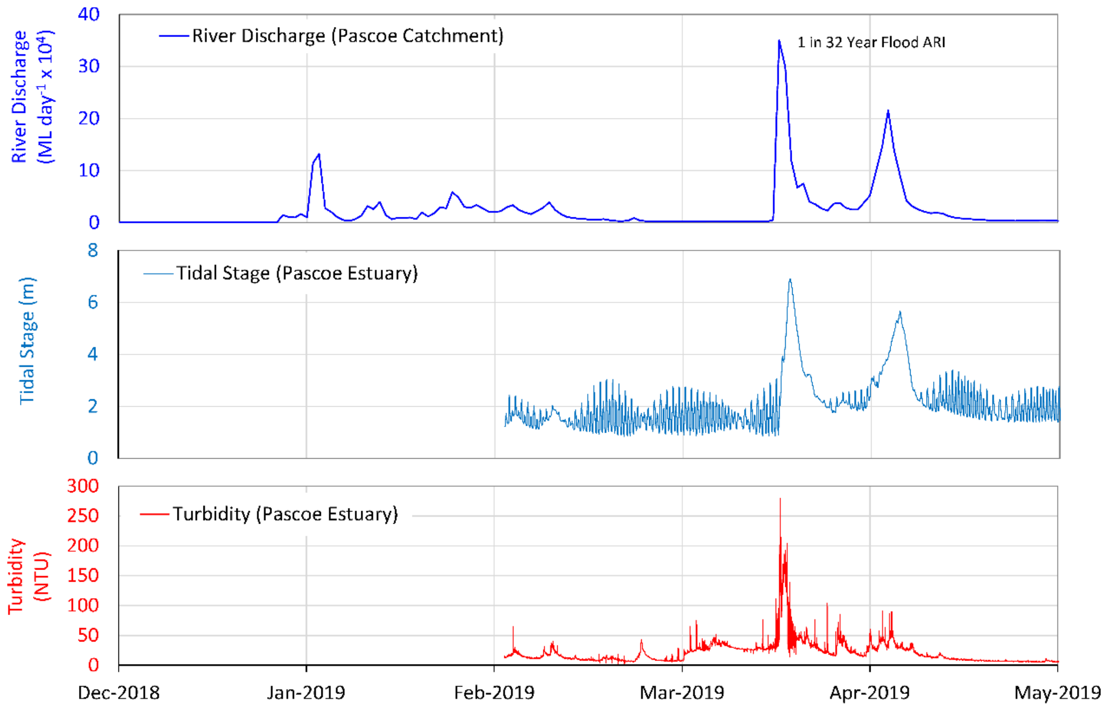

Figure 5-27: Pascoe River estuary continuous turbidity measurements compared against river discharge and tidal stage. Includes the turbidity response for the March 2019 1-in-32 year flood event. Figure supplied courtesy of J. Shellberg, L. Polglase and CSIRO.

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 5-28). 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.

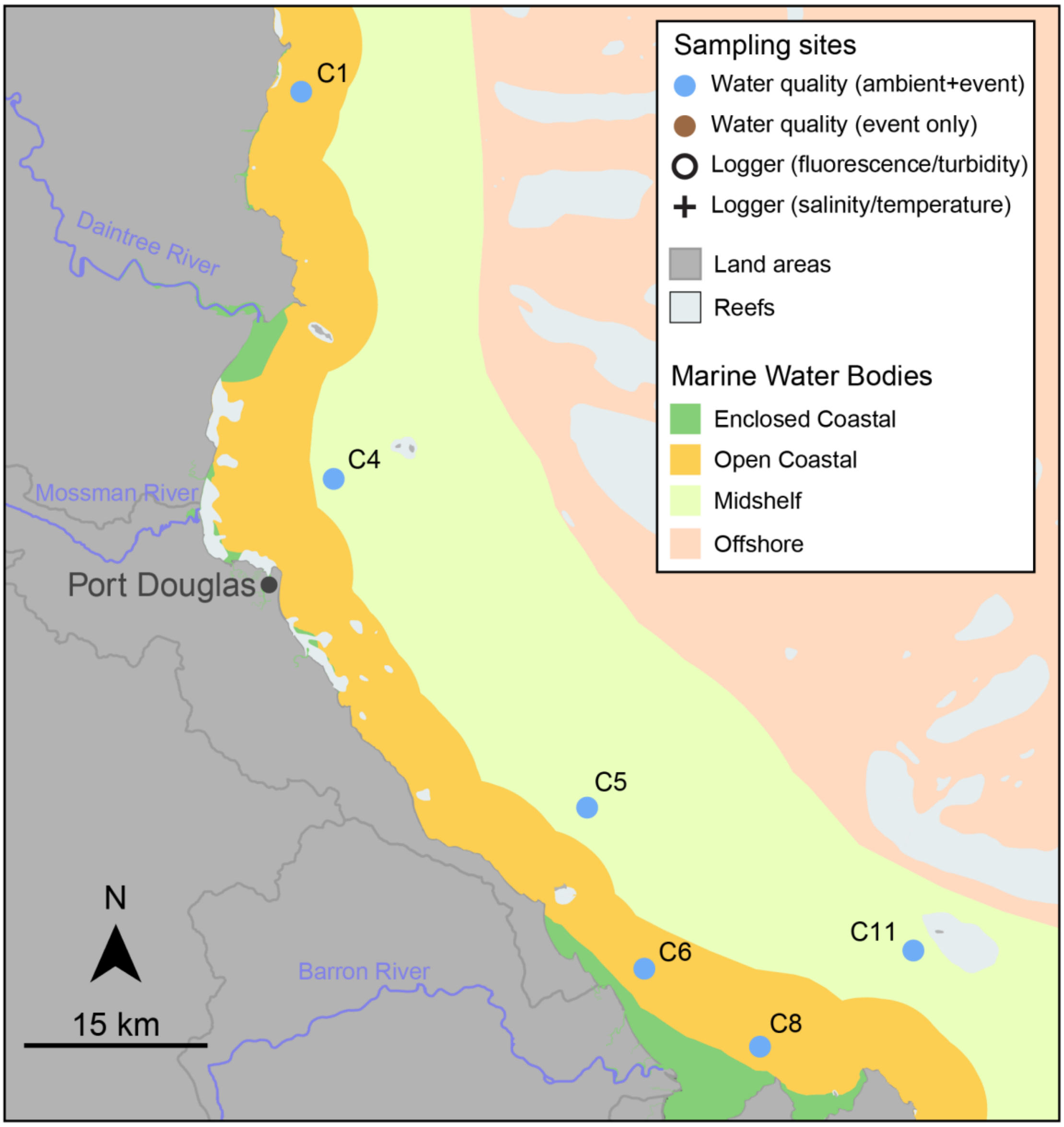

Figure 5-28: Sampling sites in the Barron Daintree focus region shown with water body boundaries.

The total discharge during the 2018–19 water year far exceeded the long-term median discharge (Figure 5-29), and was the largest on record since the start of the MMP.

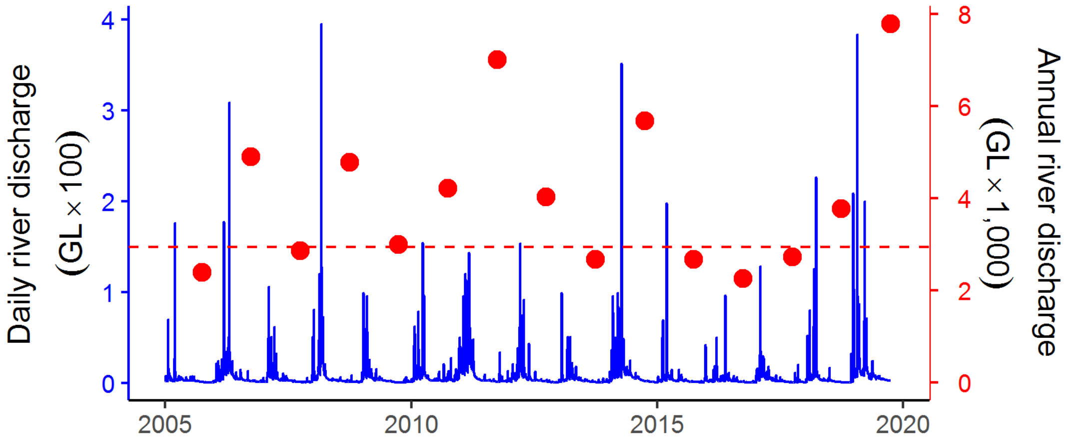

Figure 5-29: Combined discharge for the Barron (Myola gauge) and Daintree (Bairds gauge) Rivers. Daily (blue) and water year (October to September, red symbols) discharge volumes shown. Red dashed line represents long-term median of the combined annual discharge.

The combined discharge and loads calculated for the 2018–19 water year from the Barron, Daintree, and Mossman Basins were the highest recorded (Figure 5-30). The discharge from the Daintree Basin was over three times the long term median while the Mossman and Barron Basins were two to three times higher than the long-term median (Table 3-1). Over the 13-year period from 2006:

- discharge has varied from 2,518 GL (2015–16) to 8,174 GL (2018–19)
- TSS loads ranged from 156 kt (2015–16) to 697 kt (2010–11)
- DIN loads ranged from 231 t (2008–09) to 845 t (2018–19)
- PN loads ranged from 468 t (2015–16) to 2,092 t (2010–11).

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). However, in the 2018–19 water year, this focus region contributed similar discharge and consistent loads to the southern focus regions.

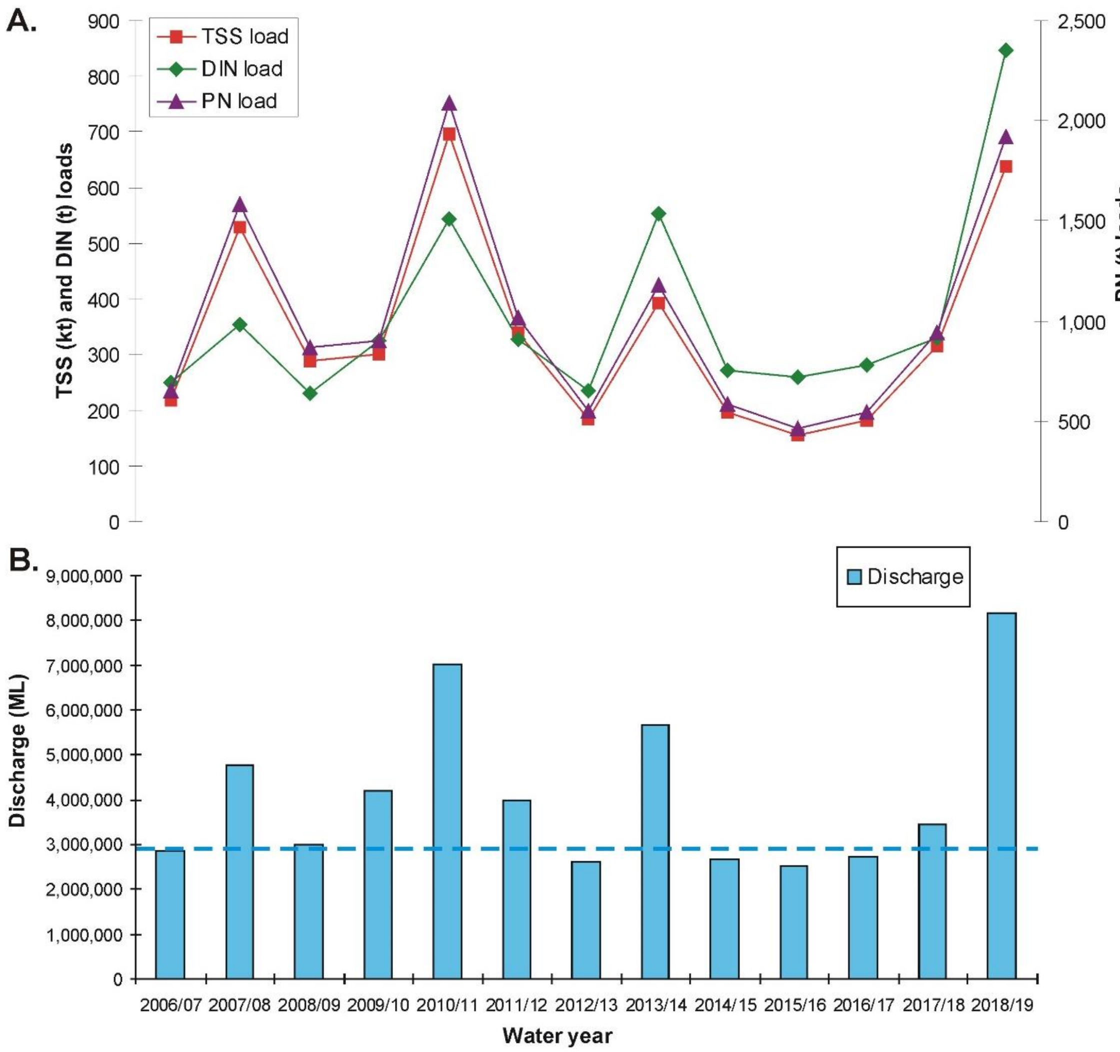

Figure 5-30: Loads of (A) TSS, DIN and PN and (B) discharge for the Barron, Daintree, and Mossman Basins from 2006–2019. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (Barron River), the DIN model 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 (e.g. not during peak flood events) of the dry and wet seasons are presented in Figure 5-31. It is important to note that the trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points can have slightly 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 in local weather and tides.

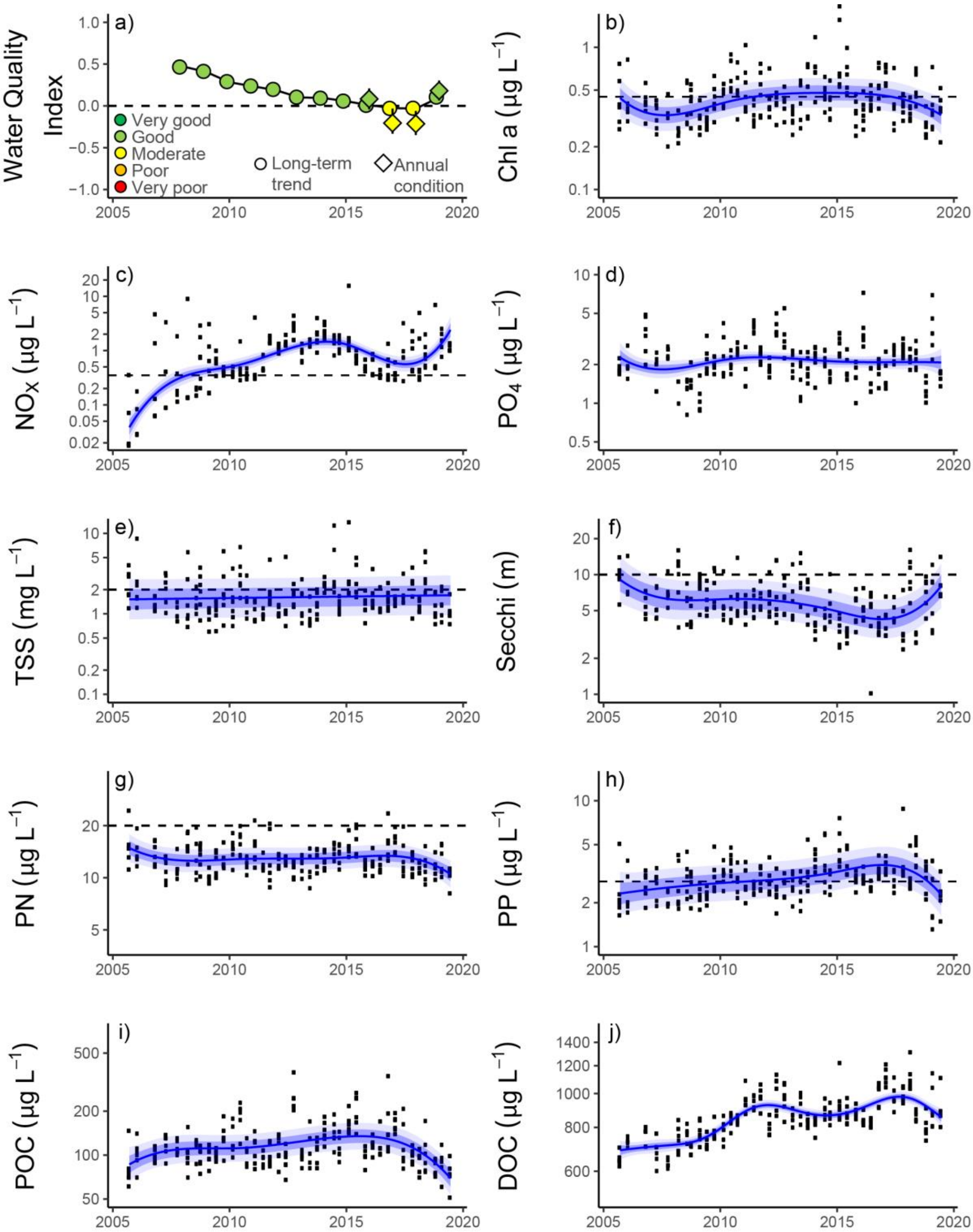

Figure 5-31: Temporal trends in water quality variables for the Barron Daintree focus region. a) WQ Index, b) chlorophyll *a* (Chl-*a*), c) nitrate/nitrite (NO_x), d) phosphate (PO_4), e) total suspended solids (TSS), f) Secchi depth, g) particulate nitrogen (PN), h) particulate phosphorus (PP), i) particulate organic carbon (POC) and j) dissolved organic carbon (DOC). The long-term trend in the WQ Index is shown by circles, while the annual condition uses diamonds. Error bars on the WQ Index represent the 95% quantile intervals. Calculations are described in Appendix D. Trends are represented by blue lines with shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves and tides after applying x-z detrending. 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 over time (Figure 5-31). Concentrations of Chl-*a* and TSS were relatively stable over time and mean values of these variables are currently very close to water quality GVs (Great Barrier Reef Marine Park Authority, 2010). Concentrations of PO_4 were relatively stable over time, whereas NO_x concentrations have generally increased since 2005 and are presently above GVs. Concentrations of NO_x reached a maximum in 2014–15 and declined in the following years; however, 2018–19 monitoring shows NO_x is currently increasing. Although Secchi depth declined (i.e. water clarity worsened) in previous years (up until 2017), current monitoring suggests that Secchi depth has increased in the last two years and is now close to the GV. Concentrations of PN are stable and below GVs, whereas PP concentrations are stable and close to GVs. Mean concentrations of POC have been relatively constant over the monitoring period, whereas concentrations of DOC have increased dramatically since monitoring began (Figure 5-31).

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) a metric for annual condition (based on the post-2015 sampling design, which increased the power to detect changes in water quality). 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 D contain details of the calculations for both indices.

The long-term WQ Index has generally scored water quality as 'good' since 2005 with two years of 'moderate' in 2017 and 2018. The long-term trend has been a small (i.e., changing by a single grade) but gradual decline in water quality since 2005 (Figure 5-31a, circles). The annual condition WQ Index scored water quality as 'moderate' in 2017 and 2018 and 'good' in 2019 (Figure 5-31a, diamonds). This version of the Index scores water quality parameters against GVs relevant to the season when samples are collected (wet versus dry GVs).

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 2018–19.

5.2.2 Russell-Mulgrave

The Russell-Mulgrave focus area is primarily influenced by discharge from the Russell-Mulgrave and Johnstone Basins and, to a lesser extent, by other rivers south of the focus area such as the Burdekin (Brodie et al., 2013; Waterhouse et al., 2017a). Three sites were sampled three times per year in this focus area 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 C-1). The monitoring sites in this new design are located in a transect from the river 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 5-32).

The combined discharge volume of the Russell-Mulgrave and Johnstone Rivers exceeded the long-term median over the 2018–19 water year and was similar to the annual discharge from the 2017–18 water year (Figure 5-33).

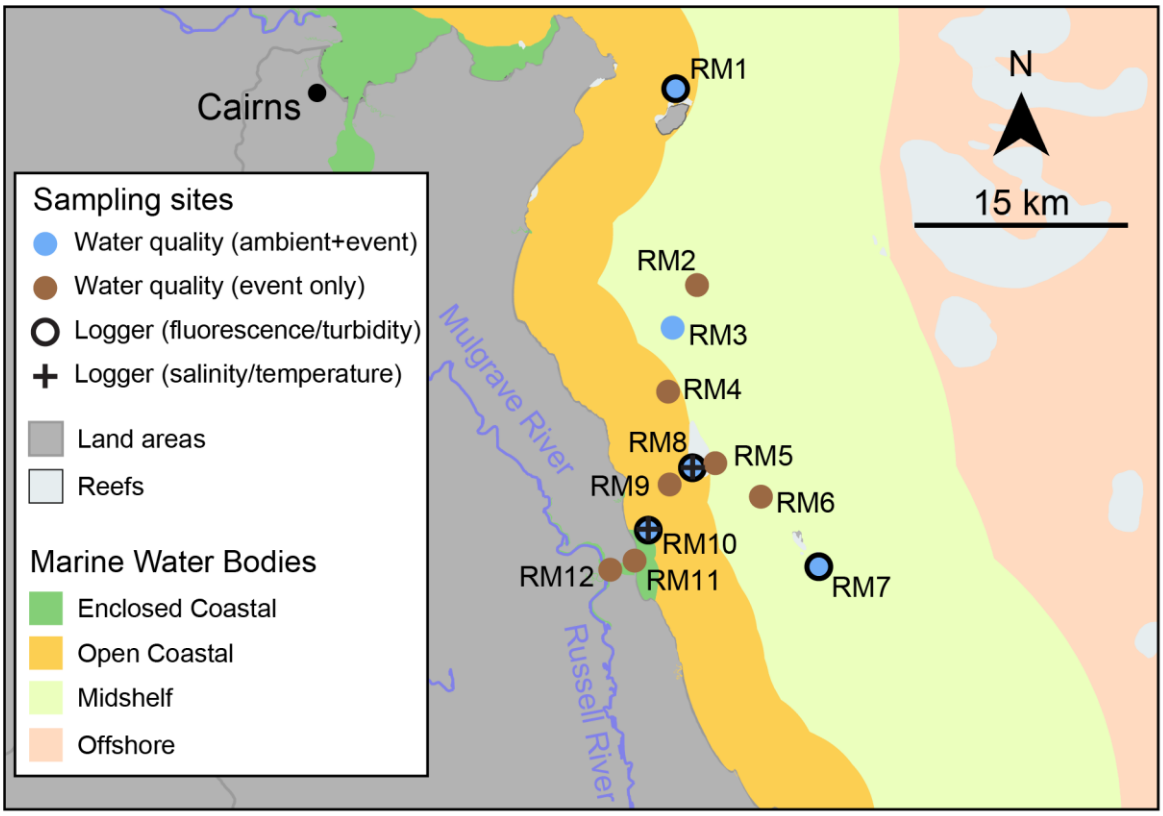

Figure 5-32: Sampling sites in the Russell-Mulgrave focus area, shown with the water body boundaries.

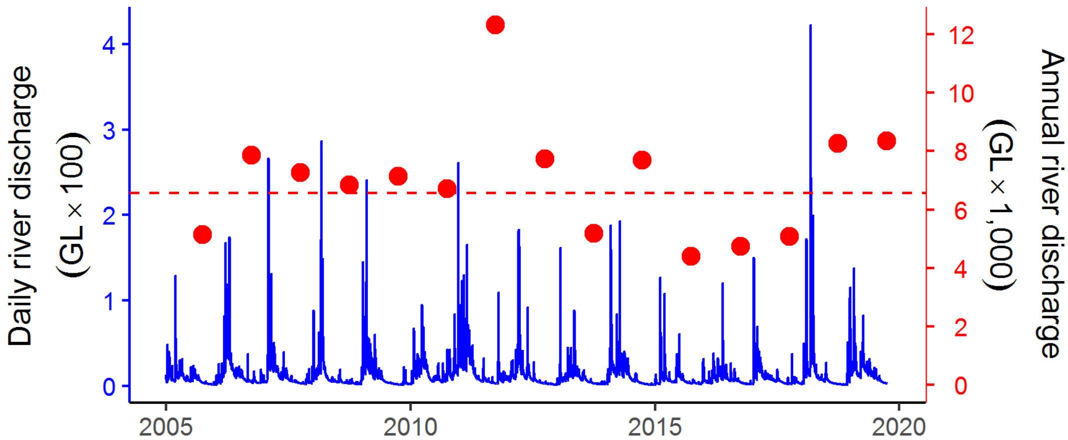

Figure 5-33: Combined discharge for the North and South Johnstone (Tung Oil and Central Mill gauges, respectively), Russell (Bucklands gauge) and Mulgrave (Peat's Bridge) Rivers. Daily (blue) and water year (October to September, red symbols) discharge is shown. Red dashed line represents the long-term median of the combined annual discharge.

The combined discharge and loads calculated for the 2018–19 water year from the Russell-Mulgrave and Johnstone Basins were in the higher range to that recorded over the past decade (Figure 5-34).

Discharge, TSS, PN and DIN loads were amongst the highest estimated since the large 2010–11 water year. Over the 13-year period:

- discharge has varied from 4,372 GL (2014–15) to 12,335 GL (2010–11)
- TSS loads ranged from 309 kt (2014–15) to 911 kt (2010–11)
- DIN loads ranged from 759 t (2014–15) to 2329 t (2010–11)
- PN loads ranged from 1290 t (2014–15) to 3783 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.

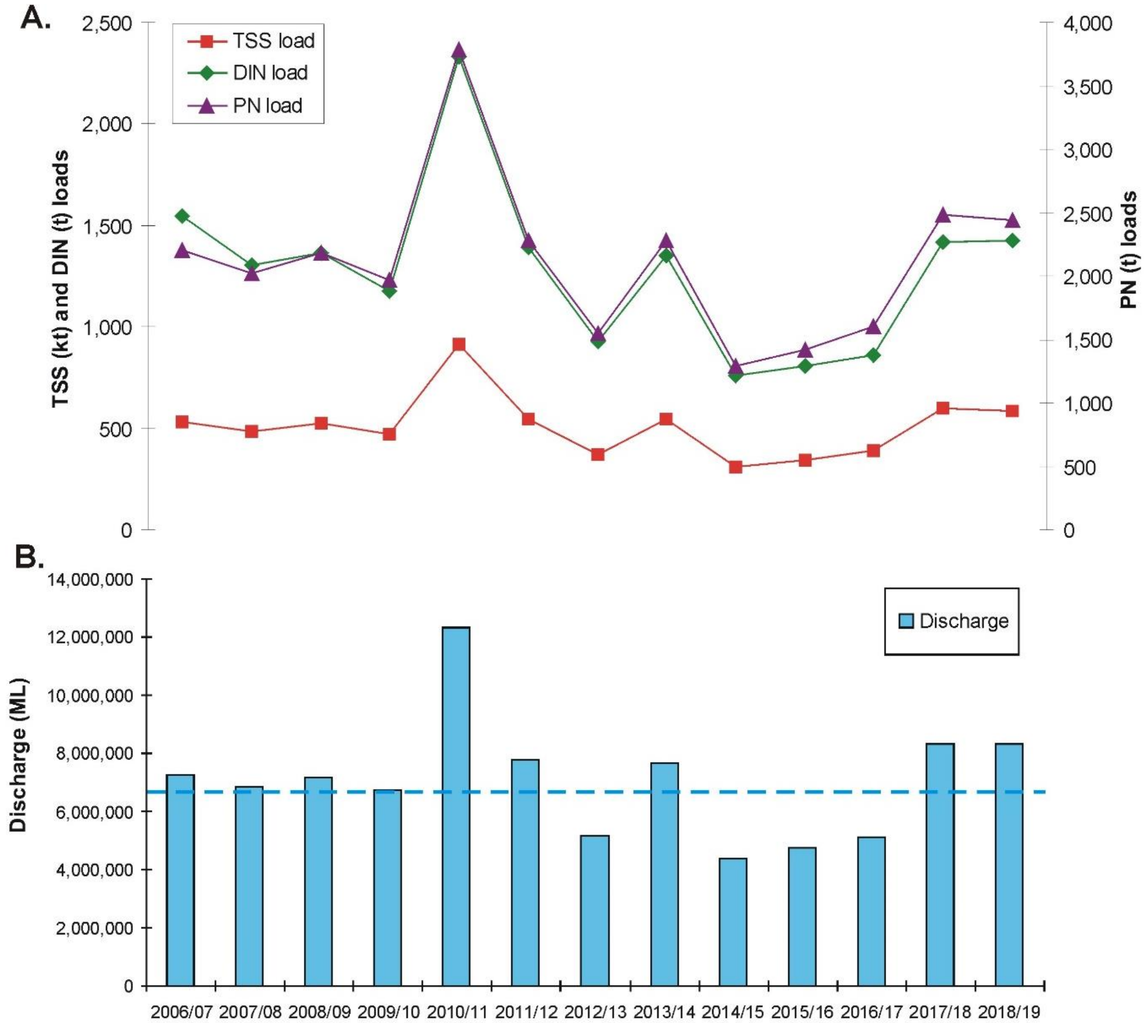

Figure 5-34: Loads of (A) TSS, DIN and PN and (B) discharge for the Russell, Mulgrave and Johnstone Basins from 2006 to 2019. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (Johnstone River), the DIN 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 (inshore to offshore gradient). Sites located in mid-estuarine and enclosed coastal water bodies (distance from river mouth = 0 km) had high concentrations of NO_x and particulate nutrients, while mid-shelf sites had much lower nutrient concentrations (Figure 5-35, Table E-2). Concentrations of Chl-*a* and TSS were greater in inshore waters (and could be highly variable), while Secchi depth increased with distance from the river mouth.

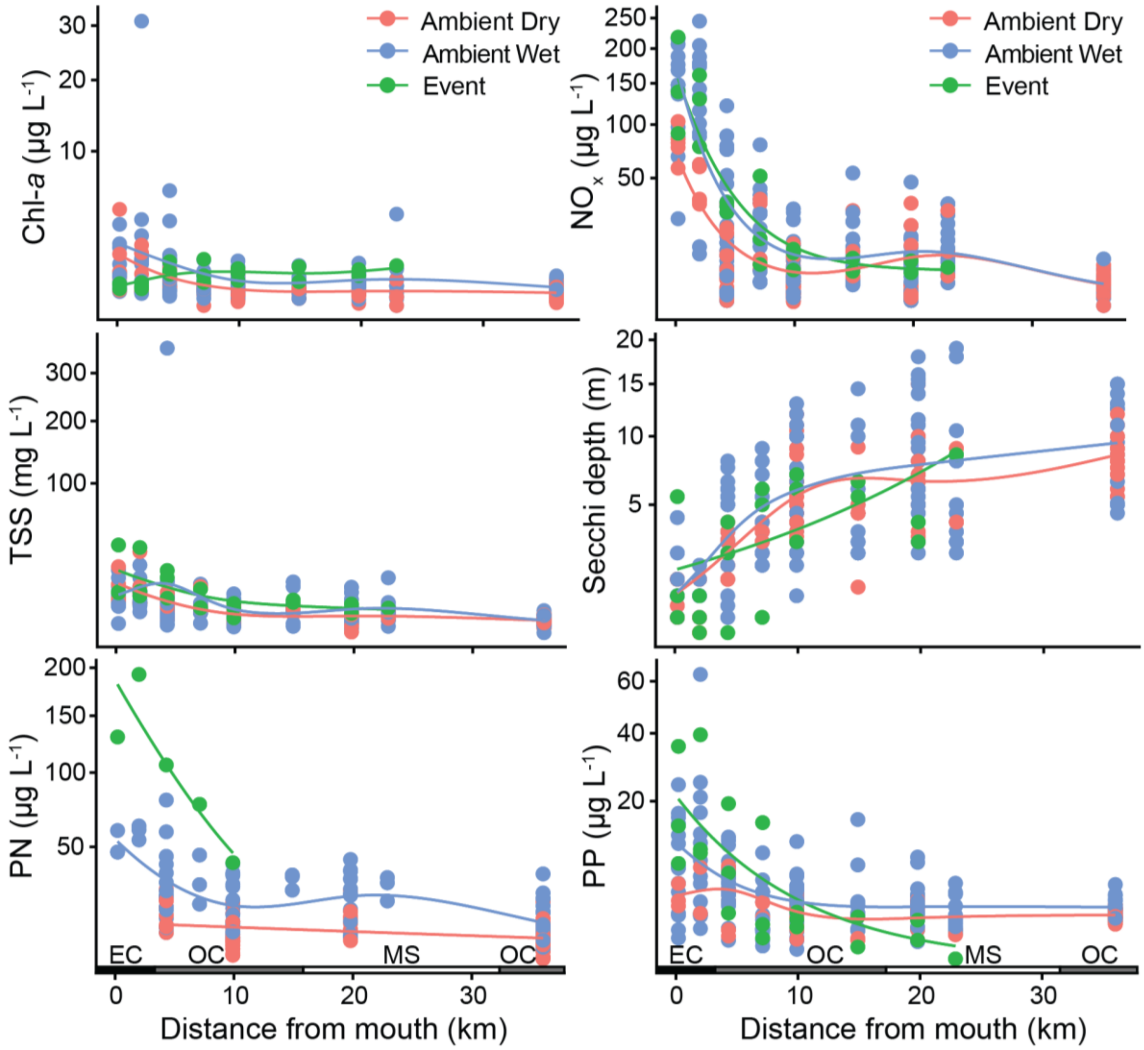

Figure 5-35: Water quality variables measured during ambient and event sampling in 2018-19 along the Russell-Mulgrave focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the Russell-Mulgrave river mouth. Water bodies are shown along the x-axes: Enclosed coastal (EC), open coastal (OC), and mid-shelf (MS). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

Seasonal differences in water quality were evident along the sampling transect. Ambient monitoring during the wet season showed generally greater values of nutrients, Chl-*a*, and TSS than dry season monitoring (Figure 5-35). Concentrations of NO_x displayed a large seasonal difference in the enclosed and open coastal water bodies near the Russell-Mulgrave River mouth but no seasonal difference at sites further from the river mouth where wet and dry season values converged, and where there is likely little influence of river discharge.

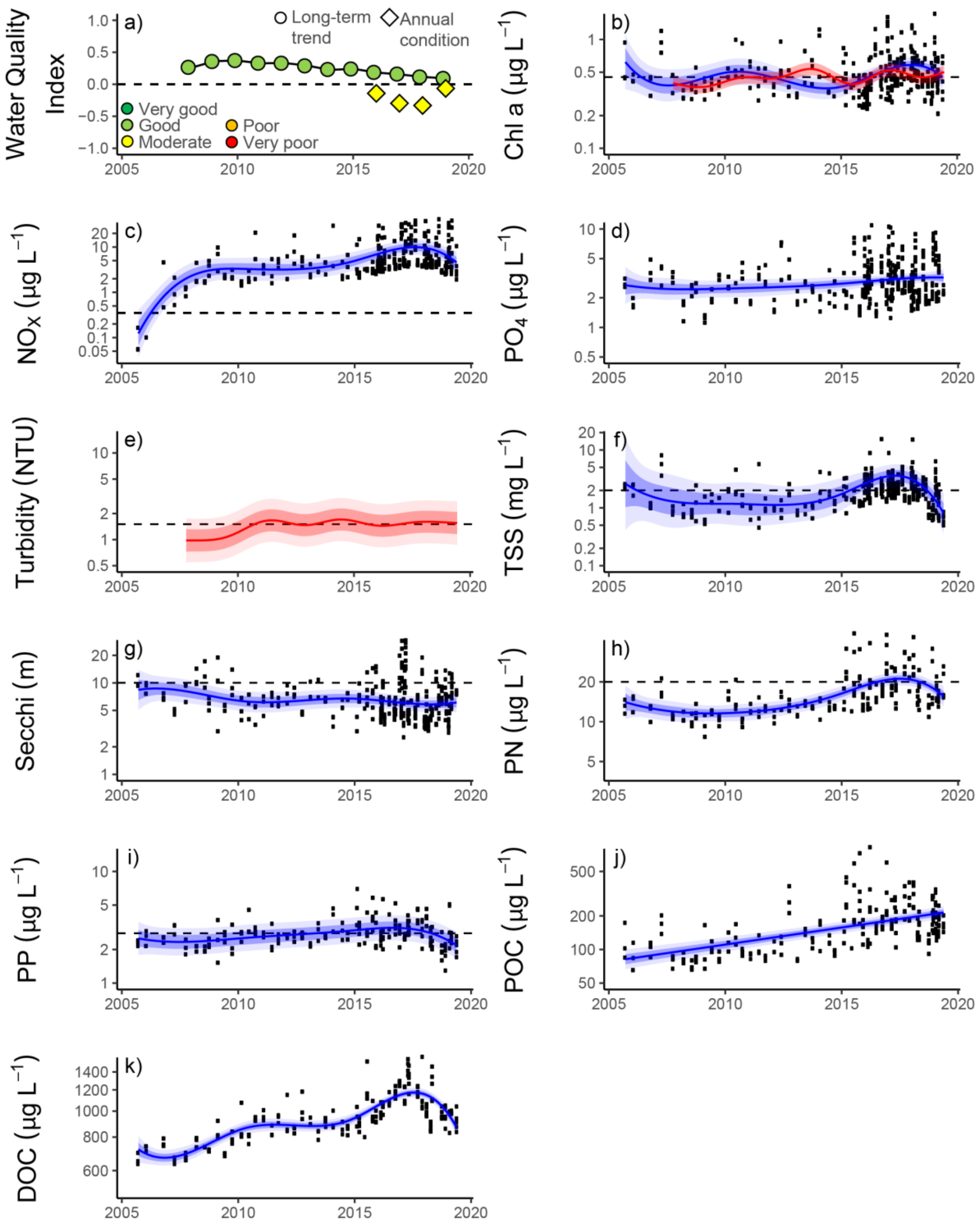

Figure 5-36: Temporal trends in water quality for the Russell-Mulgrave focus region. a) WQ Index, b) chlorophyll *a* (Chl-*a*), c) nitrate/nitrite (NO_x), d) phosphate (PO_4), e) turbidity, f) total suspended solids (TSS), g) Secchi depth, h) particulate nitrogen (PN), i) particulate phosphorus (PP), j) particulate organic carbon (POC) and k) dissolved organic carbon (DOC). The long-term trend in the WQ Index is depicted with circles, while the annual condition uses diamonds. Error bars on the WQ Index represent the 95% quantile intervals. Calculations are described in Appendix D. Trends are represented by blue lines with blue shaded areas defining 95% confidence intervals accounting for the effects of wind, waves and tides after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, individual records are not displayed (Figure E-1). Dashed horizontal reference lines indicate annual guidelines.

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 5-36. It is important to note that the trend analysis used removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points can have slightly 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 in local weather and tides.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change over time (Figure 5-36). Concentrations of Chl-*a* have been relatively stable over time, and mean values of Chl-*a* derived from logger and water samples are presently at the water quality GV (Great Barrier Reef Marine Park Authority, 2010). Concentrations of TSS have varied since 2005 and are presently meet the GV (Figure 5-36f). Concentrations of PO_4 and NO_x have been relatively stable over time, and both are presently exceeding GVs (Figure 5-36c,d). Secchi depth has gradually declined (i.e. water clarity has worsened) since 2005, and current values are not meeting the GV (Figure 5-36g). Concentrations of PN have varied since 2005 and are presently near the GV (Figure 5-36h), while PP concentrations have remained relatively stable since 2005 and are also near the GV (Figure 5-36i). Concentrations of POC and DOC have generally increased since monitoring began (Figure 5-36j,k), although DOC concentrations have declined over the last two years.

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

The long-term WQ Index has scored water quality as ‘good’ since 2005. The long-term trend has been a small but gradual decline in water quality since 2009 (Figure 5-36a, circles).

The annual condition WQ Index scored water quality as ‘moderate’ for the last four years (Figure 5-36a, diamonds). 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 Russell-Mulgrave Basin had five flow events of note over the December–April wet season period with no event reaching moderate or major flooding levels. The largest flow event for the Russell-Mulgrave in the 2018–19 water year peaked on 27 January and selected MMP sites were sampled on 30 January (Figure 5-37). Not all sites in the mid-shelf water body could be sampled during this trip due to deteriorating weather conditions.

Event water quality showed trends along the sampling transect (inshore to offshore gradient). Sites located in mid-estuarine and enclosed coastal water bodies (distance from river mouth = 0 km) had high concentrations of NO_x and particulate nutrients, while open coastal sites had much lower nutrient concentrations (Figure 5-35). Particulate nutrient concentrations (especially PN) exceeded ambient wet season concentrations during events. A Chl-*a* maximum occurred at open coastal sites (~8 km from Russell-Mulgrave River mouth) during event sampling, as this region has sufficient light and high nutrient concentrations to support phytoplankton bloom development. Concentrations of TSS were greater in inshore waters (and could be highly variable), and patterns along the transect (i.e., gradients away from the river mouth) were similar to ambient wet season monitoring. Secchi depth was much lower (water clarity was lower) during events than ambient periods at inshore sites, but Secchi depth increased with distance from the river mouth.

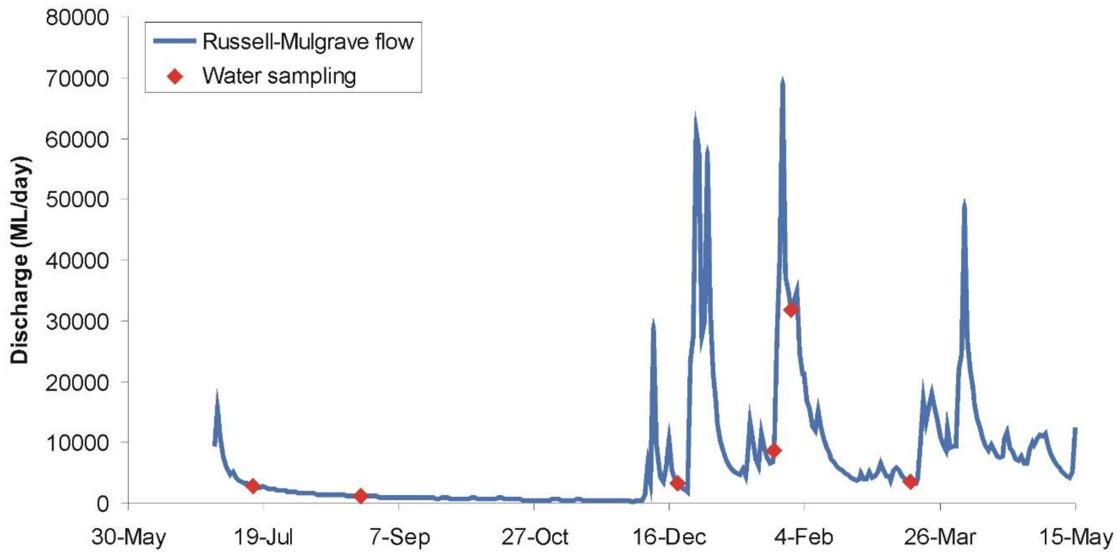

Figure 5-37: River discharge (in ML d^{-1}) from 1 July 2018–15 May 2019 for the combined Russell River at Bucklands and Mulgrave River at Peets Bridge gauges. Red diamonds show when water sampling occurred offshore from the river mouth in the Russell-Mulgrave focus area.

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).

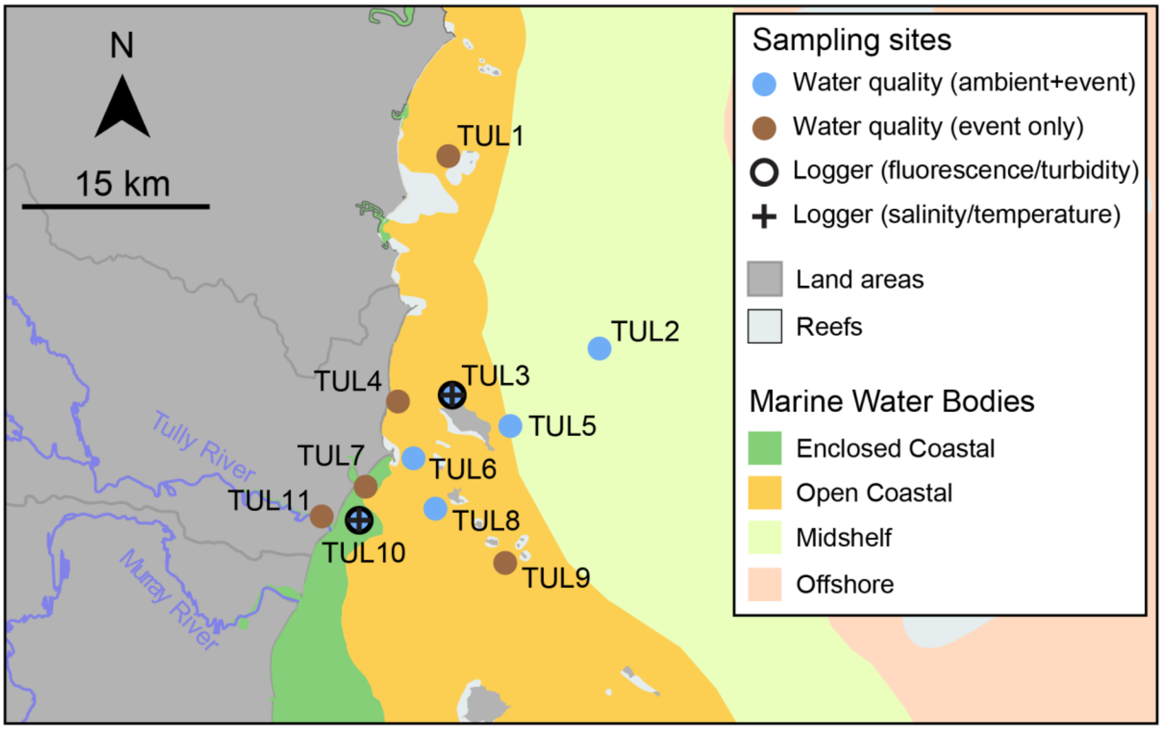

Figure 5-38: Sampling sites in the Tully focus area, shown with the water body boundaries.

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 C-1). The monitoring sites in this new design 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 5-38).

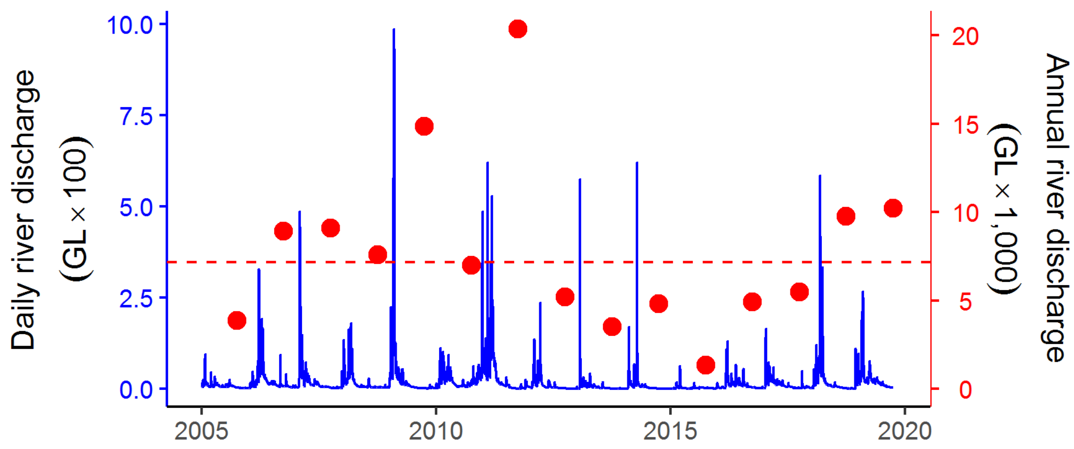

Figure 5-39: Combined discharge for Tully (Euramo gauge) and Herbert (Ingham gauge) Rivers. Daily (blue) and water year (October to September, red) discharge is shown. Red dashed line represents the long-term median of the combined annual discharge. Please note as this is the combined discharge, high flows in one river will not necessarily be visible in the graph.

The total discharge for the Tully and Herbert Rivers in 2018–19 was above than the long-term median (Figure 5-39). The total basin discharge for the 2018–19 water year (1 October 2018–September 2019) was 1.2 times above the long-term median. The annual discharge from the Herbert River was ~1.5 times higher than the long-term median, while the annual Tully River discharge was similar to the long-term median (Table 3-1).

The combined discharge and loads calculated for the 2018–19 water year from the Tully, Murray, and Herbert Basins were in the higher range recorded over the past decade (Figure 5-40). Over the 13-year period:

- discharge has varied from 3,647 GL (2014–15) to 20,738 GL (2010–11)
- TSS loads ranged from 188 kt (2014–15) to 1,530 kt (2010–11)
- DIN loads ranged from 956 t (2014–15) to 6,084 t (2010–11)
- PN loads ranged from 653 t (2014–15) to 4,330 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.

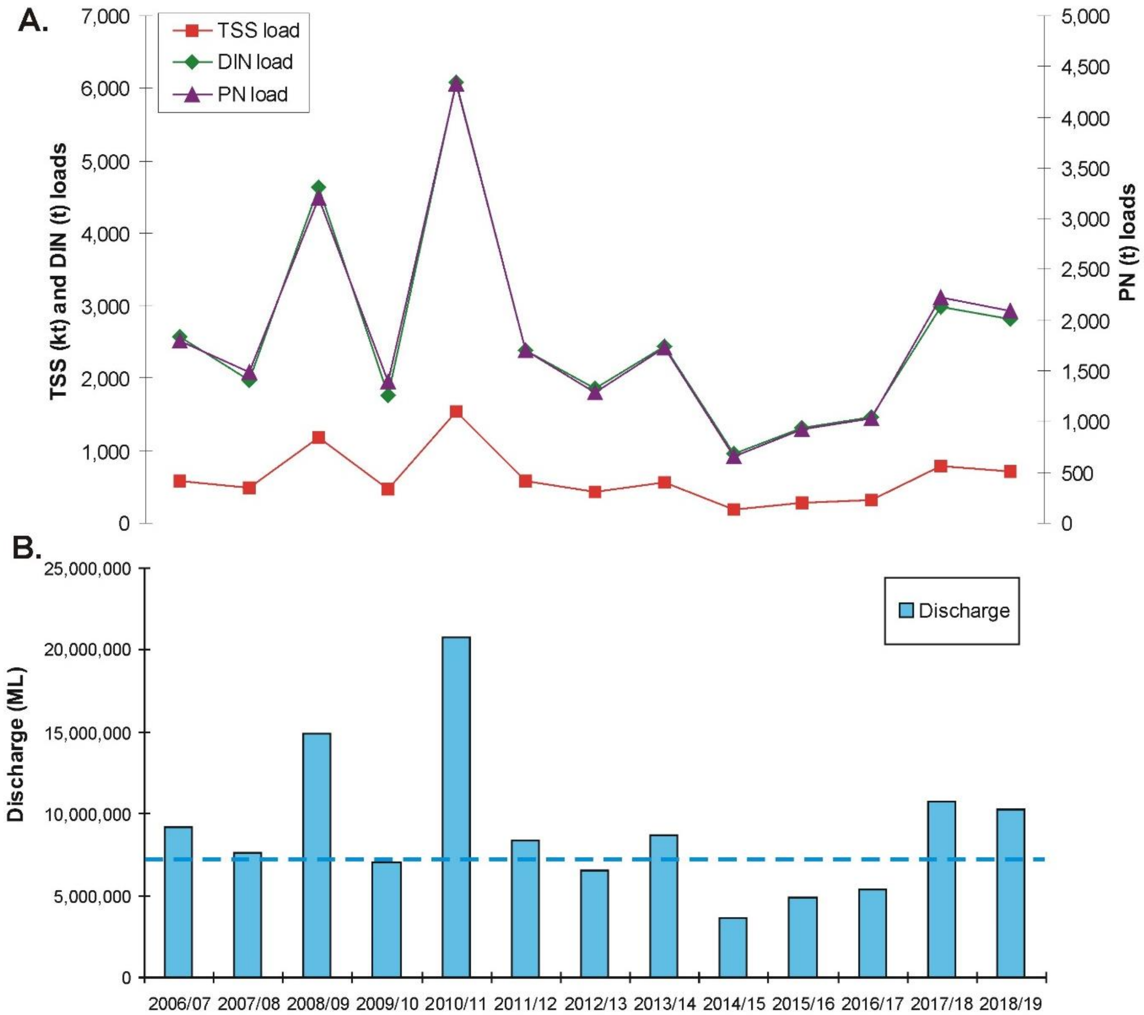

Figure 5-40: Loads of (A) TSS, DIN and PN and (B) discharge for the Tully, Murray, and Herbert Basins from 2006–07 to 2018–19. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (Tully and Herbert Rivers), 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 (inshore to offshore gradient). Sites located in estuarine water bodies (distance from river mouth = 0 km) had high concentrations of NO_x and particulate nutrients, while the mid-shelf site had much lower nutrient concentrations (Figure 5-41, Table E-2). Concentrations of TSS were greater in inshore waters (and could be highly variable), while Secchi depth increased with distance from the river mouth. Chl-*a* maxima occurred at open coastal sites (~8 km from Tully River mouth) during wet and dry seasons, as this region has sufficient light and nutrient concentrations to support high rates of phytoplankton growth.

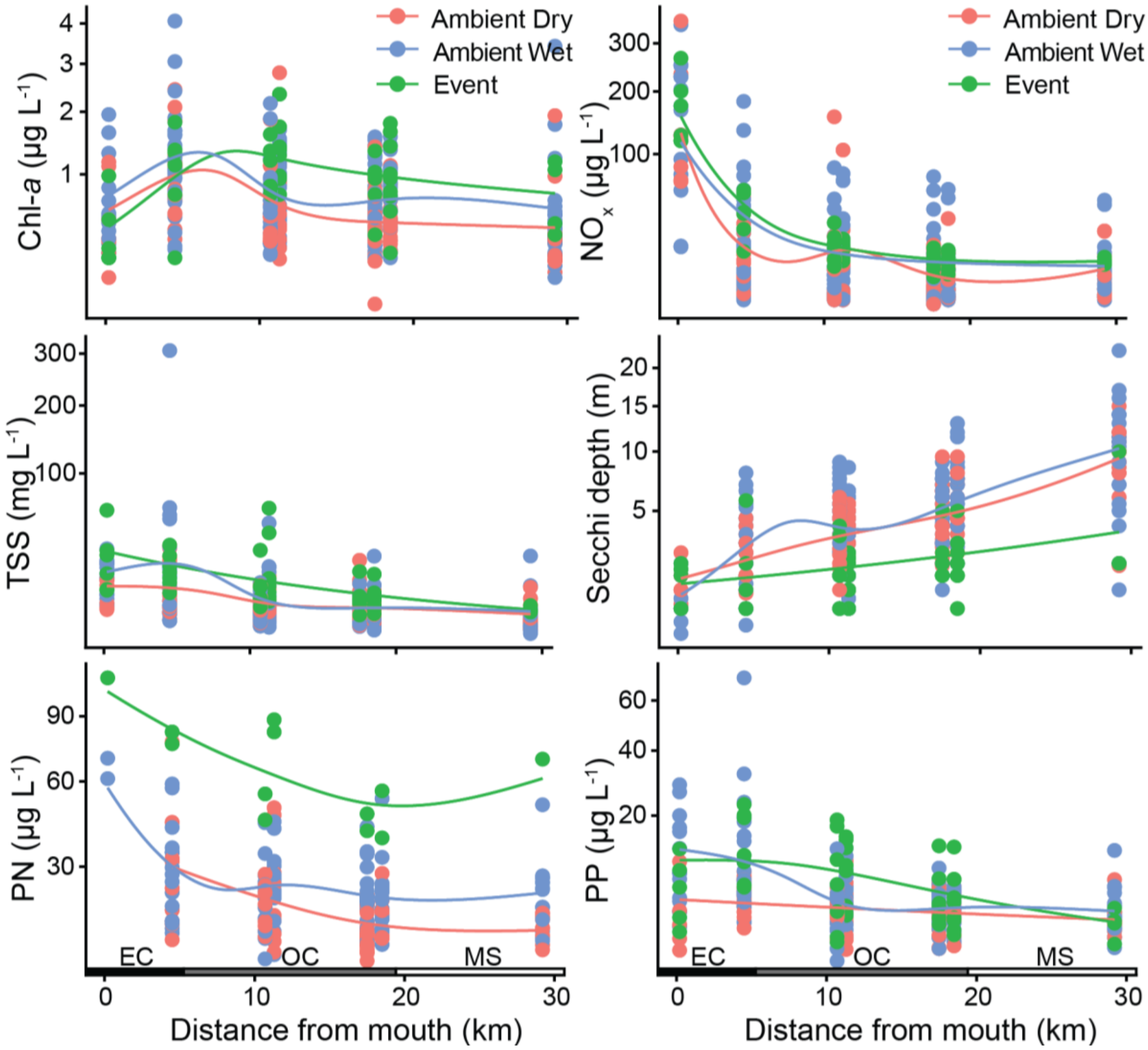

Figure 5-41: Water quality variables measured during ambient and event sampling in 2018-19 along the Tully focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the Tully river mouth. Water bodies are shown along the x-axes: Enclosed coastal (EC), open coastal (OC), and mid-shelf (MS). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

Seasonal differences in water quality were evident along the sampling transect. Ambient monitoring during the wet season showed generally greater values of nutrients and Chl-*a* than dry season monitoring (Figure 5-41). Concentrations of PP displayed a large seasonal difference in the estuarine and open coastal water bodies but no seasonal difference in the mid-shelf where wet and dry season values converged.

Long-term trends in water quality variables measured during ambient periods (e.g. not during peak flood events) of the dry and wet seasons are presented in Figure 5-42. It is important to note that the trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points have slightly 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 in local weather and tides.

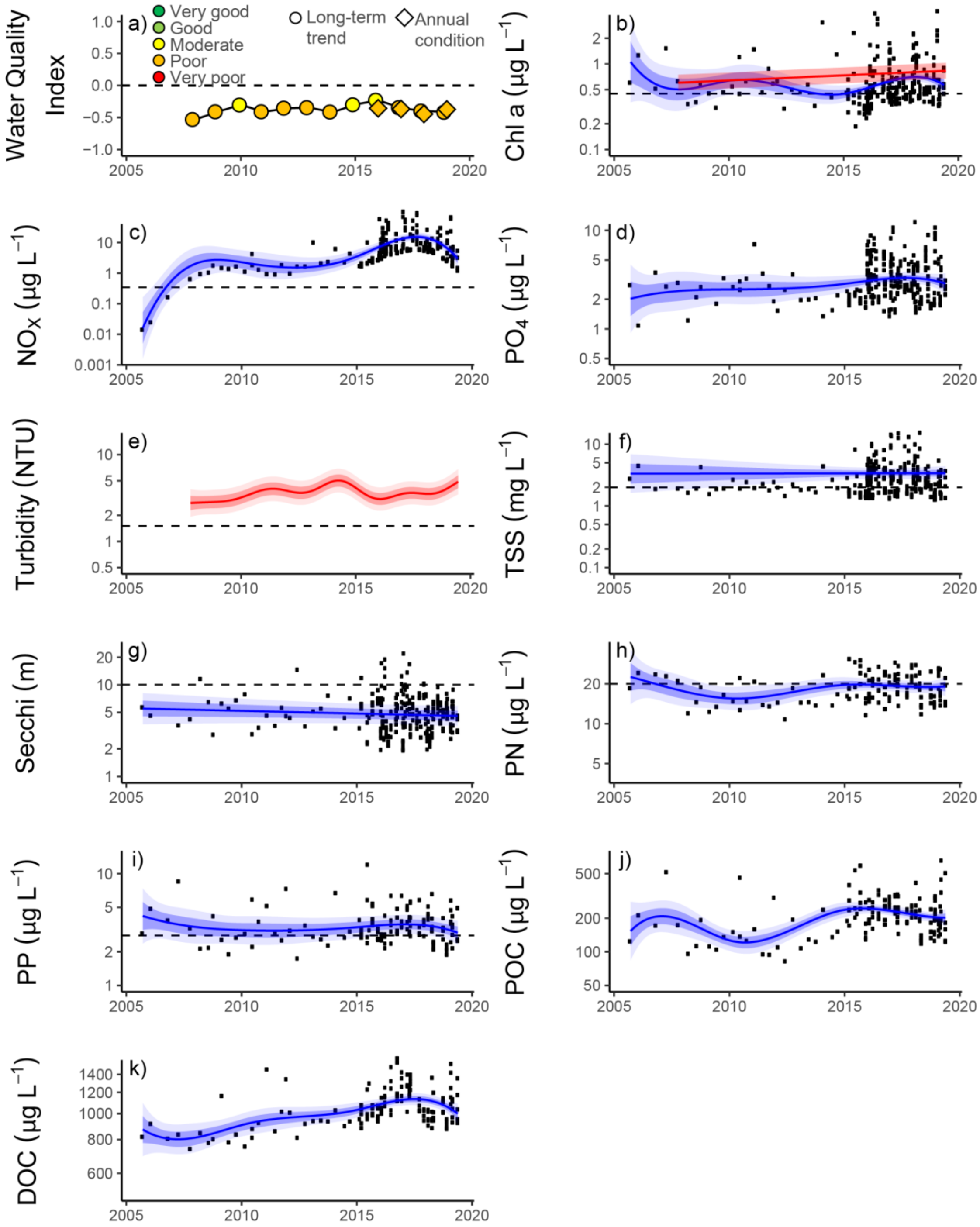

Figure 5-42: Temporal trends in water quality for the Tully focus region. a) WQ Index, b) chlorophyll *a* (Chl-*a*), c) nitrate/nitrite (NO_x), d) phosphate (PO_4), e) turbidity, f) total suspended solids (TSS), g) Secchi depth, h) particulate nitrogen (PN), i) particulate phosphorus (PP), j) particulate organic carbon (POC) and k) dissolved organic carbon (DOC). The long-term trend in the WQ Index is depicted with circles, while the annual condition uses diamonds. Error bars on the WQ Index represent the 95% quantile intervals. Calculations are described in Appendix D. Trends are represented by blue lines with blue shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind, waves and tides after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, individual records are not displayed (Figure E-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 over time (Figure 5-42). Concentrations of Chl-*a* and TSS have been relatively stable over time, and mean values of these variables are presently exceeding GVs (Great Barrier Reef Marine Park Authority, 2010), although Chl-a concentrations derived from loggers suggest an increase since 2009 (Figure 5-42b). Concentrations of NO_x have varied over time and are presently exceeding the GV (Figure 5-42c), while concentrations of PO_4 have remained stable over time. Mean Secchi depth has not changed since monitoring began; however, current values are not meeting the GV (Figure 5-42g). Mean concentrations of PN and PP have been relatively stable since monitoring began and are presently at GVs (Figure 5-42h,i). Concentrations of DOC have increased since monitoring began (Figure 5-42j), while POC concentrations have remained relatively stable (Figure 5-42k).

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

The long-term WQ Index has scored water quality as 'moderate' or 'poor' since 2005. The long-term trend has been relatively stable since 2005 (Figure 5-42a, circles).

The annual condition WQ Index scored water quality as 'poor' for the last four years (Figure 5-42a, diamonds). 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 five flow events of note over the December–April wet season period with two flow events which exceeded the minor flood level (peaks on 31 December and 28 January, respectively) and an additional three events (peaks on 10 December, 15 January, and 3 April) which peaked just below the minor flood level in the 2018–19 water year (Figure 5-43). The MMP Tully transect sites were sampled at the flood peaks on 15 January and the day following 28 January flood peak. Unfortunately, poor weather conditions prevented sampling the flow event that peaked on 31 December. Figure 5-43 shows the daily discharge for the Tully River and the red diamonds show the water sampling campaigns conducted as part of the MMP.

Comparatively fewer samples were taken in the flood plumes from the Tully and Russell-Mulgrave Rivers in 2018–19 compared to previous years, partly due to the lack of very high flows (i.e., neither river reached moderate flooding levels) and partly due to poor weather conditions that coincided with elevated catchment flows.

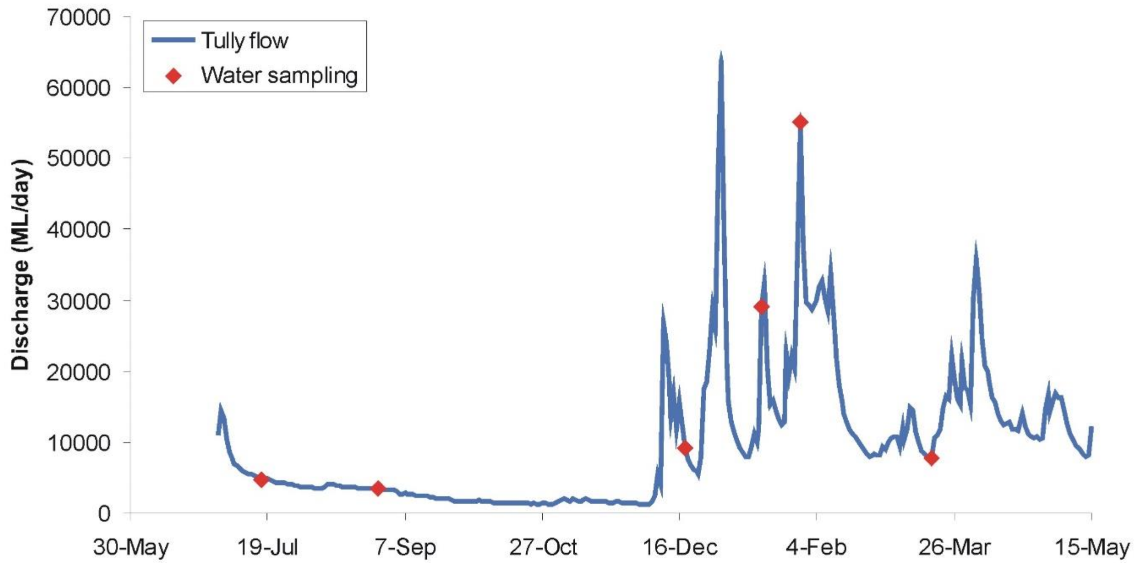

Figure 5-43: Tully River discharge (in ML d^{-1}) from 1 July 2018–15 May 2019 for the Euramo flow gauge. Red diamonds show when water sampling in the Tully focus area.

Event water quality showed trends along the sampling transect (inshore to offshore gradient). Sites located in estuarine water bodies (distance from river mouth = 0 km) had high concentrations of NO_x and particulate nutrients (especially PN), while open coastal sites had much lower nutrient concentrations (Figure 5-41). Particulate nutrient concentrations (especially PN) exceeded ambient wet season concentrations during events. It is important to note that PN is derived from all material in the water column, including phytoplankton, zooplankton, and detritus. Therefore, large concentrations during events are likely more of an indicator of high coastal productivity rather than loads of catchment-derived sediments. Detrital PN can be remineralised by bacteria to form dissolved inorganic nitrogen, which can then be used by primary producers. A Chl-*a* maximum occurred at open coastal sites (~8 km from Tully River mouth) during event sampling, as this region has sufficient light and nutrient concentrations to support phytoplankton bloom development. Chl-a concentrations were greater during events than during ambient periods, including at sites further away from the river mouth. Concentrations of TSS were greater in inshore waters during events than during ambient periods, and patterns along the transect were similar to ambient wet monitoring. Secchi depth was much lower (water clarity was lower) during events than ambient periods at inshore sites, but Secchi depth increased with distance from the river mouth.

5.3 Burdekin region

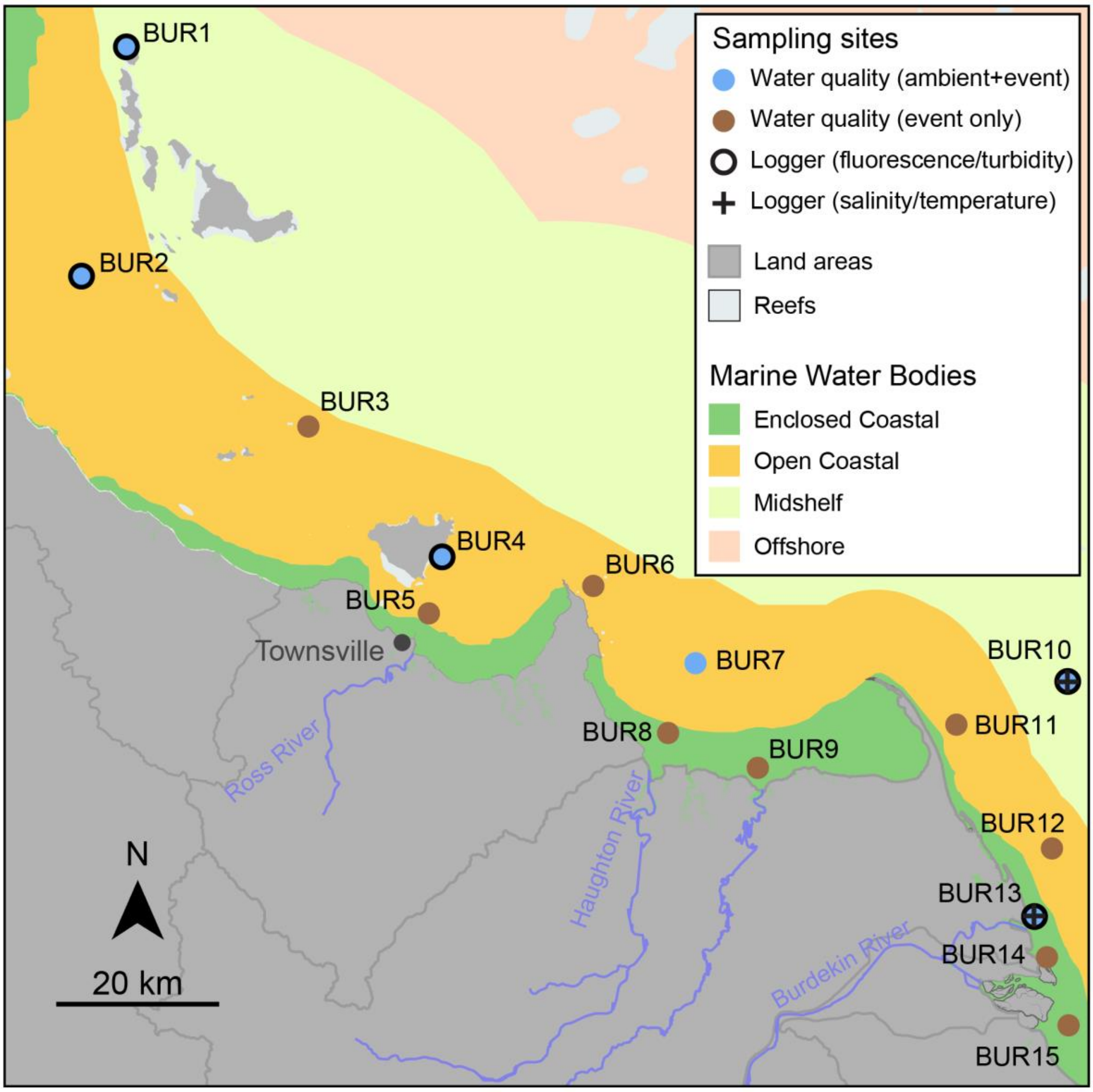

Figure 5-44: Sampling sites in the Burdekin focus area, shown with the water body boundaries.

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 monitoring 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 C-1). The monitoring sites in this new design are located in a transect from the river to mouth in a north-easterly 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 5-44).

The total discharge for the Burdekin region in 2018–19 was well above the long-term median (Figure 5-45). The annual discharge from the Burdekin River alone was nearly four times greater than the long-term median (Table 3-1). The combined discharge and loads calculated for the 2018–19 water year from the Burdekin and Haughton Basins were the highest since the 2010–11 water year (Figure 5-46).

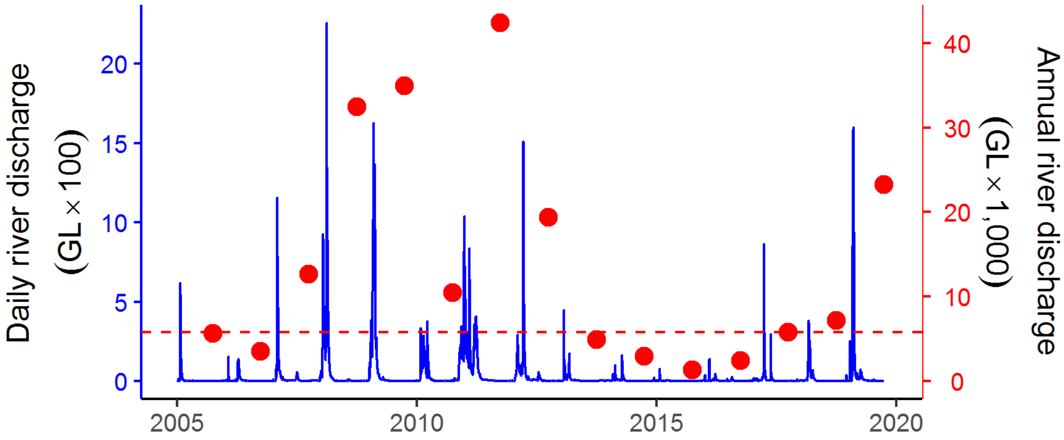

Figure 5-45: Total discharge for the Burdekin region (Table 2-2). Daily (blue) and water year (October to September, red) discharge is shown. Red dashed line represents the long-term median annual discharge.

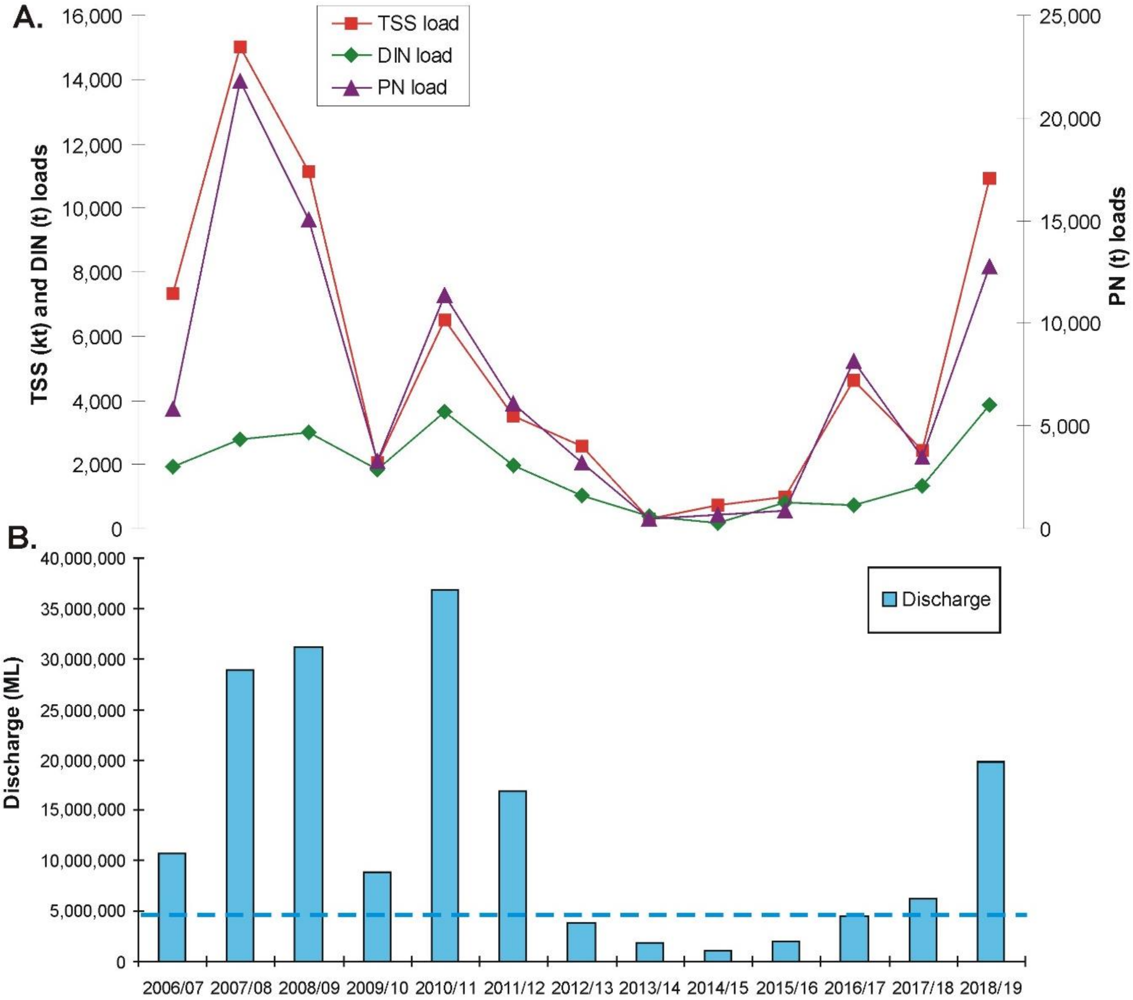

Figure 5-46: Loads of (A) TSS, DIN and PN and (B) discharge for the Burdekin and Haughton Basins from 2006–07 to 2018–19. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (Burdekin River), and annual 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.

Over the 13-year period:

- discharge has varied from 998 GL (2014–15) to 36,811 GL (2010–11)
- TSS loads ranged from 285 kt (2013–14) to 15,011 kt (2007–08)
- DIN loads ranged from 192 t (2014–15) to 3,848 t (2018–19)
- PN loads ranged from 487 t (2013–14) to 21,773 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.

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 in enclosed coastal water bodies (distance from river mouth = 0 km) had high concentrations of NO_x, Chl-*a*, and particulate nutrients, which each declined with distance from the Burdekin mouth (Figure 5-47, Table E-2). Concentrations of TSS were highly variable and declined with distance from the Burdekin mouth, while Secchi depth increased dramatically away from the river mouth. Elevated levels of some variables (Chl-*a*, NO_x, TSS, PN, and PP) could be seen at mid-distances from the Burdekin mouth (~60–110 km). These sites were located near the Haughton (BUR7, BUR6) and Ross (BUR4) rivers, and were influenced by discharge from these catchments.

Seasonal differences in water quality were evident along the sampling transect. Ambient monitoring during the wet season showed greater concentrations of NO_x, PN, TSS, and Chl-*a* than dry season monitoring (Figure 5-47). Secchi depths were generally lower (water clarity was lower) during the wet season than the dry season. Concentrations of NO_x displayed a large seasonal difference at sites near the Burdekin mouth but no seasonal difference at further sites, where wet and dry season values converged.

Long-term trends in water quality variables measured during ambient periods (e.g. not during peak flood events) of the dry and wet seasons are presented in Figure 5-48. It is important to note that the trend analysis removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points have slightly 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 in local weather and tides.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change over time (Figure 5-48). Concentrations of Chl-*a* have been relatively stable since 2005, though have increased slightly over the last two years (Figure 5-48b) and are presently exceeding the GV (Great Barrier Reef Marine Park Authority, 2010). Concentrations of TSS have varied since 2005 and have declined over the last two years, with mean values meeting but close to the GV (Figure 5-48f). Concentrations of NO_x have increased since 2005 and are presently exceeding the GV (Figure 5-48c), while concentrations of PO_4 have remained stable over time (Figure 5-48d). Mean Secchi depth has remained stable since monitoring began; however, current values are not meeting the GV (Figure 5-48g). Mean concentrations of PN and PP have been relatively stable since monitoring began and are presently at GVs (Figure 5-48h,i). Concentrations of DOC and POC have increased since monitoring began (Figure 5-48j,k), though DOC concentrations have declined slightly over the last two years.

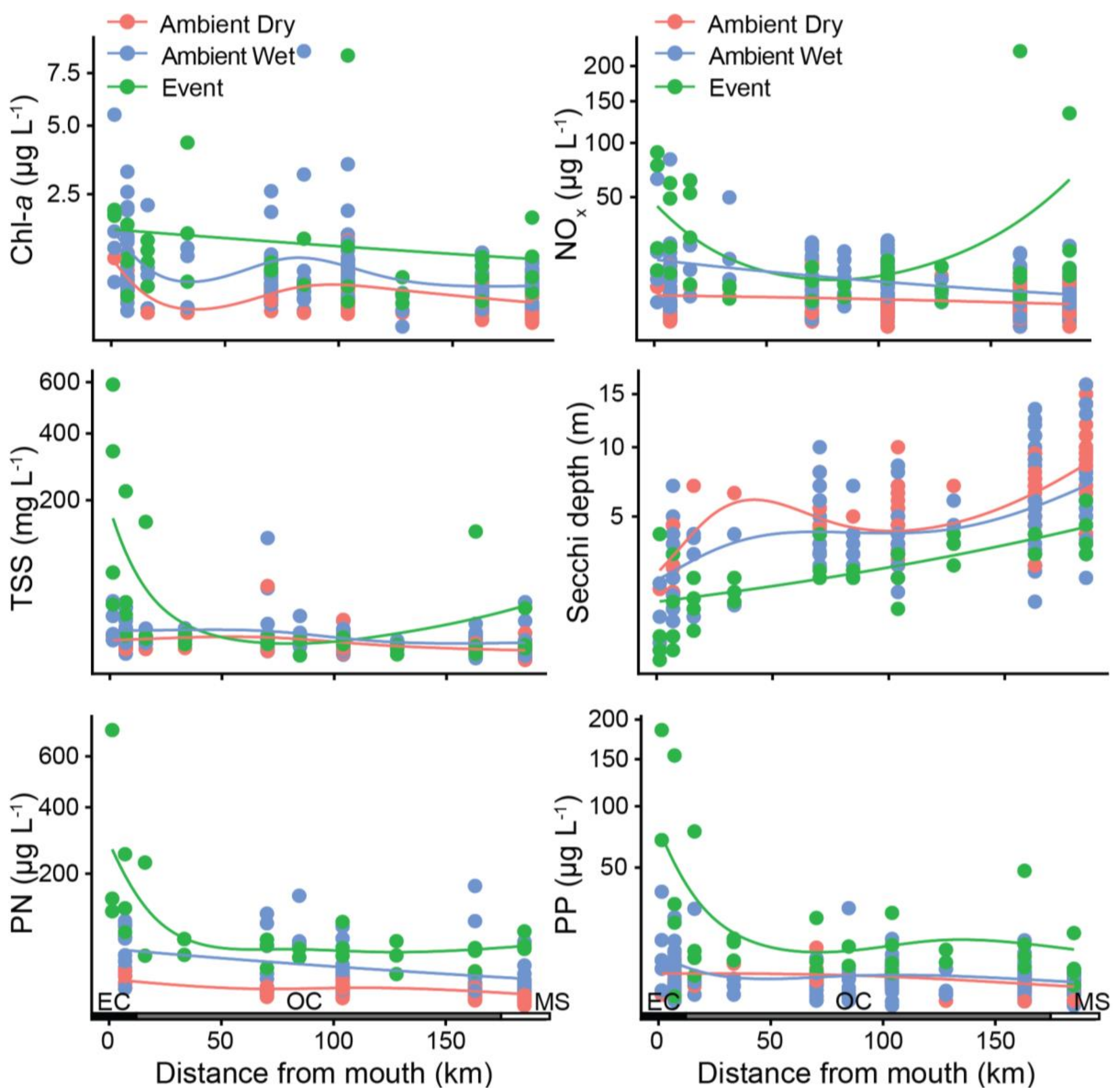

Figure 5-47: Water quality variables measured during ambient and event sampling in 2018-19 along the Burdekin focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the Burdekin river mouth. Water bodies are shown along the x-axes: Enclosed coastal (EC), open coastal (OC), and mid-shelf (MS). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

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) a metric for annual condition (based on the post-2015 sampling design, which increased the power to detect changes in water quality). The Methods section and Appendix D contain details of the calculations for both indices.

The long-term WQ Index has scored water quality as 'good' or 'moderate' since 2005. The long-term trend has showed a slight decline since 2005 (Figure 5-48a, circles).

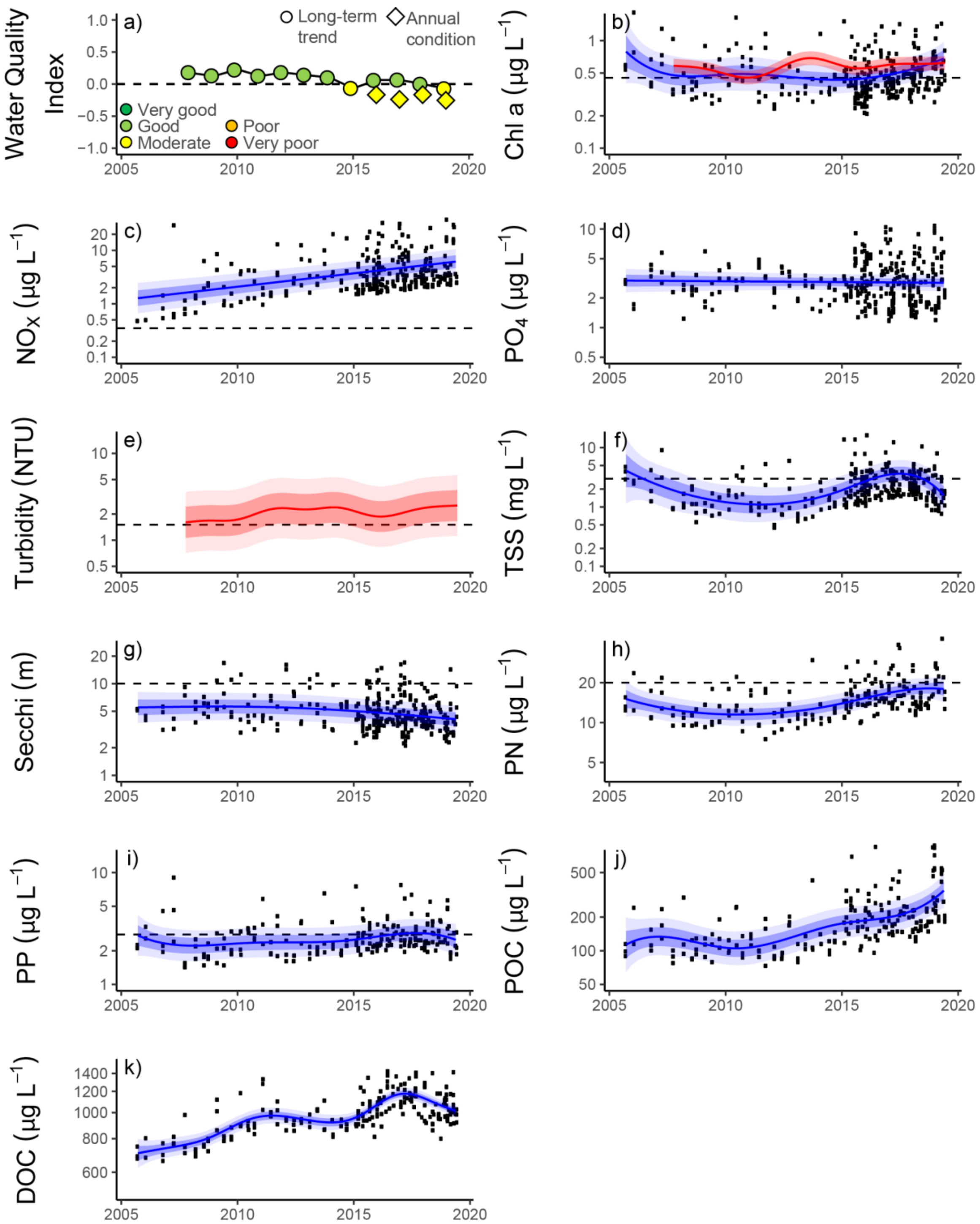

Figure 5-48: Temporal trends in water quality for the Burdekin focus area. a) WQ Index, b) chlorophyll *a* (Chl-*a*), c) nitrate/nitrite (NO_x), d) phosphate (PO_4), e) turbidity, f) total suspended solids (TSS), g) Secchi depth, h) particulate nitrogen (PN), i) particulate phosphorus (PP), j) particulate organic carbon (POC) and k) dissolved organic carbon (DOC). The long-term trend in the WQ Index is depicted with circles, while the annual condition uses diamonds. Error bars on the WQ Index represent the 95% quantile intervals. Trends are represented by blue lines with blue shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind and tides after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, individual records are not displayed (Figure E-1). Dashed horizontal reference lines indicate annual guideline values.

The annual condition WQ Index scored water quality as 'moderate' for the last four years (Figure 5-48a, diamonds). 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 remnants of cyclones Owen and Penny and an intense tropical low coupled with a very active and stationary monsoonal trough resulted in heavy rainfall occurring across the Burdekin region during periods from late-December to mid-February 2019. Major flooding was recorded in the Herbert, Black-Ross, and Haughton basins including severe flooding in and around Townsville. The Burdekin River peaked at the moderate flood level on 8 February 2019 and discharged 17.5 million ML over the water year, of which 14.5 million ML was discharged in the 3-week period between 30 January and 19 February 2019. This volume of water discharged is considered a 'very large event' for the river and has approximately a 1-in-5-year return interval. The volume of water is the largest discharged by the river in eight years since the extreme flows in 2010–11. In the 2018–19 water year, moderate to major flooding occurred in the Upper Burdekin, Cape, and Bowen-Broken-Bogie sub-catchments. There was also considerable discharge from the Haughton, Ross, Bohle, Black, and Herbert Rivers over a similar period.

Sampling of the Burdekin and Ross River flood plumes for this program targeted plume waters along the MMP defined event sites over the 11–12 February, 20–21 February and 6–7 March with some additional samples taken near the Herbert River mouth and at sites where NESP Project 5.8 sediment traps and environmental loggers are deployed (i.e. Orchard Rocks and Havannah Island). As the flood plume from the Burdekin River moved directly offshore (as opposed to northwards along the coast) during its peak flow, an additional transect of sites was sampled out to Old Reef (mid shelf) on 15 February (Figure 5-49).

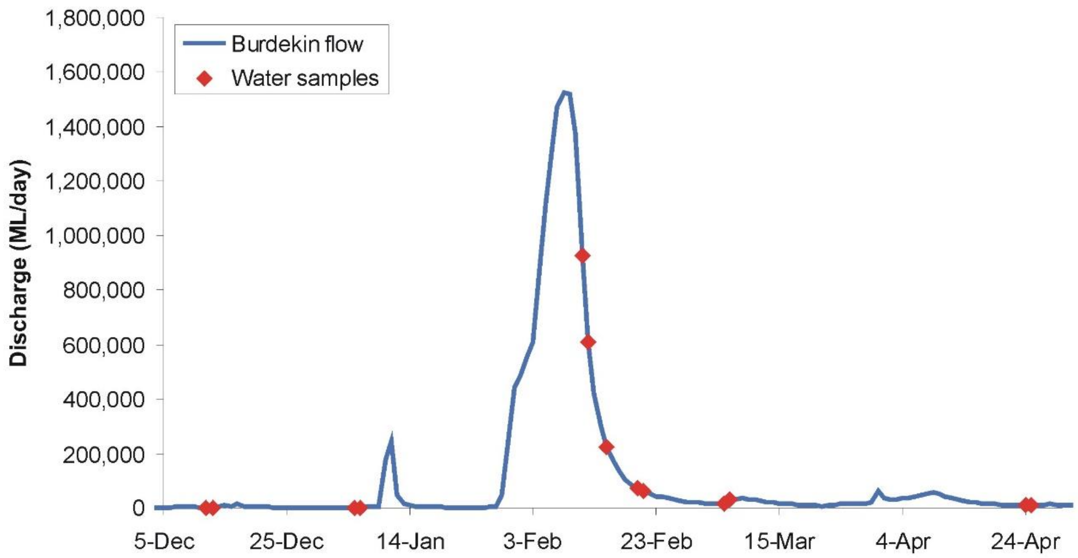

Figure 5-49: River discharge (in ML d^{-1}) from 1 December 2018–1 May 2019 for the Burdekin River (Clare gauge). Red diamonds show when water sampling occurred offshore from the Burdekin river mouth.

Event water quality showed trends along the sampling transect (Burdekin mouth to Palm Island group). Sites located in enclosed coastal water bodies (distance from river mouth = 0 km) had high concentrations of NO_x, TSS, PN, and PP, and concentrations declined with distance from the river mouth (Figure 5-47). Secchi depth was very low (water clarity was low) near the Burdekin mouth, and increased along the transect. Elevated levels of some variables (Chl-*a*, NO_x, PN, and PP) could be seen at mid-distances from the Burdekin mouth (~60–110 km). These sites were located near the Haughton (BUR7, BUR6) and Ross (BUR4) rivers, and were influenced by discharge from these catchments. Elevated levels of some variables (notably Chl-*a*, TSS, and PP) could be seen at the site furthest from the Burdekin mouth (Pelorus Island, BUR1); this site was affected by discharge from the Herbert River during event sampling. Event concentrations of Chl-*a* and particulate nutrients exceeded ambient wet season concentrations at all sites. Secchi depth was much lower (water clarity was lower) during events than ambient periods at all sites.

A collection of satellite images of the Burdekin River flood plume highlight the movement and dispersion of the flood waters in the Reef during February 2019 (Figure 5-50). The first available clear image from 10 February (two days after peak discharge) shows a well-developed plume largely moving northwards along the coast and impinging around Magnetic Island and the Palm Island Group (with likely additional influences from the Haughton and Ross Basins). Two days later, the image from 12 February shows the Burdekin River plume moving directly offshore from the mouth and approaching Old Reef in mid-shelf waters. The next day (13 February) the plume waters not only covered Old Reef but moved much further offshore reaching outer reefs (Figure 5-50). Such an event is rare for the Burdekin River, where relatively calm conditions and offshore winds during peak flows allowed the plume to remain as a buoyant layer within the upper parts of the water column. This allowed the 'turbid brown' waters to extend much further offshore from the river mouth than a typical flood event.

Aerial images were obtained from this date (morning of 13 February) using a helicopter showing the brown waters covering ~ one half of Old Reef (e.g., Figure 5-51). By 15 February, the satellite image shows that the brown waters of the plume had largely dissipated in the Reef, although the dark green plume waters were still clearly evident and covered much of the outer shelf coral reefs in this area. Plume water samples collected from Old Reef on 15 February confirmed the colour of the plume water had changed to a dark green (S. Lewis, pers. comm.). The satellite image from the next day (16 February) shows the waning flow of the most recently discharged Burdekin water moving northwards up the coast, although greenish waters persisted offshore at Old Reef and other outer reefs. The final image on 21 February shows the plume had largely dissipated at the mid and outer reefs (Figure 5-50), however, a southward movement of the greenish waters was evident.

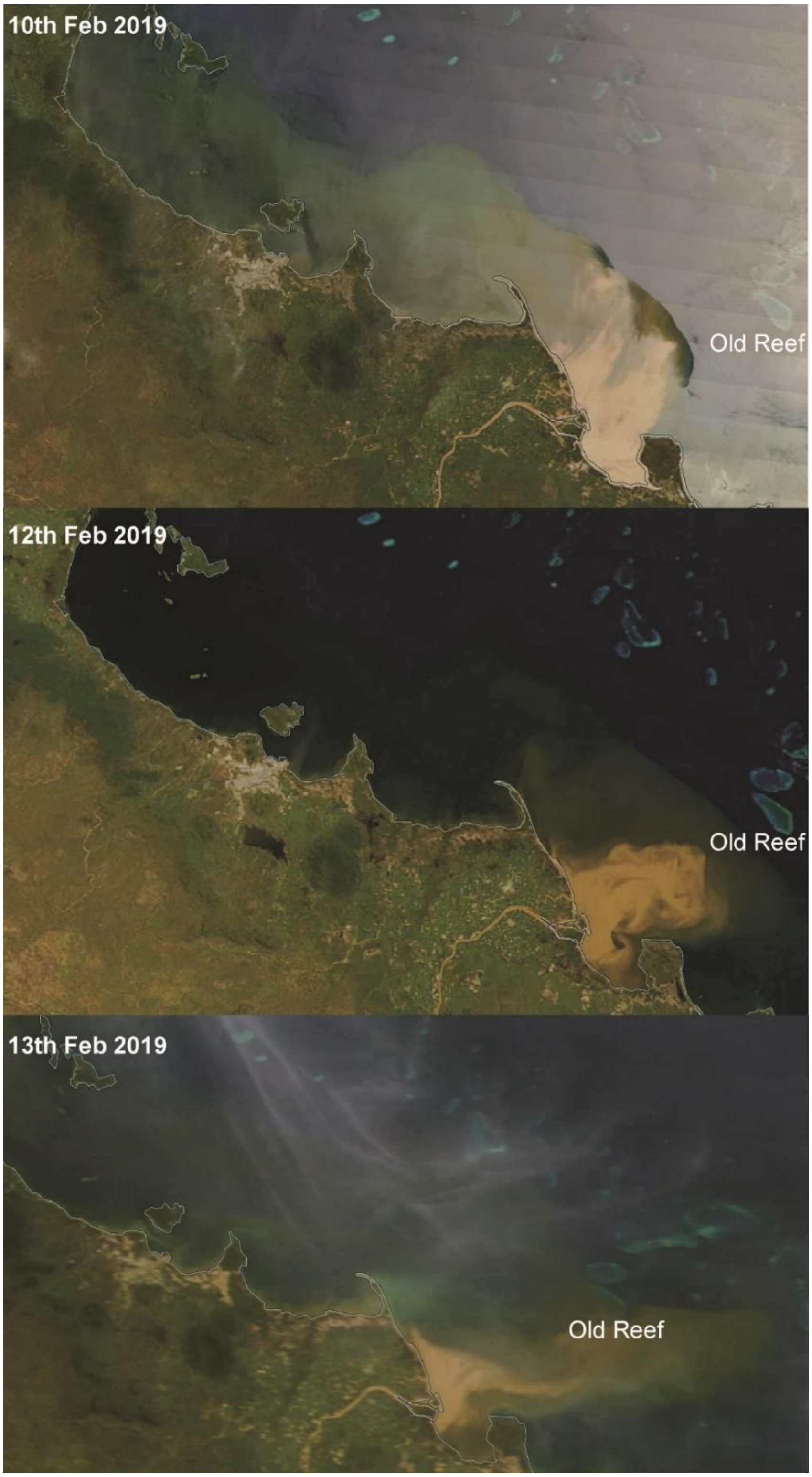

Figure 5-50: MODIS Tera satellite images of the flood plume from the Burdekin River during February 2019.

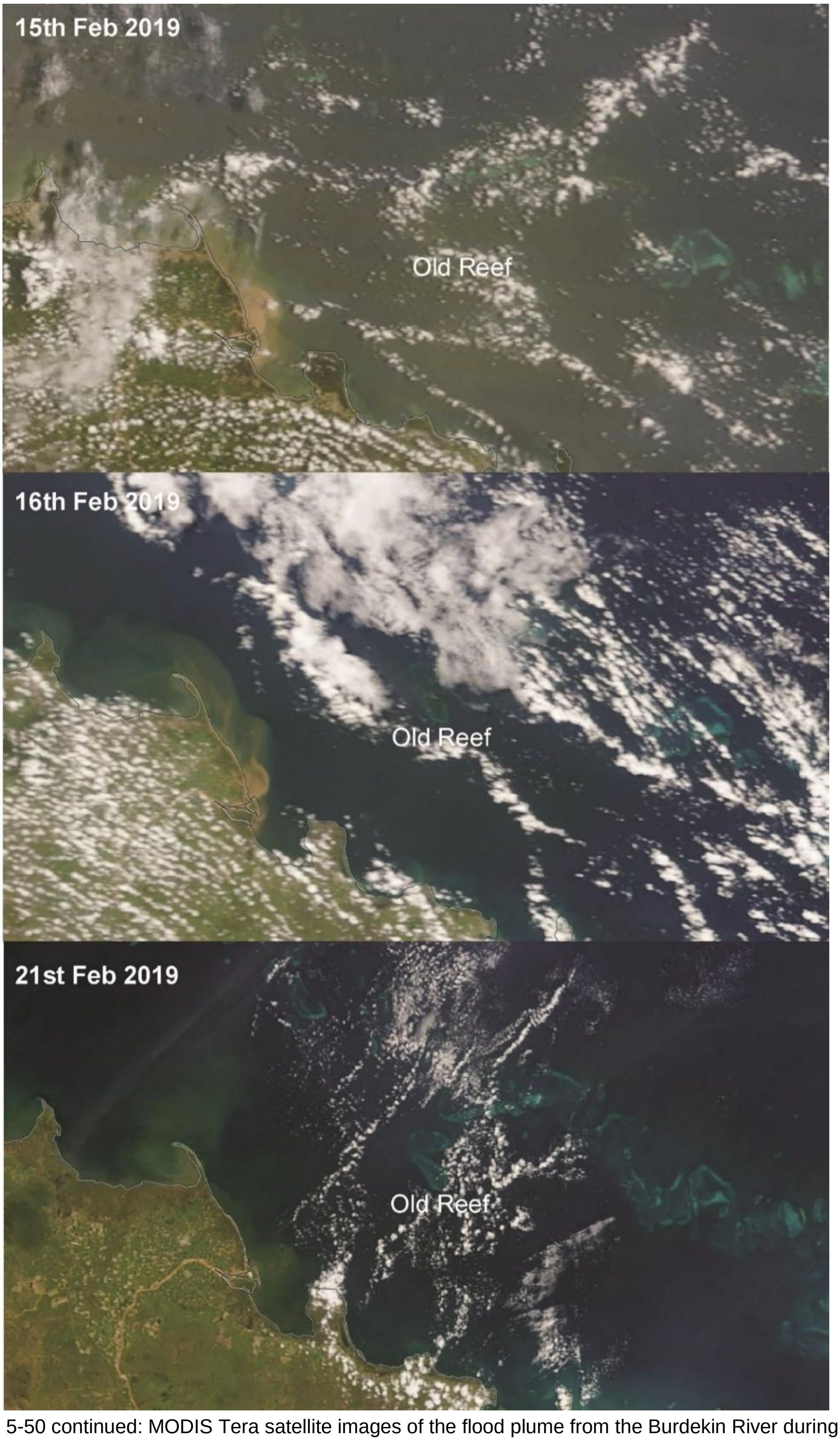

Figure 5-50 continued: MODIS Tera satellite images of the flood plume from the Burdekin River during February 2019.

Figure 5-51: Photo of the Burdekin plume impinging over Old Reef, 13 February 2019. Image by Matt Curnock. Support for the aerial footage was provided by TropWATER JCU, the Marine Monitoring Program - Inshore Water Quality through the Great Barrier Reef Marine Park Authority, the Queensland Government, the Landholders Driving Change project led by NQ Dry Tropics, CSIRO and the National Environmental Science Program Tropical Water Quality Hub.

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 Burdekin and Fitzroy Rivers during extreme events or through longer-term transport and mixing.

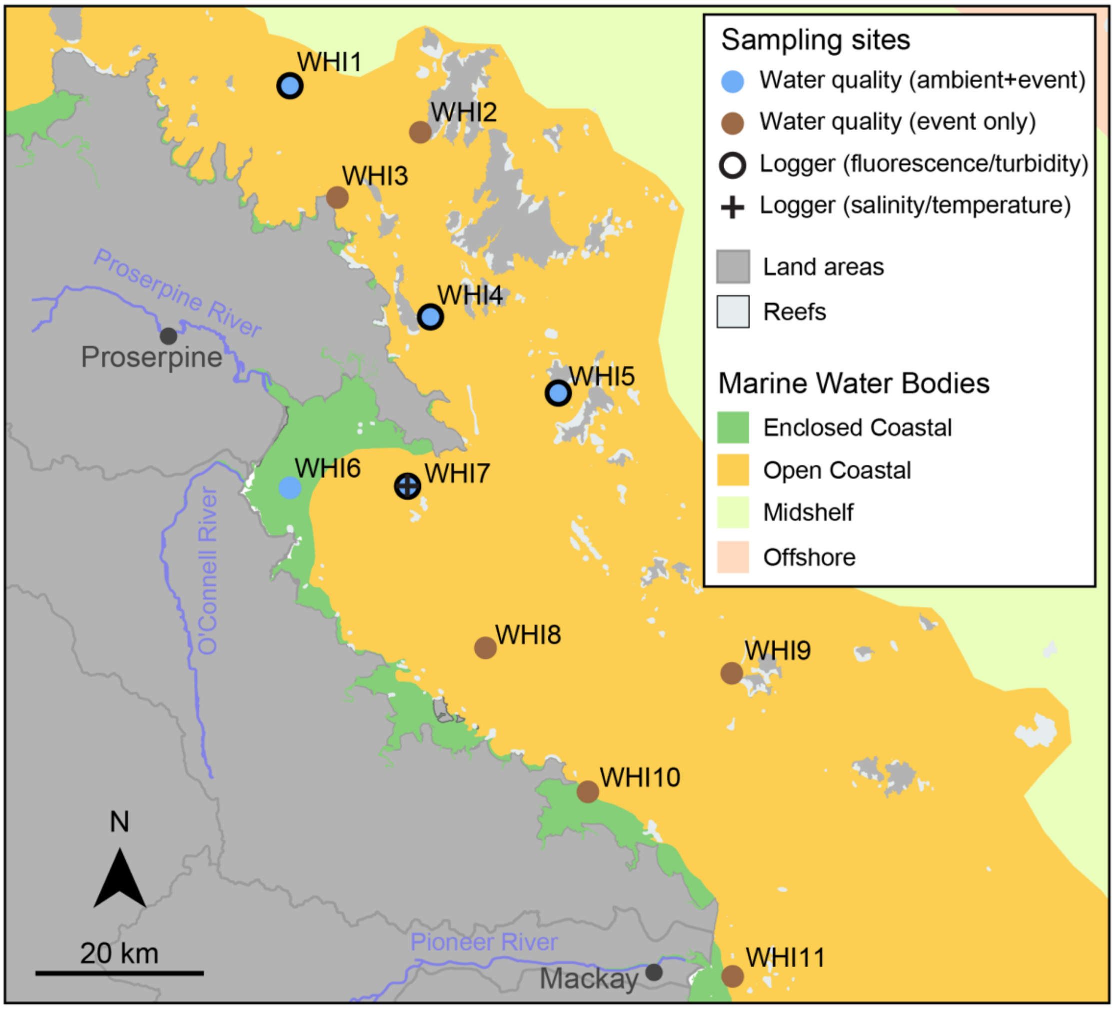

Figure 5-52: Sampling sites in the Mackay-Whitsunday focus area, shown with the water body boundaries.

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, five monitoring sites are sampled in this focus region up to five times per year. Those five sites plus an additional six sites aim to be sampled during major flood events, although it depends on the event (Table C-1). The monitoring sites in this design are located in a transect from the O'Connell River mouth to open coastal waters, representing a gradient in water quality. Four of the routine sites are located in the open coastal water body and one site is in enclosed coastal waters (Figure 5-52).

Annual discharge for the Mackay-Whitsunday region was above long-term median levels (Figure 5-53) and was similar to discharge during the 2016–17 water year. Annual discharge from the Proserpine and O'Connell Rivers was 2–3 times the long-term median, while discharge from the Pioneer River was ~1.5 times the long-term median (Table 3-1).

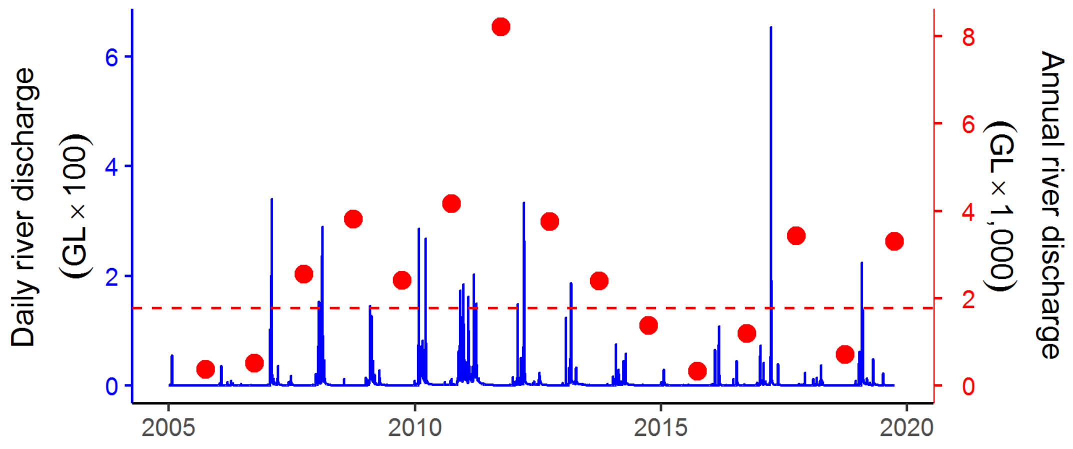

Figure 5-53: Combined discharge for the Mackay-Whitsunday focus region. Daily (blue) and water year (October to September, red) discharge is shown. Red dashed line represents the long-term median of the combined annual discharges. See Table 2-2 for a list of flow gauge data used. Please note as this is the combined discharge, high flows in one river will not necessarily be visible in the graph.

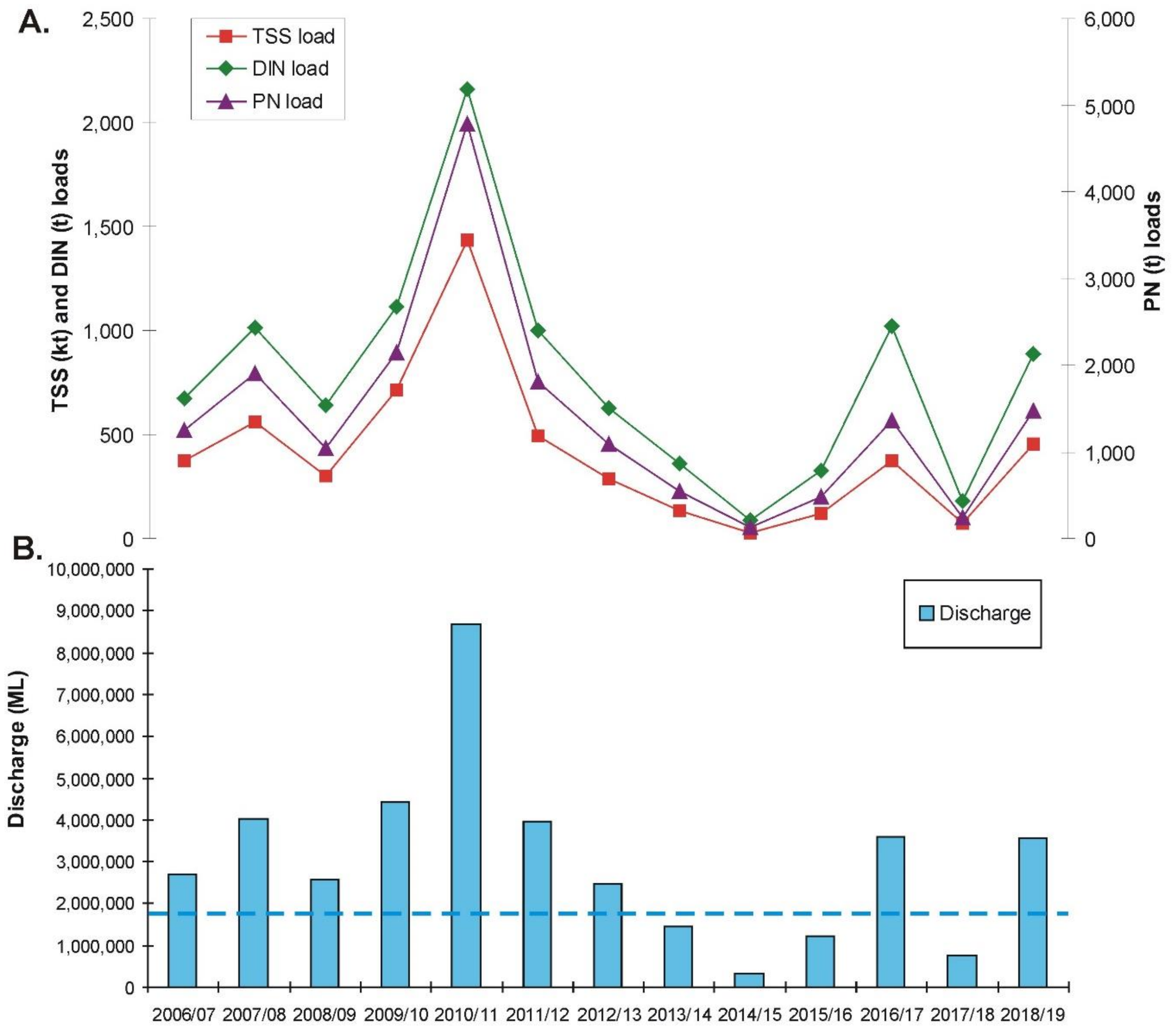

Figure 5-54: Loads of (A) TSS, DIN and PN and (B) discharge for the Proserpine, O'Connell, Pioneer, and Plane Basins from 2006–07 to 2018–19. The loads reported here are a combination of 'best estimates' for each basin based on 'up-scaled discharge data from gauging stations, monitoring data (O'Connell 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.

The combined discharge and loads calculated for the 2018–19 water year from the Proserpine, O'Connell, Pioneer and Plane Basins (Figure 5-54, Figure 5-56) were similar to that measured in the 2016–17 which was influenced by cyclone Debbie. Over the 13-year period:

- discharge has varied from 337 GL (2014–15) to 8,675 GL (2010–11)
- TSS loads ranged from 29 kt (2014–15) to 1,436 kt (2010–11)
- DIN loads ranged from 85 t (2014–15) to 2,158 t (2010–11)
- PN loads ranged from 122 t (2014–15) to 4,782 t (2010–11).

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 (distance from river mouth = 0 km) had high concentrations of NO_x, Chl-*a*, and particulate nutrients, which each declined with distance from the river mouth (Figure 5-55, Table E-2). Concentrations of TSS were highly variable in this focus region, which is likely related to its large tidal range. Secchi depth increased dramatically with distance from the river mouth (Figure 5-55).

Seasonal differences in water quality were evident along the sampling transect. Ambient monitoring during the wet season showed greater concentrations of NO_x, PN, PP, TSS, and Chl-*a* than dry season monitoring (Figure 5-55). Secchi depths were lower (water clarity was lower) during the wet season than the dry season. Concentrations of NO_x and TSS displayed a large seasonal difference at sites near the river mouth but no seasonal difference at further sites, where wet and dry season values converged.

Long-term trends in water quality variables measured during ambient periods (e.g. not during peak flood events) of the dry and wet seasons are presented in Figure 5-56. It is important to note that the trend analysis used removes variability associated with wind, tides, and seasons (see Methods). Thus, individual data points have slightly 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 in local weather and tides.

Distinct long-term trends (since 2005) were observed in some water quality variables, while others showed little change over time (Figure 5-56). Mean concentrations of Chl-*a* and TSS have been relatively stable since 2009 (Figure 5-56b,f) and are presently exceeding the water quality GVs (Great Barrier Reef Marine Park Authority, 2010). Mean concentrations of PO_4 have steadily declined over time (Figure 5-56d), while NO_x concentrations have been relatively stable since 2009 and are presently exceeding the GV (Figure 5-56c). Mean Secchi depth has remained stable since monitoring began; however, current values are not meeting the GV (Figure 5-56g). Mean concentrations of PN and PP have been relatively stable since monitoring began and are presently at GVs (Figure 5-56h,i). Concentrations of DOC and POC have increased since monitoring began (Figure 5-56j,k), though concentrations have declined slightly over the last two years.

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

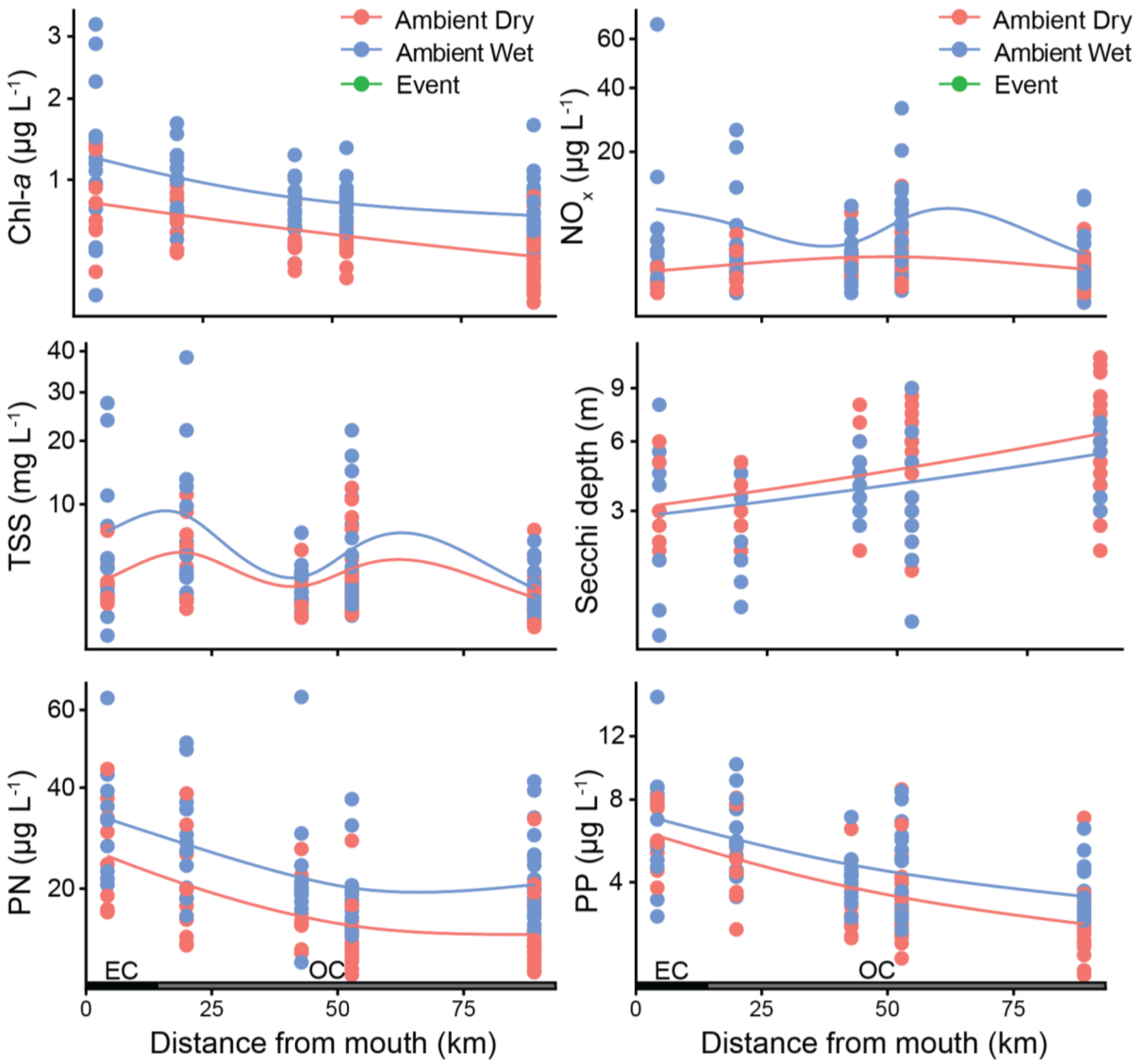

Figure 5-55: Water quality variables measured during ambient and event sampling in 2018-19 along the Mackay-Whitsunday focus region transect. Chlorophyll *a* (Chl-*a*), nitrate/nitrite (NO_x), total suspended solids (TSS), Secchi depth, particulate nitrogen (PN), and particulate phosphorus (PP) are shown with distance from the O'Connell River mouth. Water bodies are shown along the x-axes: Enclosed coastal (EC), open coastal (OC), and mid-shelf (MS). Note the y-axes are logarithmic scales. Fitted lines are generalised additive models.

The long-term WQ Index has scored water quality as 'moderate' or 'poor' since 2006. The long-term trend has showed a decline since monitoring began (Figure 5-56a, circles).

The annual condition WQ Index scored water quality as 'poor' for the last two years (Figure 5-56a, diamonds). 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

No event sampling was conducted in the Mackay-Whitsunday focus area during 2018–19.

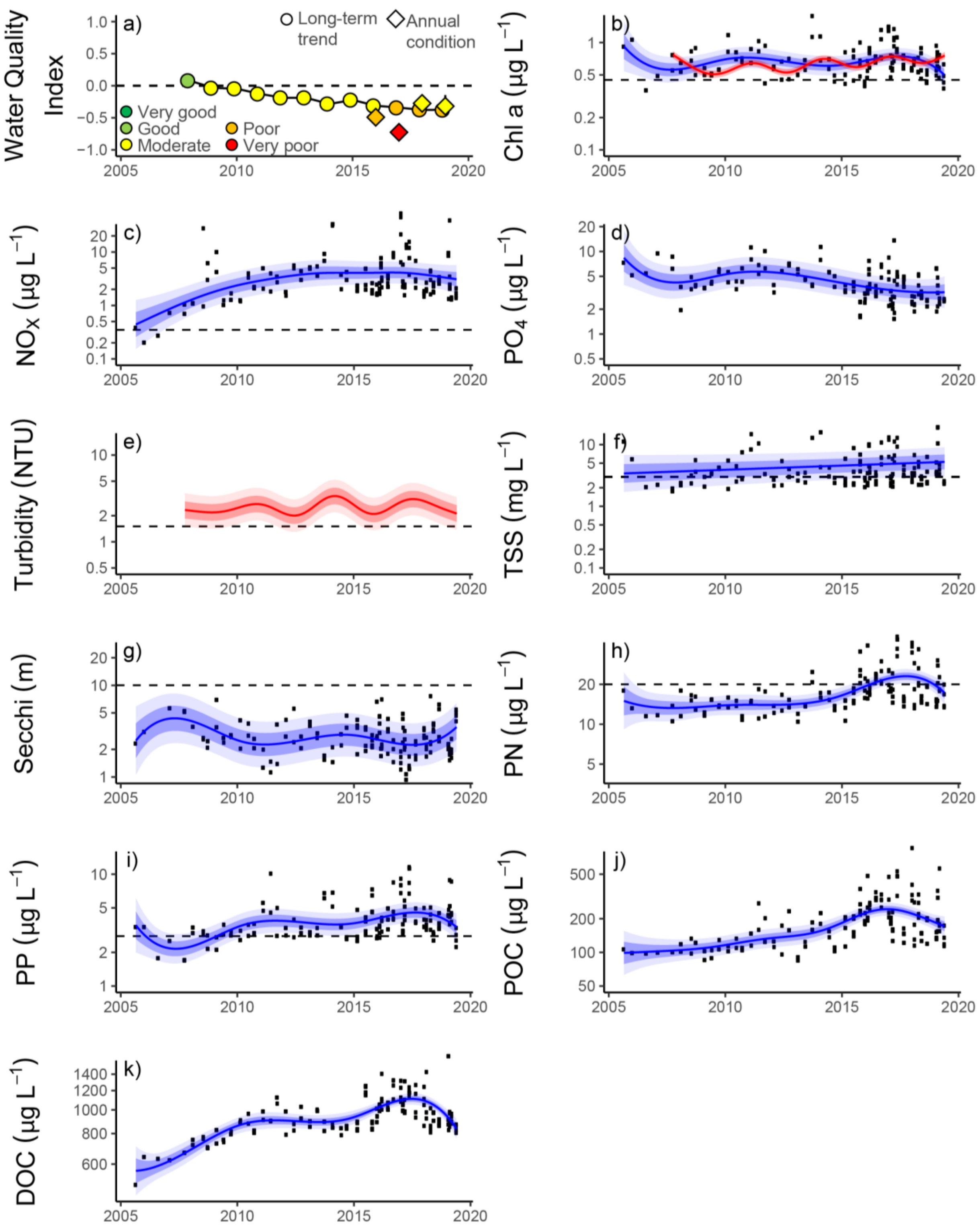

Figure 5-56: Temporal trends in water quality for the Mackay-Whitsunday focus-region. a) WQ Index, b) chlorophyll *a* (Chl-*a*), c) nitrate/nitrite (NO_x), d) phosphate (PO_4), e) turbidity, f) total suspended solids (TSS), g) Secchi depth, h) particulate nitrogen (PN), i) particulate phosphorus (PP), j) particulate organic carbon (POC) and k) dissolved organic carbon (DOC). The long-term trend in the WQ Index is depicted with circles, while the annual condition uses diamonds. Error bars on the WQ Index represent the 95% quantile intervals. Trends are represented by blue lines with blue shaded areas defining 95% confidence intervals of those trends accounting for the effects of wind and tides after applying x-z detrending. Trends of records from ECO FLNTUSB instruments are represented in red, individual records are not displayed (Figure E-1). Dashed horizontal reference lines indicate annual guideline values.

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 some focus regions (e.g. Barron Daintree and Mackay-Whitsunday) have experienced declines in water quality over the previous 14 years, while other regions (e.g. Russell-Mulgrave, Tully, and Burdekin) appear to be stable.

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 (GVs), inshore ecological communities often 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). Multiple lines of evidence demonstrate that water quality influences the state of inshore coral reefs and seagrass. In addition, ecological community response to water quality is confounded by factors such as organism sensitivity and resilience. This complexity makes it difficult to tease out ecosystem response specific to river inputs.

The results for 2018–19 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. 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 five years of MMP water quality data showed significant variability between years and locations (Schaffelke et al., 2012). Most variation was explained by temporal factors (seasons, years, and river flow), 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 suggest that some variables showed no long-term net increases or decreases in concentration, whereas other variables have increased in concentration over time.

In most focus regions:

- at or below GVs:
  - Concentrations of PN have increased in some regions and remained stable in others since 2005.
- exceeding or close to GVs:
  - TSS and Chl-*a* concentrations. No major long-term changes since 2005.
- relatively stable and exceeding GVs:
  - NOx in recent years, having increased in most focus regions since monitoring began.
- generally at or exceeding GVs:
  - Concentrations of PP having remained stable in most focus regions since 2005.
- not meeting GVs:
  - Secchi depths, have declined or remained stable.

The most dramatic long-term changes have been for DOC and POC concentrations, which have increased substantially in most focus regions since 2005. Monitoring results from 2018–

19 suggest that DOC has declined slightly in some focus regions (Russell-Mulgrave, Burdekin, and Mackay-Whitsunday) over the last two years, though the overall trend remains increasing. There is no guideline value for these parameters.

Increases in DOC over time are the result of many complex biotic and abiotic processes that occur in the coastal ocean. Our results suggest that the inputs of DOC and/or the transformation rates of DOC have changed since 2005. Most of the DOC pool in the Reef lagoon is derived from phytoplankton production, and therefore increases in plankton community production would result in elevated DOC concentrations. Plankton communities have been shown to increase their DOC production in response to environmental stress (e.g. changing light, temperature, and nutrient conditions) and changes in the plankton community structure (e.g. Church et al., 2002; Thornton, 2014).

Although productivity experiments have been episodically conducted in the Reef lagoon, no long-term monitoring of productivity has occurred to test this hypothesis. Increases in the coastal DOC pool could be related to catchment loading from changing land use (and time-lags associated with this, see Darnell et al., 2012), although there are no monitoring data available on the DOC loads from rivers since 2005.

Measured increases in DOC are nonetheless concerning as they could impact benthic ecological communities. DOC constitutes the major carbon source for heterotrophic microbial growth in marine pelagic systems and increases in DOC have previously been shown to promote microbial activity and coral diseases (Kline et al., 2006; Kuntz et al., 2005). Without further information on the form of the DOC (i.e. what it is composed of), the source of the DOC (i.e. where it is generated) and the transformation rates of the DOC (i.e. how fast it is produced and consumed), it is difficult to understand these changes and their ramifications for ecological communities. Process-based monitoring (e.g. rates of productivity and nutrient transformation) would improve the ability to determine the sources of changes in water quality.

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 identify where coastal ecosystems may be at risk from exposure to 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 (Fabricius et al., 2014, 2016) or a combination of *in situ* and satellite-derived data (Petus et al., 2019).

Our capacity to link coastal water quality to end-of-catchment loads and our 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 improve our ability to report on these objectives is expected to improve (e.g. eReefs hydrodynamic and biogeochemical models).

In addition to data needs, there are several key knowledge gaps that will improve our ability to predict and manage linkages between land management and marine water quality. For example, further research on understanding 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 (Waterhouse et al., 2018). Further research on organic and particulate nutrient pools will improve our ability to determine how these sources compare with nitrate in supporting phytoplankton production. Addressing these knowledge gaps 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, and has an effect on certain physico-chemical properties such as water clarity (light attenuation). Aspects of water quality, such as nutrient concentrations, also influence key ecological processes including rates of primary productivity (especially in phytoplankton) and nutrient cycling. In addition to anthropogenic stressors, the Reef lagoon is influenced by many natural factors that affect suspended nutrient and sediment concentrations including: the upwelling of deeper Coral Sea waters onto the continental shelf (Benthuysen 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). 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 (e.g. Done, 1982; Wismer et al., 2009). The premise underpinning the Reef 2050 Plan is that loads of nutrients, sediments and pesticides delivered by rivers suppress ecological resilience. A review of the effects of water quality on seagrass and coral communities can be found in the MMP reports specific to ecological monitoring (McKenzie et al., 2020; Thompson et al., 2020).

The *2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Re*ef 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).

6.3 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 (Anon, 2003). In 2015, the Australian and Queensland governments released the *Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan) (Commonwealth of Australia, 2015). 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 government, 2018) 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; Kroon et al., 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 water quality program. The complexity of the relationship between land-based runoff and water quality, the influence of interannual 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. The main findings are separated into results from ambient (routine sampling during wet and dry seasons) and event-based (sampling during flood events) monitoring.

7.1 Cape York

As this was only the third year of sampling in the Cape York region under the MMP, no long-term trends could be evaluated.

Discharge from the Cape York focus regions was two to five times above the long-term median discharge for each river in this year. There were two cyclones and three extended flood periods across the focus regions over the wet season, and peak discharge from flood events reached record highs in the Normanby Basin, Stewart River and Pascoe River.

Ambient water quality

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

- Dry season: TSS, NO_x, PO_4 and Chl-a exceeded the open coastal GVs in most regions.
- Wet season: NO_x, PO_4 and Chl-a exceeded the GVs for most regions. TSS, PN and PP also exceeded GVs in some areas.
- Annual mean/median: Secchi depth, Chl-*a*, NO_x and PO_4 exceeded the GVs.

Caution should be used interpreting PN and PP results as only a small number of samples were analysed. Ambient PN and PP concentrations increased compared to previous years due to changes in laboratory methods.

Annual GVs were also exceeded for Chl-*a*, NO_x and PO_4 in mid-shelf waters, although limited sampling means the results are not representative of ambient condition.

Event water quality

- Floodwater carrying elevated (above ambient) concentrations of nutrients and sediments reached open-coastal and mid-shelf reefs in all focus regions, and off-shore reefs in the Normanby Basin.
- High turbidity, nutrient, and Chl-*a* concentrations were present for periods of several weeks during and after flood events in a number of locations.
- eReefs hydrodynamic model exposure output showed that enclosed coastal and open coastal waters were heavily affected by river discharge from the Normanby River, which also reached mid-shelf and offshore sites.
- Open coastal waters off Cooktown had a relatively lower three-dimensional exposure to discharge from the Annan and Endeavour rivers.
- River discharge was mainly transported in northerly and easterly directions. The eReefs outputs for this region have not been fully validated and should be treated with caution.
- Large flood plumes off the Annan, Endeavour, Normanby and Pascoe rivers were captured in satellite imagery across a number of events through the season.

- Approximately 20% of the total area of the Cape York region, 37% of the Cape York coral reefs and 88% of the Cape York seagrasses were exposed to a potential risk (combined potential risk categories II-IV). These areas were much higher than the long-term average areas (although MMP monitoring has only been underway for three years), particularly for coral reefs (37% compared to 5%).

7.2 Wet Tropics

Discharge from the Daintree Basin was over three times the long-term median while the Mossman and Barron Basins were two to three times higher than the long-term median. The combined discharge and loads from the Russell-Mulgrave, Johnstone, Tully, Murray and Herbert Basins were in the higher range to that recorded over the past decade. 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). However, this year, the Barron-Daintree focus region contributed similar discharge and loads to the southern focus regions.

Ambient water quality

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

- Exceeded guidelines: TSS (Tully region), NO_x (all focus regions), and Secchi depth (all focus regions)
- Near guidelines: Chl-*a* (all focus regions), TSS (Barron Daintree and Russell-Mulgrave regions), PP (all focus regions), and PN (Russell-Mulgrave and Tully regions)
- Below guidelines: PN (Barron Daintree region)
- Increases in DOC concentrations have occurred since 2005 in all focus regions, and POC concentration has increased in the Russell-Mulgrave region
- Water quality has declined since 2005 in the Barron Daintree and Russell-Mulgrave regions, and is stable for the Tully region. Water quality was scored as ‘good’ in the Barron Daintree region for the 2018–19 monitoring year, ‘moderate’ in the Russell-Mulgrave and ‘poor’ in the Tully region

Wet season and event water quality

- The eReefs hydrodynamic model output showed that enclosed and open coastal waters were moderately affected by river discharge from the Barron, Russell-Mulgrave, and Tully Rivers. River discharge was mainly transported in northerly and south-easterly directions from all rivers, with plumes sometimes making it seaward to mid-shelf and offshore waters.
- Two major flood events influenced the Wet Tropics during the 2018–19 wet season with large flood plumes captured with satellite imagery off the Tully and Herbert Rivers.
- Approximately 20% of the total area of the Wet Tropics region, 4% of the Wet Tropics coral reefs and 96% of the Wet Tropics seagrasses were exposed to a potential risk (combined potential risk categories II-IV). The areas were similar to the long-term average areas (within 2–4%).

7.3 Burdekin

The remnants of cyclones Owen and Penny and an intense tropical low coupled with a very active and stationary monsoonal trough resulted in heavy rainfall across the Burdekin region. The combined discharge and loads calculated for the 2018–19 water year from the Burdekin and Haughton Basins were the highest since the 2010–11 water year.

Ambient water quality

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

- Exceeded guidelines: Chl-*a*, NO_x, and Secchi depth
- Near guidelines: TSS, PN, and PP
- Increases in DOC and POC concentrations have occurred since 2005 in the region, although DOC has declined over the last two years
- Water quality has declined in the region since 2005. Water quality was scored as 'moderate' for the 2018-19 monitoring year and has been 'moderate' for the previous three years.

Wet season and event water quality

- The eReefs hydrodynamic model output showed that open coastal and mid-shelf waters from Cape Upstart to Cape Cleveland had moderate exposures to river discharge. The extent of three-dimensional exposure to river discharge was high in all directions. Plumes travelled ~200 km northwest (to Hinchinbrook Island) and were also transported ~80 km east into mid-shelf and offshore waters.
- Large flood plumes were captured with MODIS satellite imagery during periods from late December to mid-February 2019. Primary plume waters from the Burdekin River flowed east, pushed by offshore wind, and reached mid-shelf Old Reef during the first week of February (2–8 February). This was an unusual event, as Burdekin plumes typically move northwards along the coast.
- Approximately 21% of the total area of the Burdekin region, 5% of the Burdekin coral reefs and 98% of the Burdekin seagrasses were exposed to a potential risk (combined potential risk categories II-IV). The region area was greater than the long-term average area (7%) and the coral and seagrass areas were similar (3% difference).

7.4 Mackay-Whitsunday

The combined discharge and loads calculated for the 2018–19 water year from the Proserpine, O'Connell, Pioneer and Plane Basins were similar to those measured in the 2016–17 which were influenced by cyclone Debbie. One major flood event influenced the Mackay-Whitsunday region during the 2018–19 wet season and was associated with extensive rainfall in late January–early February 2019.

Ambient water quality

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

- Exceeded guidelines: TSS, NO_x, and Secchi depth
- Near guidelines: Chl-*a*, PN, and PP
- Increases in DOC and POC concentrations have occurred since 2005 in the region, although DOC has declined over the last two years
- Water quality has shown a large and continuous decline in the region since 2005. Water quality was scored as 'moderate' for the 2018–19 monitoring year and has improved following 'very poor' water quality during the 2016–17 year.

Wet season and event water quality

- A large flood plume was captured with MODIS satellite imagery off the Pioneer River during the second week of February (9–15 February).
- eReefs hydrodynamic model output showed that moderate exposure to river discharge occurred mainly in enclosed coastal waters of Repulse Bay, especially near the O'Connell mouth. Open coastal waters near Repulse Bay had low exposures and mid-shelf waters were not affected by O'Connell River discharge. Extent of exposure was relatively low compared to other modelled rivers. Plumes travelled ~30 km east (to Cape Conway).
- Approximately 22% of the total area of the Mackay-Whitsunday region, 7% of the Mackay-Whitsunday coral reefs and 93% of the Mackay-Whitsunday seagrasses were exposed to a potential risk (combined potential risk categories II-IV). These areas were similar to the long-term average areas (within 1%).

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Appendix A. Patterns of fluorescent dissolved organic matter in the inshore Reef lagoon

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A-1 Introduction

Dissolved organic matter (DOM) represents a major pool of carbon, nitrogen, and phosphorus in the ocean. Rather than being defined by its chemical composition, DOM is instead operationally defined as any organic matter that passes through a certain filter pore size, which is typically 0.2–0.7 µm (He et al., 2016). The DOM pool contains a diverse array of constituents including low molecular weight compounds like sugars and amino acids, medium molecular weight compounds like humics, and heavier compounds such as proteins, polysaccharides, and DNA (Benner 2002). The sources of DOM in the coastal ocean are complex and are a function of phytoplankton production, river discharge, and the dynamic physical processes operating in the coastal zone (Cauwet 2002). There are several key physical processes that impact on coastal DOM, including degradation by sunlight (Stedmon et al., 2007), aggregation (or dis-aggregation) through hydrodynamic forces, and adsorption onto (or de-sorption from) particles (He et al., 2016).

The chemical compounds comprising DOM vary in their lability, or ease with which they can be broken down by bacteria; thus, lability is a measure of the biological 'relevance' of DOM. Some compounds, such as carbohydrates or proteins are relatively labile (Lønborg et al., 2017), while others like humics are highly refractory, or difficult for bacteria to access (Tanaka et al., 2014). This lability is critical to the role marine DOM plays in the cycling of nutrients and carbon, as highly labile DOM is quickly remineralised and thus becomes available to fuel further phytoplankton production.

Water quality monitoring under the MMP has shown that concentrations of dissolved organic carbon (DOC) have been steadily increasing within inshore regions of the Reef since monitoring began in 2005 (see Section 5). This trend is of concern, as it is not presently clear what the causes or implications of increased DOC concentrations are for the coastal ocean. There is a limited amount of research demonstrating that certain types of DOC (in this case, simple sugars) can increase coral mortality by affecting the interactions between the coral and its microbial community (Kline et al., 2006). In addition, increases in DOC may indicate changes in coastal biogeochemistry, such as the impact of ocean warming (Thornton 2014) or enhanced productivity related to riverine nutrient inputs.

Therefore, it is critical that we more deeply investigate changes in the coastal DOM pool, including determining its composition, source, and lability. This case study is a preliminary exploration of the composition of inshore DOM using fluorescence spectroscopy, a method which uses the optical properties of fluorescent DOM (fDOM) to identify unique peaks within a set of samples (Murphy et al., 2008). These peaks can be compared to a global library of peaks to determine the composition of fluorescent DOM within a given sample.

A-2 Methods

Water sample collection was done during wet (January–February), late-wet (March), and dry (May–July) seasons during ambient MMP sampling. A total of 202 samples were collected for fDOM analysis, and came from sites within the Barron Daintree, Russell-Mulgrave, Tully, Burdekin, and Mackay-Whitsunday focus regions. Sampling was conducted at the site locations routinely monitored by AIMS, and so contained a mixture of enclosed coastal, open coastal, and mid-shelf sites. At each site, samples were collected from surface (~0.5 m below water surface) and near-bottom (~1 m above the sediment) waters using Niskin samplers. Samples were filtered (0.2 µm, Pall Acrodisc supor membrane) into acid-washed 50 mL amber glass vials and stored in cool and dark conditions during transport. For fluorescence spectroscopy, samples are filtered to 0.2 µm to exclude bacteria and larger colloids which otherwise can alter the composition of DOM or interfere with its optical and fluorescence properties. Back at the laboratory, samples were stored refrigerated (4° C) and were analysed within seven days of collection.

Samples were analysed for coloured dissolved organic matter (CDOM) absorbance spectra (250–750 nm range) using 10 cm quartz cells on a spectrophotometer (Shimadzu UV). Samples were equilibrated to room temperature prior to analysis and MilliQ water was used as a blank. The absorption coefficient at any wavelength, $a_{CDOM}(\lambda)$ (in m^{-1}), was calculated as:

$$a_{CDOM}(\lambda) = 2.303 \times [Abs(\lambda) - Abs(650)]/L$$

where the factor 2.303 corrects for effects of the cell, *Abs* is absorbance, and *L* is the cell pathlength (in m).

Samples were then analysed for emission-excitation spectra using a 1 cm quartz cell in a Jasco FP-8500 spectrofluorometer. Excitation wavelengths ranged from 240–450 nm with a 5 nm increment, while emission wavelengths ranged from 300–600 nm with a 2 nm increment. MilliQ baseline scans were collected at the beginning of each run.

Correction and analysis of the fDOM dataset was conducted using the drEEM (Decomposition routines for Excitation Emission Matrices) toolbox 0.2.0 for Matlab (Murphy et al., 2013). Absorbance scans (a_{CDOM}) from each sample were used to correct the excitation-emission matrices for inner filter effects and MilliQ blank scans were subtracted from each sample. Raman water blanks were extracted from MilliQ blanks for each run.

Parallel factor analysis (PARFAC) was used to determine the locations of significant fluorescence peaks within the entire dataset (202 scans). This method allows the user to set the expected number of peaks within a sample database, and then perform validation tests to determine which model is the most robust for representing the dataset. We looked for between four to seven fluorescence components in our dataset, with the six-component model showing the most stability. Several components were highly correlated within models, so scan intensities were normalised for model determination and then reverse-normalised for further validation. Models were evaluated based on the randomness of residuals, observation of spectral loadings, least squares models, and split half analysis (Stedmon and Bro 2008). A 6-component model was determined to be the best fit for this dataset, where each component describes a unique peak.

Identified components were compared with a global fDOM library (OpenFluor, https://openfluor.lablicate.com/) to determine their chemical characteristics and identify other studies with similar results (Murphy et al., 2014). The fluorescence intensity (Fmax) for each of the 6 components (peaks) was then exported for each sample for comparison with other water quality and physico-chemical data collected during MMP sampling.

A-3 Results and Discussion

PARAFAC analysis identified six main peaks present within this sample database (total of 202 samples from Wet Tropics, Burdekin, and Mackay-Whitsunday regions during both wet and dry seasons). Peaks are referred to as "components" because each one represents a unique type of dissolved organic matter that is present to some extent in all samples (Figure A-1). Components (peaks) 1–3 were humic-like and likely derived from terrestrial sources such as river discharge (Ishii and Boyer 2012). Components 4 and 5 have fluorescence characteristics similar to tryptophan, an amino acid used as a building block for proteins (Stedmon and Markager 2005; Amaral et al., 2016). Component 6 had fluorescence characteristics similar to tyrosine, another amino acid which is used to synthesize proteins (Yamashita et al., 2013). Components 4–6 are likely related to phytoplankton production or other *in situ* primary production. It is important to note that the size of coloured areas of peaks does not reflect their concentration in samples, but rather their fluorescence properties (e.g., humics are highly fluorescent and so have larger coloured areas in Figure A-1).

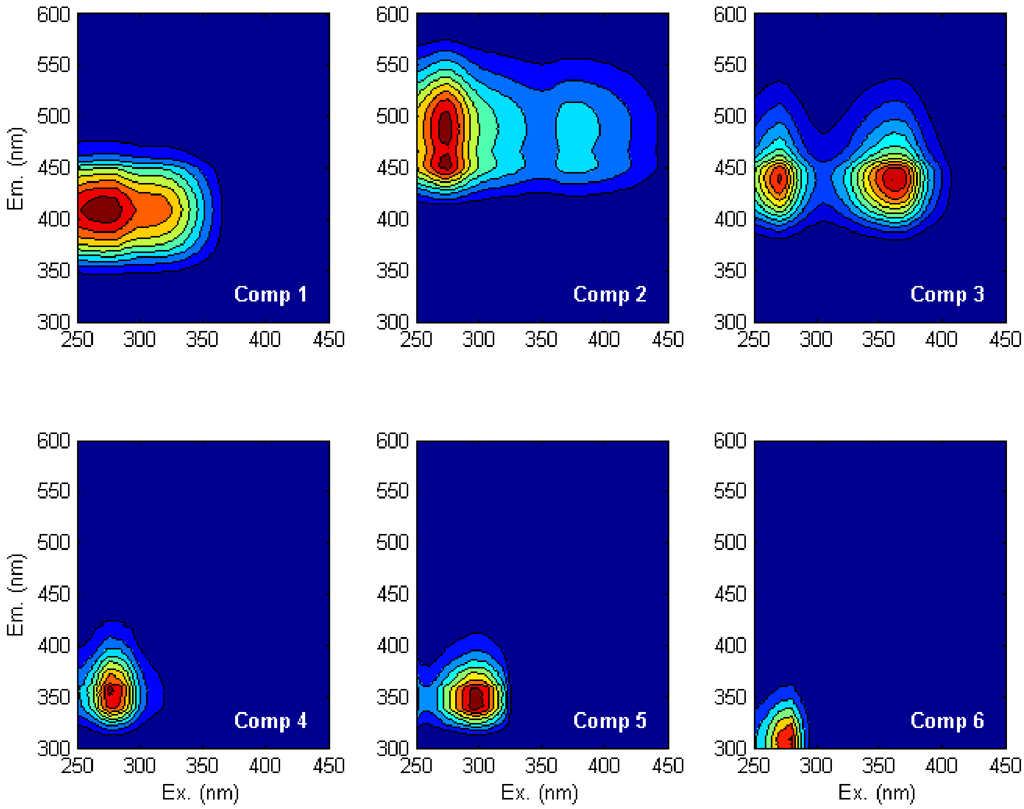

Figure A-1: Components (peaks) identified during parallel factor analysis of the entire fDOM dataset (202 samples). Components 1–3 are humic-like compounds likely derived from river discharge, while components 4–6 are amino acid-like compounds likely derived from phytoplankton production. The size of the components does not reflect their concentration in samples, but rather their fluorescence properties (e.g., humics are highly fluorescent and so have larger coloured areas above).

The identification of Components 1–3 as humic compounds was further supported by their relationships with salinity. All three components showed strong linear (conservative) relationships with salinity, where samples from very wet periods (high river discharge) showed high peak intensities (F_{max}) and fully marine samples showed low peak intensities (Figure A-2). This indicates that these humic compounds are related to river discharge and affected by dilution in the coastal ocean. Components 4 and 5 did not show relationships with salinity, but Component 6 was relatively conservative with salinity and showed higher intensities in low salinity waters (Figure A-3).

Humics tend to be highly refractory (taking a long time to break down) in terms of use by bacteria, but they can be quickly broken down by exposure to sunlight (Tanaka et al., 2015). Some work has shown that dissolved organic nitrogen can be rapidly photo-oxidised to form ammonia, a highly labile form of nitrogen (Stedmon et al., 2007); however, humics generally are depleted in nitrogen compared to other forms of DOM, and thus the addition of photo-oxidised ammonia to the Reef lagoon may be small.

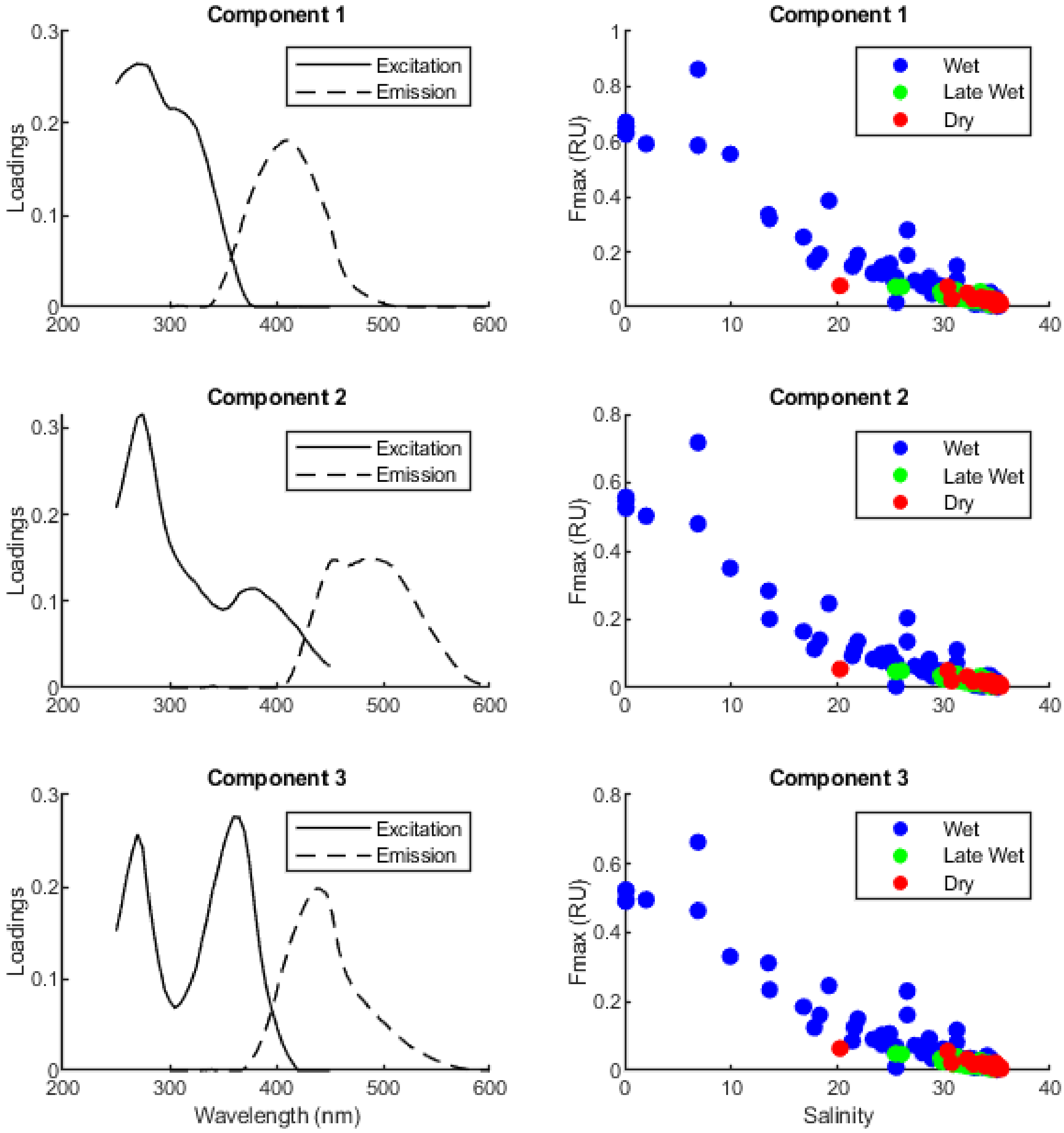

Figure A-2: Loadings of components 1–3 describe peak location in the excitation-emission space and are shown in the left panel. The fluorescence intensity (F_{max}) in Raman units is shown in the right panel for all samples as a function of salinity. Linear relationships between F_{max} and salinity show that these components are conservative with salinity.

Previous work on DOM in the Reef lagoon has suggested that proteins (which contain more nitrogen and phosphorus than other DOM compounds) may form a small fraction (~13%) of the overall DOM pool (Lønborg et al., 2017). However, compounds with high fractions of nitrogen and phosphorus are more attractive for bacteria to break down. This work has shown that 22–28 µg L^{-1} of dissolved organic nitrogen may be highly labile (readily broken down), which is an order of magnitude higher than dissolved inorganic nitrogen concentrations in the inshore Reef lagoon. Thus, a portion of these amino acid-like components (Components 4–6) is likely to be relatively labile and used by bacteria on time-scales of days.

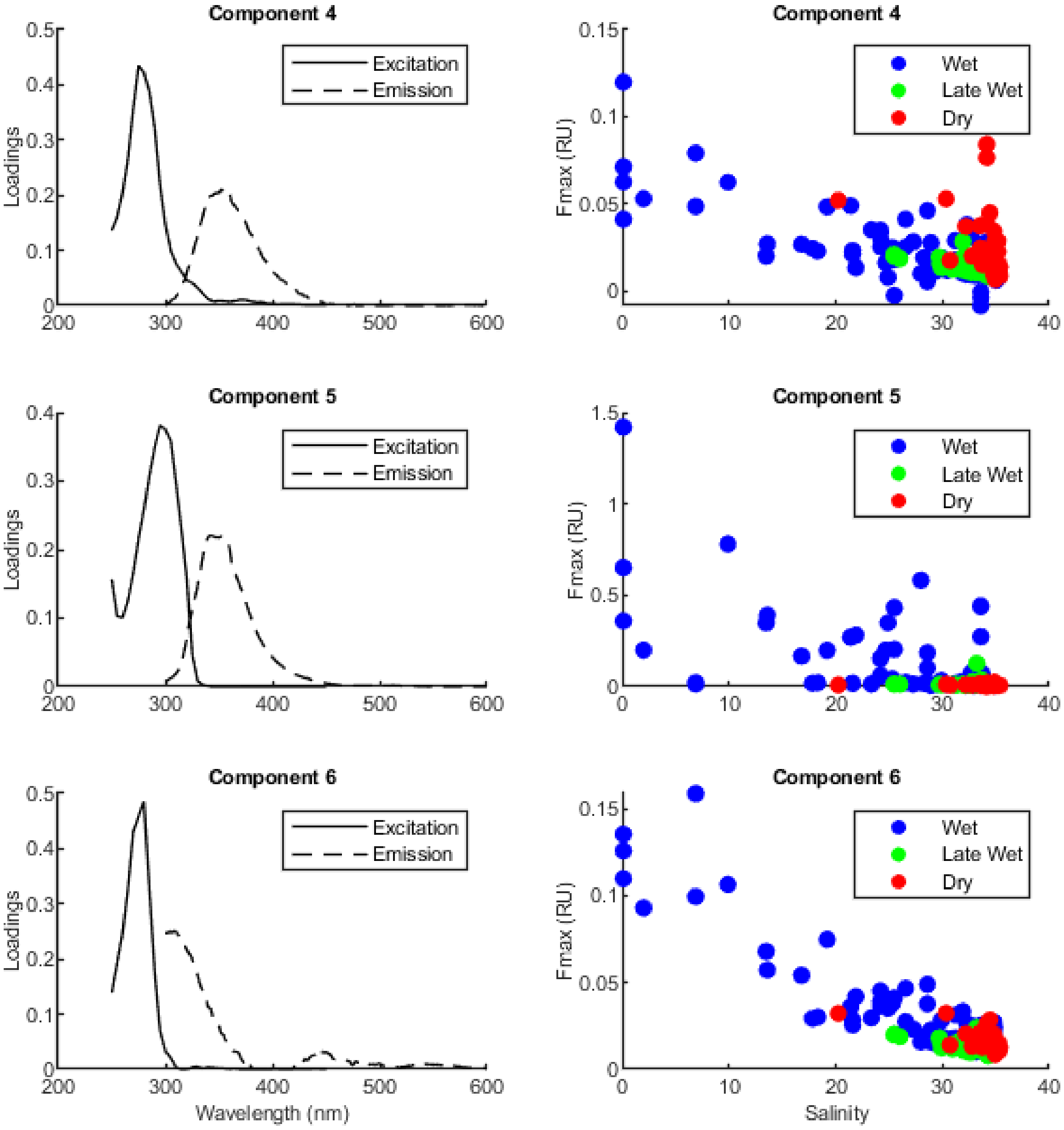

Figure A-3: Loadings of components 4–6 describe peak location in the excitation-emission space and are shown in the left panel. The fluorescence intensity (F_{max}) in Raman units is shown in the right panel for all samples as a function of salinity. Linear relationships between F_{max} and salinity show that Component 6 is conservative with salinity, while Components 4 and 5 do not have strong relationships with salinity.

Relationships between component peak intensities (F_{max}) and chlorophyll *a* show a bi-modal distribution that is related to salinity (Figure A-4). Very low salinity waters (flood plumes or sites close to river mouths) show high amounts of all components, especially humics (Components 1–3), with no relationship to Chl-*a* concentration. These higher humic concentrations occur due to river discharge during the wet season. Whereas, moderate-salinity waters (associated with more developed river plumes) show a linear relationship between Chl-*a* and humic components; this is likely an effect of phytoplankton blooms (e.g., secondary plume waters) occurring simultaneously with dilution of fresh water. Component 6 (amino acid-like) shows similar relationships to Chl-*a* as humic components, which may be related to phytoplankton production in plume waters or may be a factor of dilution. Surprisingly, Components 4–5 did not show strong relationships with Chl-*a* concentrations. Further analysis of this dataset is needed to determine which water quality variables these components are related to.

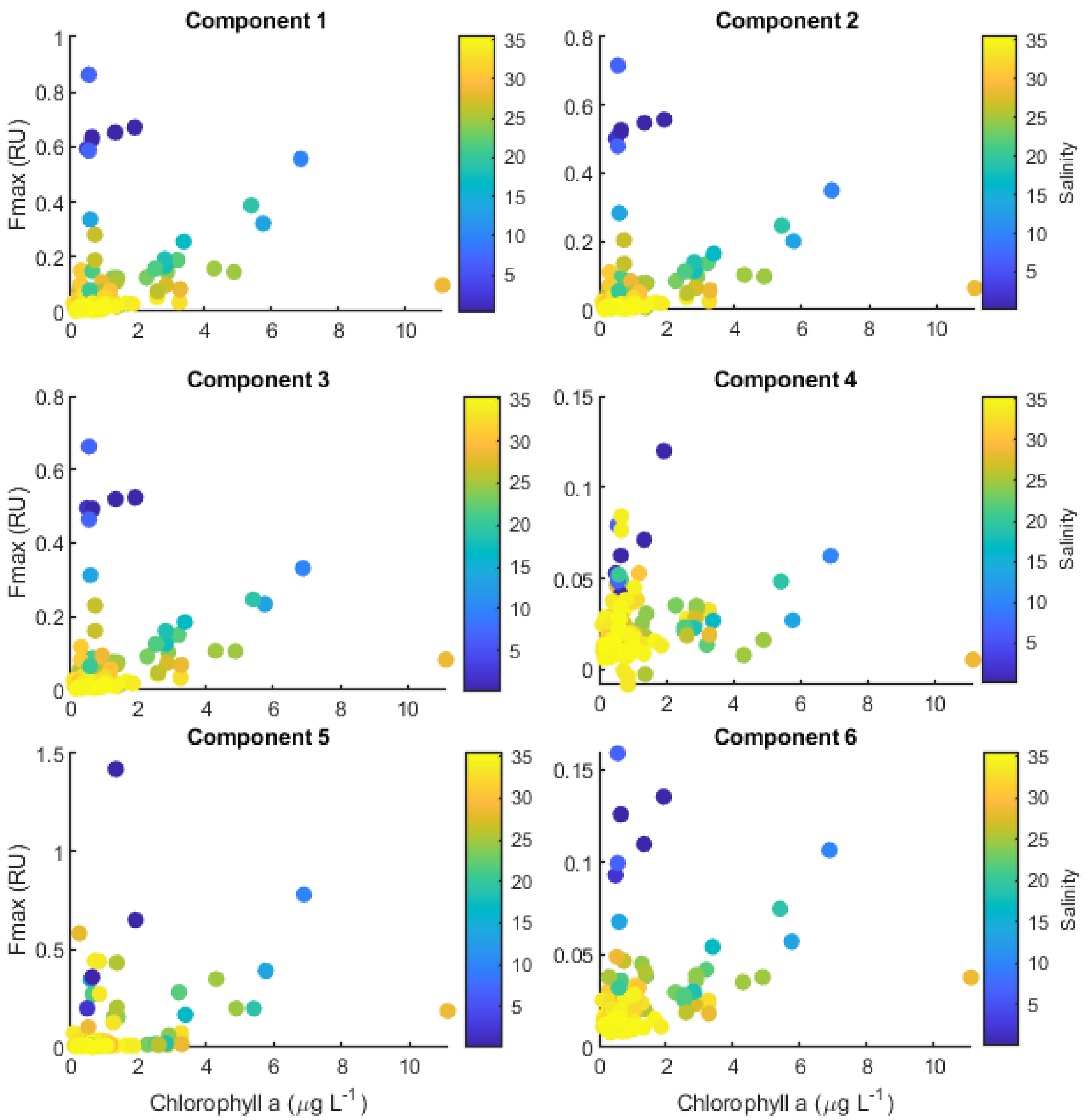

Figure A-4: Relationship between the fluorescence intensity (F_{max}) in Raman units and chlorophyll *a* concentration for each peak. Colour shading denotes salinity values.

Regional differences in the intensities of some components were found in this dataset. Humics components (Component 1, for example) showed linear relationships with salinity (due to dilution, as discussed above). However, these relationships had the greatest slope for samples from the Mackay-Whitsunday region, followed by Burdekin, and Wet Tropics regions (Figure A-5). This indicates several possibilities including: 1) that the specific humic compounds coming from river discharge may differ among regions, 2) that the concentrations of humics in river discharge may differ among regions, or 3) that the timing or frequency of rainfall events may alter which humic compounds are exported from rivers. These regional differences were not present for phytoplankton production-derived DOM (Component 4, for example). This suggests that the products of phytoplankton production are similar across the inshore Reef lagoon, which is what we would expect.

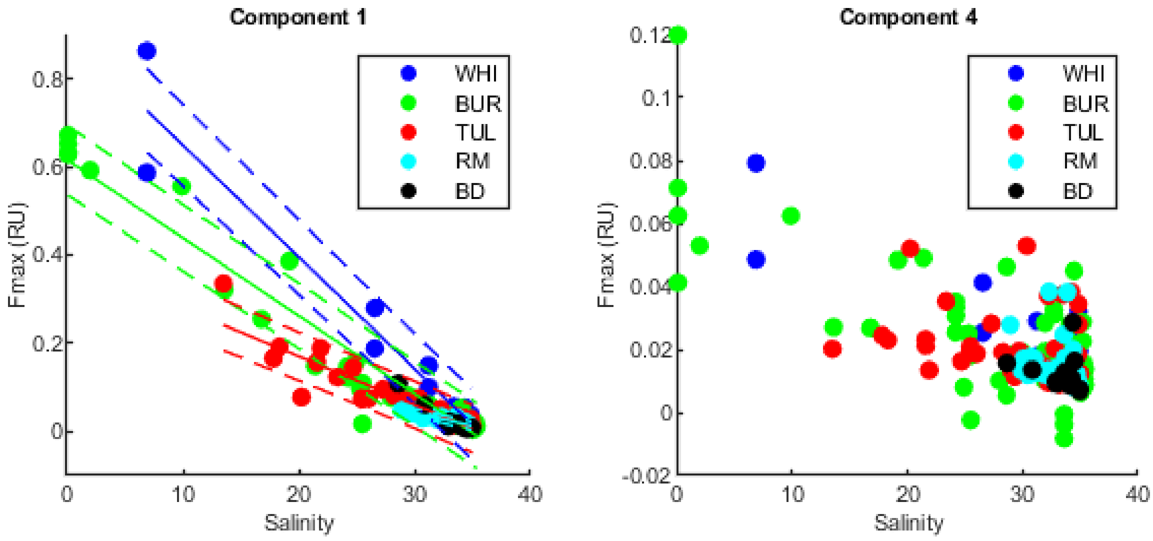

Figure A-5: Regional differences in fluorescence intensity (F_{max}) in Raman units of components 1 and 4 along salinity gradients. Trend lines (solid lines) in the left panel indicate a linear trend with 95% confidence intervals (dashed lines) shown. Clear regional differences can be seen for Component 1 (humic-like), while Component 4 (phytoplankton-derived) shows no regional differences.

This study has provided a preliminary look at dissolved organic matter fractions present in the inshore Reef lagoon. It has identified humic and phytoplankton production-derived compounds as the main fluorescent DOM present during wet and dry seasons. This is the first step in understanding the composition and lability of DOM, and will help guide future research on long-term changes in DOC concentrations. Further analyses of these data are needed to determine which water quality and abiotic variables they are closely associated with. Additionally, process-based studies of these DOM pools are needed to determine their lability and contribution to biogeochemical cycles of coastal waters.

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Appendix B. Case study: The dissipation of suspended particulate matter in river flood plumes and implications for marine ecosystems

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B-1 Introduction

The influence of newly delivered riverine particulate matter on marine ecosystems across the continental shelf of the Great Barrier Reef (the Reef) has received considerable attention over several decades. While it is widely accepted that suspended sediment loads exported from the Reef catchment area have increased considerably since European settlement (c. 1850) (Kroon et al., 2012), the cornerstone of the debate is largely centred on the role of this 'new anthropogenic sediment' on turbidity and light regimes in the Reef (e.g. Woolfe and Larcombe, 1998; Larcombe and Woolfe, 1999; Orpin and Ridd, 2012; Fabricius et al., 2013, 2014, 2016; Lewis et al., 2014). In that regard, the suspended particulate matter (SPM) delivered via riverine flood plumes influences turbidity/light in the Reef during the period of flood plume exposure (e.g. Petus et al., 2018). Additional influence potentially occurs in the following months due to the newly settled particles being more easily resuspended back into the water column compared to the existing sediments which are relatively more compacted on the seafloor (e.g. Fabricius et al., 2013, 2014 and 2016). Indeed, the level of temporal exposure of primary plume waters (characteristic of elevated SPM concentrations and reduced light) on parts of the inshore Reef is correlated with variability in seagrass meadow area (Petus et al., 2014a) and appears to exert some influence on coral reef health (Thompson et al. 2014; Petus et al., 2016; Ceccarelli et al., 2019). However, other researchers question the importance of the new sediment delivered in flood plumes suggesting that wind-driven resuspension of the existing Holocene terrigenous sediment wedge controls SPM concentrations along the inner Reef (Woolfe and Larcombe, 1998; Larcombe and Woolfe, 1999; Orpin and Ridd, 2008).

The initial area influenced by newly delivered SPM is controlled by the movement and coverage of the flood plume in the Reef as well as the dispersal of the SPM within the plume. The movement and composition of flood plumes in the Reef have received considerable research attention which include: data from direct measurements in plume waters (e.g. Wolanski and Jones 1981; Wolanski and van Senden, 1983; Taylor, 1996; Devlin et al., 2001; Devlin and Brodie, 2005; Wu et al., 2006; Wolanski et al., 2008; Brodie et al., 2010; Bainbridge et al., 2012; Howley et al., 2018; Gruber et al., 2019); remote sensing of flood plume water types including analysis of plume frequency, exposure, and risk (e.g. Burrage et al., 2002; Devlin and Schaffelke, 2009; Devlin et al., 2012, 2015; Schroeder et al., 2012; Álvarez-Romero et al., 2013; Petus et al., 2016, 2018, 2019); and modelling (King et al., 2002; Delandmeter et al., 2015; Margvelashvili et al., 2018; Xiao et al., 2019).

While the lateral dispersal of SPM over surface plume waters of the estuarine mixing zone has been well described in several manuscripts (Devlin et al., 2001; Devlin and Brodie, 2005; Brodie et al., 2010; Bainbridge et al., 2012; Howley et al., 2018), the dispersal of SPM within the water column has received comparatively less focus. The available empirical data on the dispersal of SPM within the water column in river plumes provide seemingly contradictory findings. Some observations document that SPM is concentrated within the buoyant low-salinity section of the upper water column (Taylor, 1996), while others report that SPM appears to be well-mixed at various depths in the water column (Taylor, 1997; Bainbridge et al., 2012) and have measured concentrated SPM towards the bottom water column (i.e. development of nepheloid layer) of the plume (Wu et al., 2006; Wolanski et al., 2008). Indeed, all scenarios have been reported in the international literature and are related to variability in river discharge and distance offshore whereby the SPM becomes trapped (and potentially concentrated relative to the riverine source) in plume frontal zones (e.g. Geyer et al., 2004).

The quantification of the relative influence of SPM from river plumes compared to the suspended sediment contributed through wind-driven resuspension of existing Holocene bay fill deposits has yielded conflicting findings (Larcombe and Woolfe, 1999; Orpin et al., 1999; Wolanski et al., 2008; Orpin and Ridd, 2012; Fabricius et al., 2013).

Earlier studies applied the turbidity profiles of Taylor (1996) from the Barron River plume where SPM levels (equivalent to <10 mg L^{-1}) were concentrated in the buoyant upper 2 m water column. These measurements combined with the plume area were used to estimate the mass of sediment carried in plumes (Larcombe and Woolfe, 1999; Orpin et al., 1999). This first-order sediment budget estimation suggested that the sediment mass dispersed in wind-driven resuspension events may be 'several orders of magnitude' higher than SPM supplied in river flood plumes on the inner Reef (Larcombe and Woolfe, 1999; Orpin et al., 1999).

Wolanski et al. (2008) subsequently showed that SPM delivered in the Tully River plume was well-mixed throughout the water column and was decoupled from the buoyant low salinity wedge with possibly higher SPM concentrations towards the seafloor; similar findings have been reported for other river plumes in the Reef including the Herbert (Wu et al., 2006), Burdekin (Bainbridge et al., 2012), and in another plume from the Barron following cyclone Sadie (Taylor, 1997). Turbidity sensors, light loggers, and sediment traps deployed by Wolanski et al. (2008) during the 2007 Tully flood plume showed increased sediment exposure and considerable reductions in light irradiance. Orpin and Ridd (2012) offered an alternative interpretation of this dataset suggesting that wind-driven resuspension played the dominant role during this event citing, among other factors, the higher SPM concentrations measured in the offshore plume waters than measured in the Tully River.

More recently, detailed statistical modelling exercises have been applied on comprehensive *in situ* turbidity logger (Fabricius et al., 2013) and satellite photic depth (Fabricius et al., 2014, 2016) datasets, which highlighted the considerable influence of newly delivered sediment on turbidity regimes in the Reef.

The vast majority of research on terrigenous sediment dynamics in the Reef lagoon has been conducted on the inner shelf as:

1) the river plumes were thought to rarely reach the middle and outer Reef shelves (Devlin et al., 2001; Devlin and Brodie, 2005)

2) the SPM carried in the plumes that reach the middle and outer shelves of the Reef is considered 'very little' (Lambeck and Woolfe, 2000; Larcombe and Carter 2004)

3) wave-driven sediment resuspension and the 'terrigenous sediment wedge' is constrained to within the 22 m depth zone (i.e. the inner shelf; Orpin et al., 1999).

However, recent modelling exercises using satellite photic depth (Fabricius et al., 2014, 2016) and eReefs (Margvelashvili et al., 2018) highlight that newly delivered sediment from plumes has the potential to influence light regimes out to the mid- and possibly even some parts of the outer Reef shelf (see also Petus et al., 2018).

This study draws on samples collected offshore from the Tully and Burdekin Rivers to examine the dispersal of SPM within river plumes over the estuarine mixing zone under different environmental conditions. Our case study briefly documents the spatial variability of plumes in the Reef including the periodicity of influence on the middle shelf and the dispersal of SPM over the estuarine mixing zone. We examine the amount of light reduction as a result of the plume waters including new data from the mid-shelf and quantify the length and exposure of such events. We show that euphotic depth may be greatly reduced in the flood plumes by several metres even when the plume impinges on the mid-shelf. Finally, we produce a first-order estimate of sediment transport in the plumes from the Wet and Dry Tropics and consider the implications of the increased sediment supply since European settlement.

B-2 Methods

The flood plume data presented in this study have been collected through the Marine Monitoring Program (MMP) which was established in 2005. The water quality component of the MMP examines the condition and trend of various physiochemical and nutrient parameters measured multiple times at established sites over the year with a focus on the wet season (e.g. Gruber et al., 2019).

From 2005–2014, the surface waters of flood plumes were monitored targeting the salinity gradient over the estuarine mixing zone with sites chosen in the field based on visual changes in the plume or targeting specific salinity zones. A review of the program led to the establishment of set locations which are sampled at the surface and depth (typically 1 to 2 m from the seafloor) throughout the year in both ambient and flood plume conditions. This new design allows direct inter- and intra-annual comparisons to be made in ambient conditions and in flood plumes to examine spatial and temporal trends in water quality condition. The sites in each region were selected to cover a gradient from the major river mouths. The focus areas of this case study includes the sites off the Tully and Burdekin Rivers which have been well-sampled by the MMP. The main dataset presented was collected in the 2018–19 field season for the Burdekin River, and a combination of 2017–18 and 2018–19 for the Tully River including data from Ellison Reef (mid-shelf reef seaward of the Tully River) in 2017–18. A broader dataset covering several seasons was used to model plume mixing over the estuarine zone.

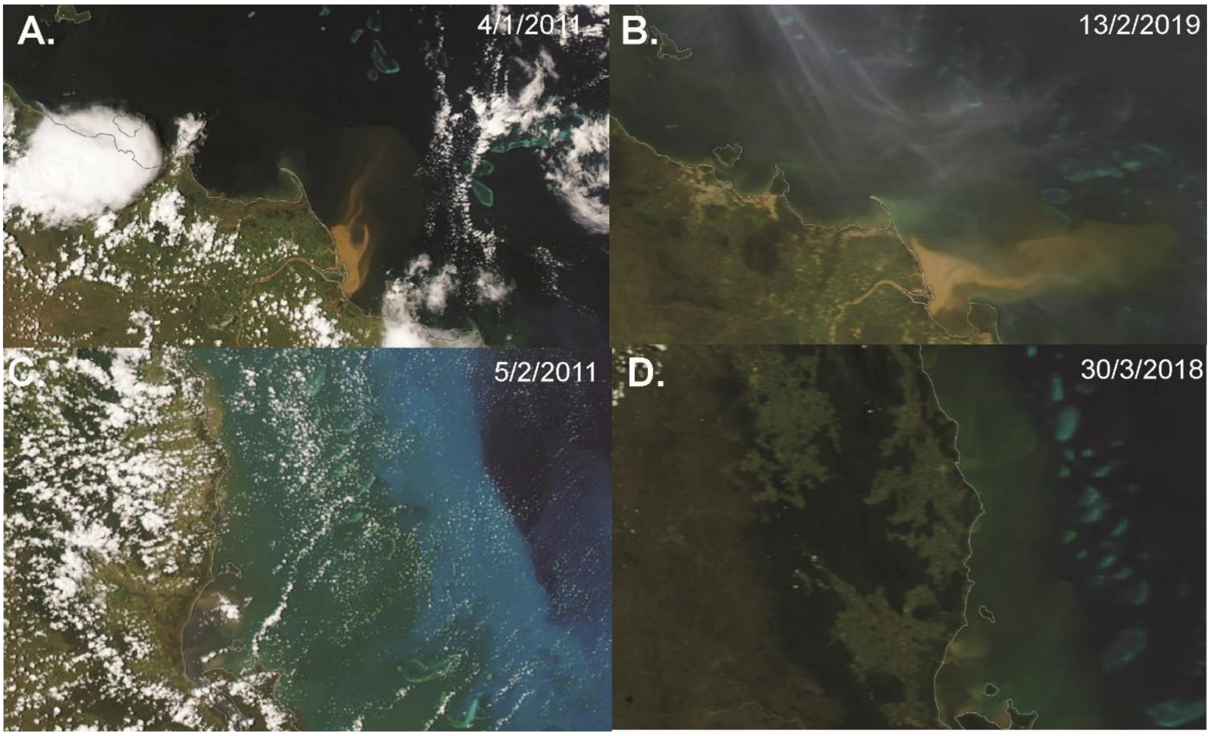

Figure B-1: MODIS satellite images from the Burdekin (A and B) and the Tully (C and D) plumes in 2011 and 2019. Note the variable movements across the Reef under moderate to large flow events including the influence on the mid-shelf reefs.

To highlight the spatial variability of the flood plumes from the Tully and Burdekin Rivers we chose two moderate-to-large discharge years for comparison. The years included 2011 and 2018 for the Tully and 2011 and 2019 for the Burdekin (Figure B-1). During these years the observed movement of the plume covered different spatial areas of the Reef due to different environmental conditions. True colour satellite images are presented (MODIS Aqua and MODIS Terra) for periods coinciding close to the peak discharge (Figure B-1).

Burdekin plume 2019

Major flooding was recorded in the Herbert, Black-Ross, and Haughton basins including severe flooding in and around Townsville in February 2019. The Burdekin River peaked at the moderate flood level on 8 February 2019 and discharged 17.5 million ML over the 2018–19 water year (1 Oct 2018–30 September 2019), of which 14.5 million ML was discharged in the three week period between 30 January and 19 February 2019 (Figure B-2). This volume of water discharged is considered a 'very large event' for the river and has approximately a 1-in-5-year return interval.

Sampling of the Burdekin River flood plume for this program targeted plume waters along the MMP defined event sites over 11–12 February, 20–21 February, and 6–7 March with some additional samples taken from sites where NESP project 5.8 sediment traps and environmental loggers are deployed (i.e. Orchard Rocks and Havannah Island). As the flood plume from the Burdekin River moved directly offshore (as opposed to northwards along the coast due to offshore winds) during its peak flow, an additional transect of sites was sampled out to Old Reef (mid-shelf) on 15 February.

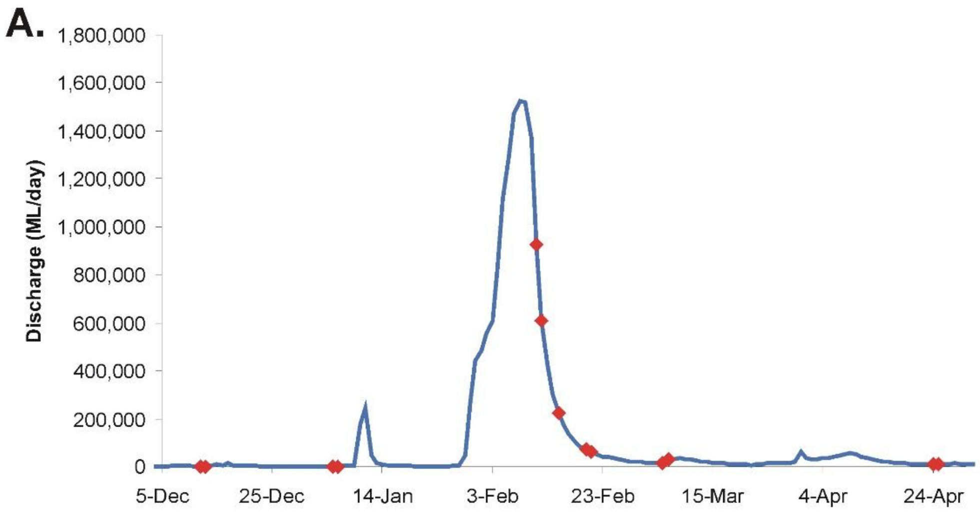

Figure B-2: River discharge (in ML d^{-1}) from 5 December 2018–30 April 2019 for the Burdekin (Clare gauge). Red diamonds show when sampling occurred seaward from the river mouths (including ambient monitoring periods).

Tully plume 2018

The Wet Tropics region experienced an above average wet season in 2017–18 with major flooding occurring in many rivers including the Herbert and Tully Rivers. In fact, the Tully River had two major flow events (peaked on 10 March and 28 March 2018, respectively) as well as two moderate level flow events (peaked on 19 January and 7 February, respectively) and one minor event (peaked on 27 January). The total discharge for the water year (1 October–30 September) was 4.2 million ML for the Tully River (Figure B-3) and 6.4 million ML for the Herbert River.

Sampling of the Tully flood plume in 2018 was restricted on several occasions to shorter times on the water or until a few days after peak river flow due to poor weather. However, extensive sampling of the Tully plume waters across the estuarine mixing zone over January to March 2018 was conducted including one visit to Ellison Reef on 14 February (Figure B-3).

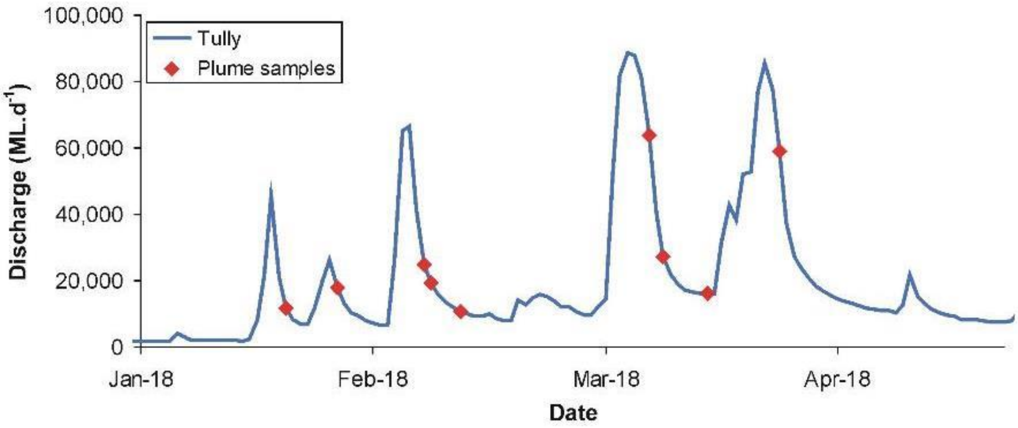

Figure B-3: River discharge (in ML d^{-1}) from 1 January 2018–30 April 2018 for the Tully at Euramo gauge. Red diamonds show when sampling occurred offshore from the river mouths (including ambient monitoring periods).

Plume sampling

At each location, depth profiles were performed using a conductivity-temperature-depth (CTD) probe from SeaBird Electronics (SBE-19Plus) equipped with sensors for temperature, salinity, depth, and Photosynthetically Active Radiation (PAR). The profiles were carried out from the sunny side of the boat and the probe was kept for 3 min at the water surface for sensor stabilisation before starting the downcast. Under the MMP, these casts are normally processed and largely used to provide information for remote sensing as well as to refine the loading maps for suspended sediment and dissolved inorganic nitrogen dispersal and exposure in the Reef. However, these casts also provide valuable data on the mixing of plume waters in the marine environment and the light availability under these conditions. The raw cast data were downloaded and the upper section of the data where the instrument equilibrates at the surface was discarded (i.e. the instrument is held ~1 m below the surface for ~3 mins so the sensors can equilibrate). Both the down-casts and up-casts were plotted to examine the reproducibility of the data at each site (not shown). In most cases, the down- and up- casts were highly comparable, although differences in the sharpness and depth of the salinity profile were evident where a strong salinity gradient in the water column occurred. In those circumstances it is likely the down-cast (and subsequent up-cast) disturbed the water column where a more 'mixed' profile was produced in the up-cast. Based on this finding, we favoured the down-cast data; however, as the down-cast data misses the upper ~1 m of the water column due to the equilibration step, the up-cast data of the upper 1–1.5 m of water column was patched onto the downcast data to produce a full profile of the water column.

Suspended Particulate Matter sampling and analysis

SPM samples were collected in a 10 L container at the surface and a 5 L Niskin bottle for depth samples (typically 1–2 m from the seafloor) before being transferred into a 1 L bottle. The samples were kept refrigerated at 4° C and analysed by the Total Suspended Solids (TSS) method using the standard gravimetric filtration method (Method 2540D; APHA, 2005). Known volumes of sample were vacuum filtered onto pre-weighed 0.4 µm polycarbonate filter papers and dried overnight in a 105°C oven.

Modelling of plume freshwater mixing

The salinity data from the individual CTD profiles collected during flood plume events were processed first by matching the salinity pattern with depth via a simple model and secondly by quantifying the key parameters of each profile. These parameters included the minimum salinity, maximum salinity, inflection point, and the salinity change (Figure B-4). These parameters best describe the amount and depth of freshwater plume mixing in the water column across our plume transects and can then be compared with other key parameters such as discharge, distance offshore, wind speed, and wind direction.

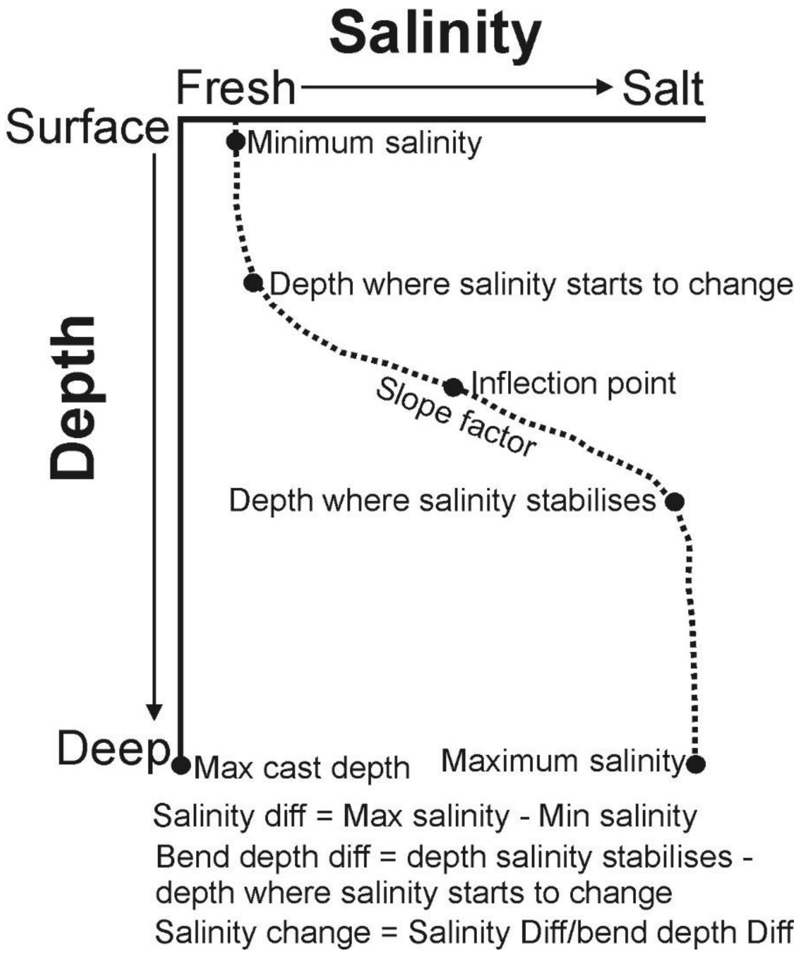

Figure B-4: The Seabird CTD data measured across the plumes were processed to determine key parameters of the salinity curve. These parameters were then used to examine correlations with other factors such as wind speed and direction, river discharge, and distance offshore.

B-3 Results

Plume extent

Our observations of the plume extents from the Tully and Burdekin Rivers are consistent with what has been described previously in the Reef (e.g. Devlin et al., 2001; Devlin and Brodie, 2005; Devlin and Schaffelke, 2009). Specifically, the spatial extent of the plume is predominantly driven by river discharge volume and the wind speed and direction. The most common scenario is when elevated river discharge coincides with south-easterly winds which drive the low salinity plume waters northwards while remaining relatively close to the coast (e.g. 2011 floods in Burdekin: Figure B-1). When calmer conditions coincide with moderate to large river discharge, the resulting plumes push further seaward and impinge on the mid- (and possibly outer) Reef, which was highlighted in the satellite imagery for the Tully River in 2011 and for the Burdekin River in 2019 (Figure B-1).

Burdekin plume trends

The transect of sites measured on 11 February (three days after peak Burdekin River flow) showed very low salinity levels (<10) at the surface within 30 km from the Burdekin River mouth. At these sites, a strong salinity gradient existed in the water column between 1–4 m below the surface, indicating the plume waters remained at the surface as a relatively thin buoyant layer (not all data shown). The site 4 km off the mouth of the Burdekin River showed freshwater at the surface (salinity 0.1) while at 3 m, salinity reached 33.5 (not shown; however similar for 10 km location in Figure B-5). While a salinity gradient was still evident in the casts taken further seaward from the Burdekin mouth, it was not as large as the inshore sites with salinities around 25–30 at the surface and >33 at depth (Figure B-5). However, the section of the water column where the greatest transition in salinity occurred (generally >5 m) was much deeper at the more seaward sites. This result indicates that the plume waters were further mixed through the water column as the flood waters moved further seaward (Figure B-5). We note that the sea state was calm on the day of sampling (winds <10 knots) so there was little opportunity for wind-driven mixing.

The salinity mixing model for the Burdekin plume data showed that there was a significant correlation between river discharge and plume salinity offshore which has been confirmed previously (e.g. Devlin et al. 2001). Interestingly, there was no apparent relationship in the mixing of the freshwater plume in the water column over the variable wind speeds sampled (ranging from calm to ~20 knots). However, there was a relationship with the wind direction as the freshwater plume was mixed deeper into the water column when the wind directions were from the southeast (120° bearing) compared to winds from a southerly direction (160° bearing) (Figure B-6).

Tully plume trends

In contrast to the Burdekin plume, the freshwater lens in the Tully plume in 2019 remained in the upper 5 m of the water column as it progressively mixed with seawater (Figure B-5). The salinity mixing model showed there was a significant correlation between discharge and plume salinity with increased seaward distance, although as with the Burdekin no correlation existed between the wind speeds measured (calm to ~25 knots) and the amount of freshwater mixing through the water column (data not shown). Similarly to the Burdekin model findings, wind direction had an influence on the mixing of the plume waters with deeper mixing occurring into the water column when the wind directions were from the southeast (120° bearing) compared to winds from a southerly direction (200° bearing) (Figure B-7).

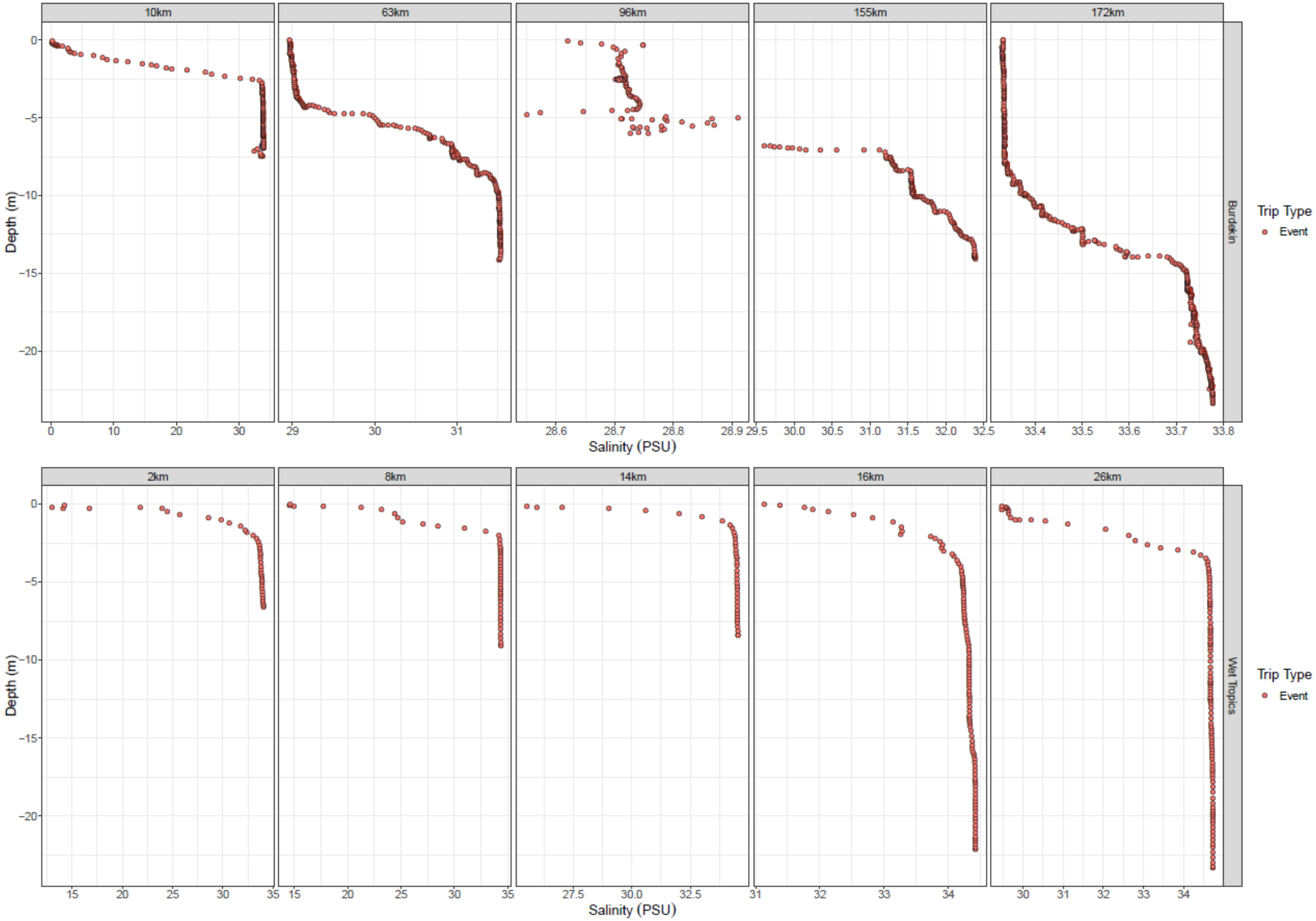

Figure B-5: Salinity-depth profile transects with distance offshore for the Burdekin River (top panels) and Tully River (bottom panels) plumes measured in the 2018–19 season. Note change in the salinity scale (x-axis) across the transects.

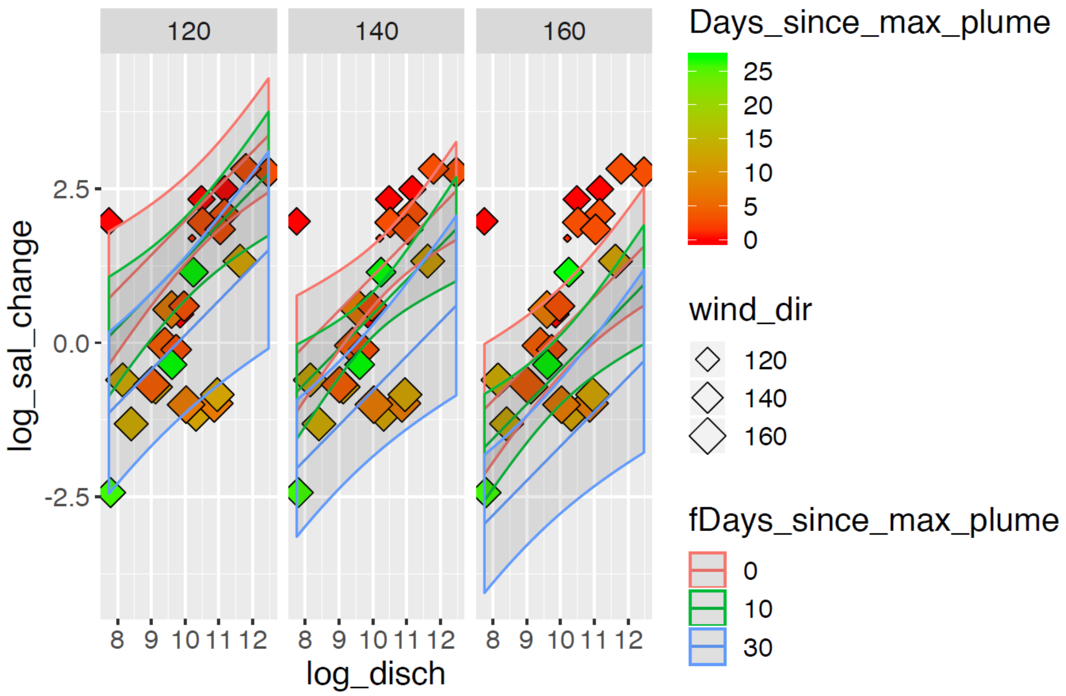

Figure B-6: Model of the salinity change (incorporates salinity difference and slope of change) against log discharge (incorporates discharge and distance from river mouth) for multiple Burdekin River plumes. Left to right: wind directions from the south east (120° bearing) compared to winds from a southerly direction (160° bearing).

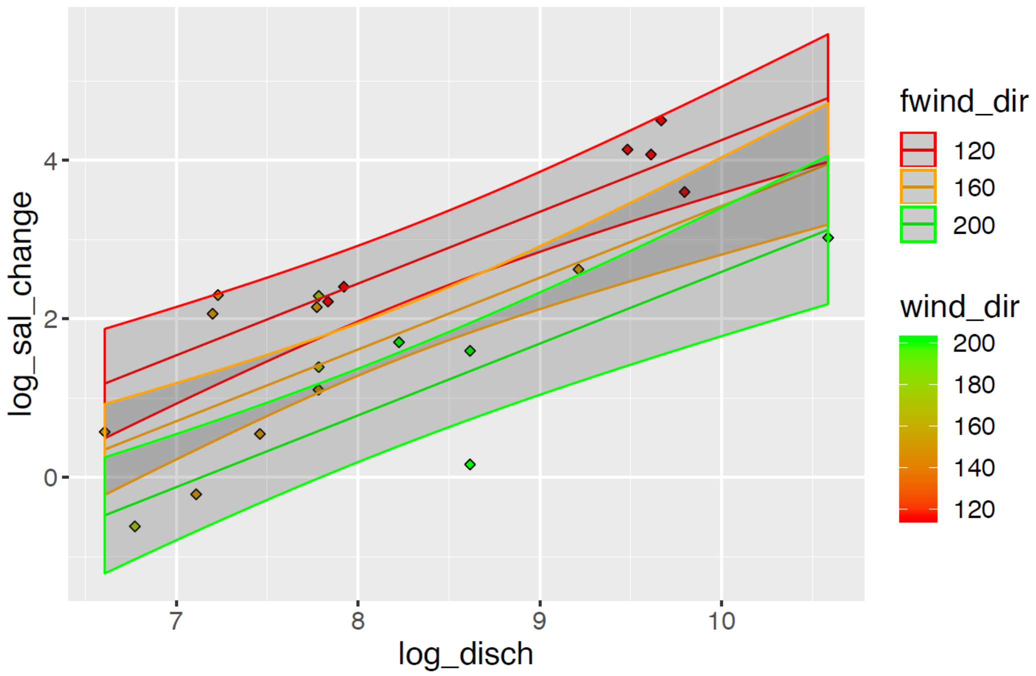

Figure B-7: Model of the salinity change (incorporates salinity difference and slope of change) against log discharge (incorporates discharge and distance from river mouth) for multiple Tully River plumes.

Mixing of SPM with depth

The plots of total suspended solids (TSS) or SPM concentrations over the estuarine mixing zone of the Burdekin River from 11, 12, 15, 20, and 21 February 2019 (Figure B-8) show patterns consistent with previous sampling years, with the bulk of the SPM falling out by the ~5 to 10 salinity zone. However, the collection of depth samples in the Burdekin flood plume in 2018–19 provided some interesting and somewhat unexpected results. In the past, the collection of water quality samples in Reef flood plumes have almost exclusively been taken from the surface partly due to resource limitations (with a few exceptions listed previously). Our results demonstrate a decoupling of the SPM-salinity relationship in the depth samples at some sites and over the evolution of the flood plume. For example, at the Burdekin mouth site (BUR13) the samples taken on 11 February display what would typically be expected where the surface sample recorded SPM concentrations of 420 mg L^{-1} at salinity of 0.1 and the sample taken at 6 m depth had a SPM concentration of 26 mg L^{-1} at 33.7 salinity.

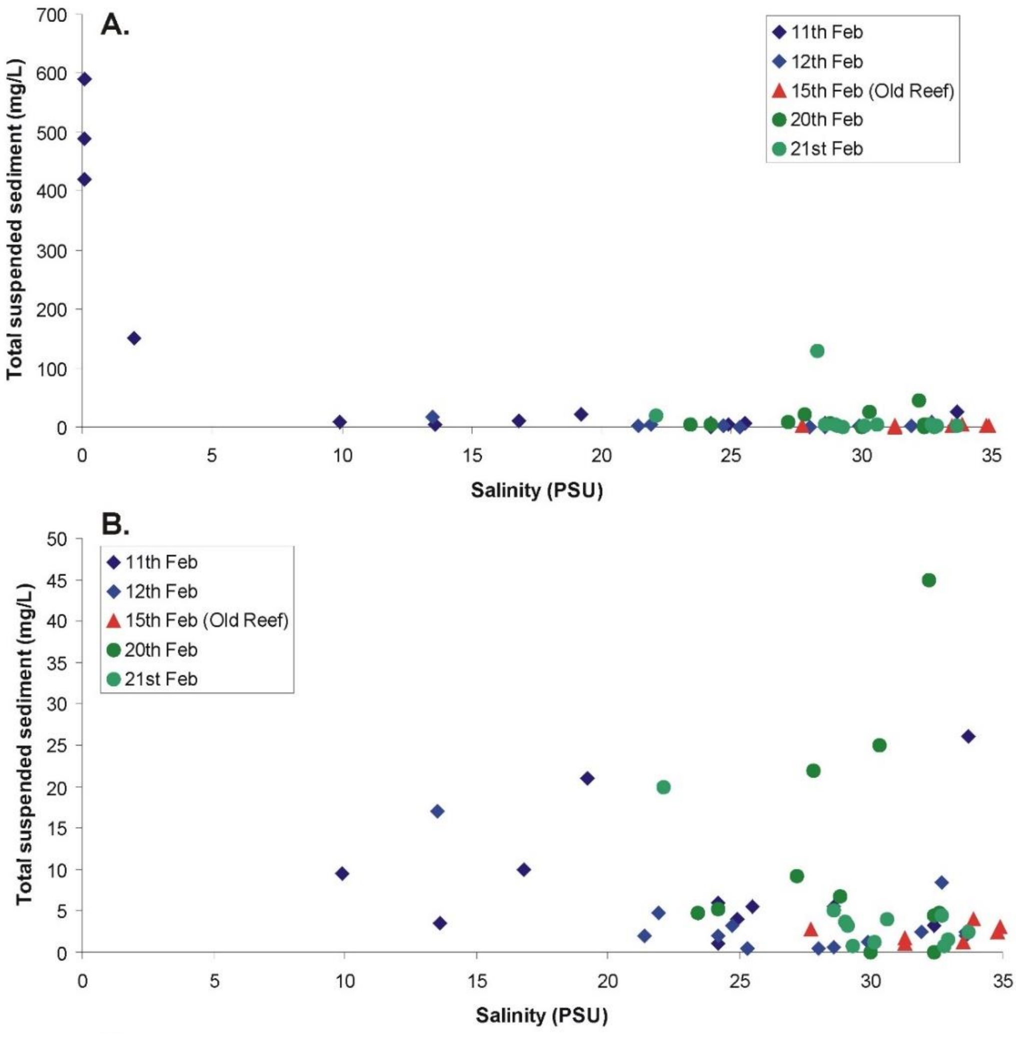

Figure B-8: Water quality data from the 2019 Burdekin River flood plume including total suspended solids (A and B with restricted y-axis) highlighting variations in concentrations over the salinity gradient and over the different days of sampling.

However, the samples taken on 20 February at the same location were quite different. The SPM concentration at the surface was 9.2 mg L^{-1} at 27.2 salinity which was lower than the sample taken at 7 m depth which had SPM of 45 mg L^{-1} at a higher salinity of 32.2. In other cases, SPM concentrations were similar between the surface and depth samples despite a shift towards higher salinities in the deeper water column. Importantly, this relationship was consistent even for the further seaward sites measured in the Burdekin plume including at Orchard Rocks (off Magnetic Island: surface 2.0 mg L^{-1}, depth 8.5 mg L^{-1}), Havannah Island (surface 0.5 mg L^{-1}, depth 1.3 mg L^{-1}), midway out to Old Reef (surface 1.0 mg L^{-1}, depth 2.8 mg L^{-1}) and at Old Reef (surface 2.7 mg L^{-1}, depth 1.2 mg L^{-1}). The SPM data from the Tully River plume also displayed fairly consistent concentrations (commonly between 1.5 and 7.5 mg L^{-1}) between the surface and depth (within 2 m from the seafloor) samples (data not shown).

Light reduction in flood plumes

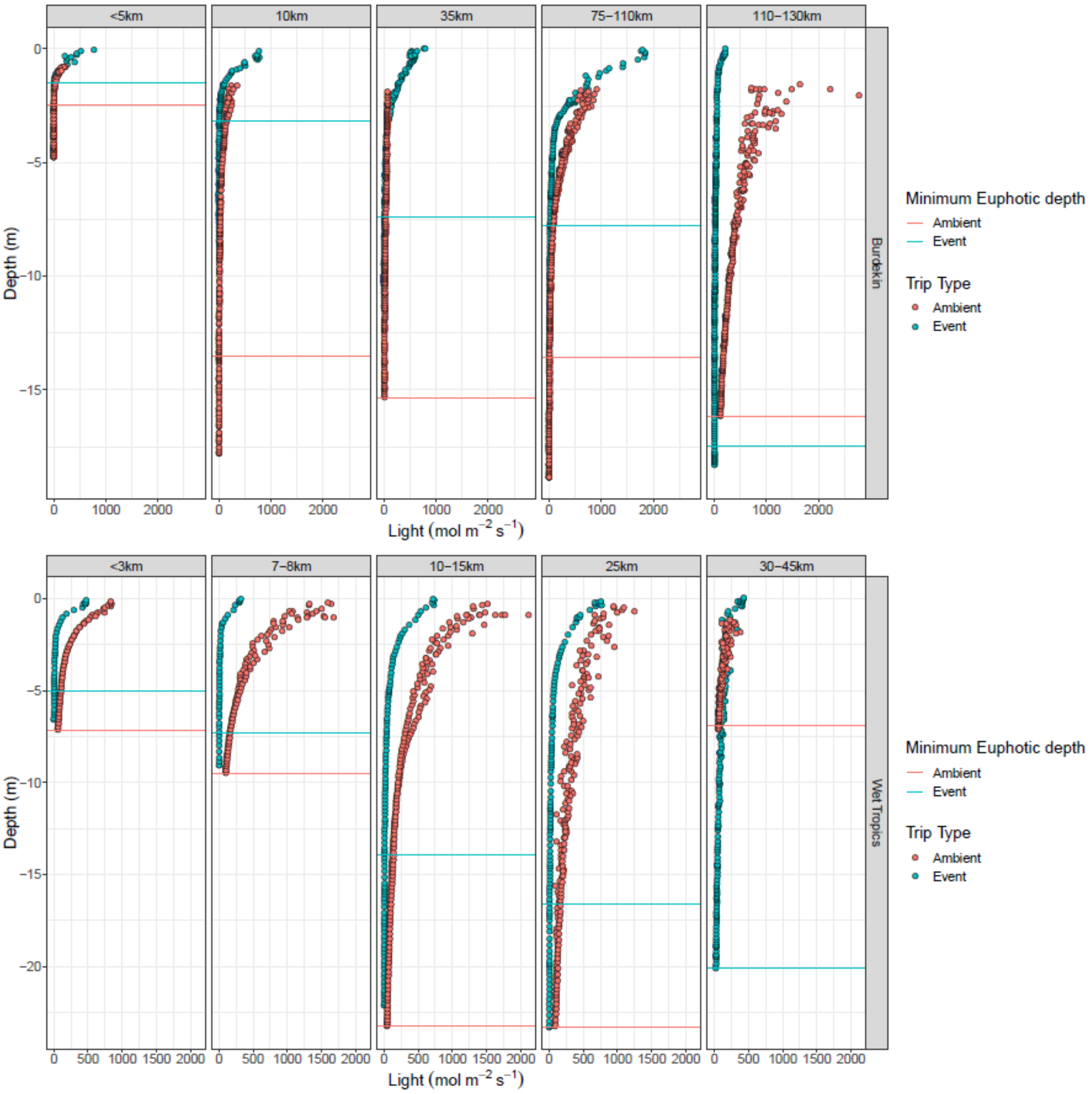

Figure B-9: PAR-depth profile transects with distance offshore for the Burdekin River (top panels) and Tully River (bottom panels) plumes measured in the 2018–19 season. Euphotic depth for ambient and event samples marked as lines on the plots.

Our PAR data profiles from the flood plumes from both the Burdekin and Tully Rivers reveal considerable reductions in light availability compared to the casts taken during ambient dry season conditions (Figure B-9). When the euphotic depth (when PAR reaches 1% of the surface value considered to be the threshold of light requirements for benthic phototrophs) is determined on the casts, there is a difference of several metres between flood plume and ambient conditions across large distances in the plume (lines on profiles in Figure B-9). While the raw PAR data show that light is reduced in the event flood plumes compared to the ambient sampling, there are occasions where the euphotic depth line is lower in the depth profile in the event flood plumes compared to ambient conditions (Figure B-9). This is an artefact of the surface light reading where during event conditions the light measured at the "surface" (i.e. ~20-50 cm in the water column) is already supressed and hence the 1% euphotic depth in the events becomes deeper than the ambient condition reading which has much higher light at the surface. Future refinements of this work will apply an improved surface light reading (i.e. before attenuation in the water column occurs) which will address this artefact.

Old Reef transect results

The three sites sampled along a transect from the Burdekin River mouth to Old Reef on 15 February (Figure B-10) also showed a salinity gradient in the water column from the surface to the deeper waters, although this gradient was not as strong as was measured in casts from 11 February. Surface salinities of ~31 and bottom salinities of ~34 were observed in the cast profiles of the two sites closest to the Burdekin mouth (16 and 38 km; Figure B-11A). However, both sites showed differences where the greatest transition in salinity values took place. The site 16 km off the mouth of the Burdekin showed a fairly sharp transition between 14 and 18 m depth while the site 38 km offshore showed a more gradual transition with the largest change between 7 and 14 m depth. Interestingly, the site at Old Reef (58 km offshore) had a lens of lower salinity water (~30) in the upper ~50 cm of the water column but thereafter displayed a gradual increase in salinity from 32.8 to 33.6 from 0.5 m below the surface to the bottom of the profile at 11.5 m (Figure B-11A). All the salinity readings from the casts point to at least some influence of freshwater, even in the deeper water column where salinity was ~34 to 34.5. Similar to the observations from 11 February, the PAR profiles suggest little light is penetrating through the water column below ~5 m depth (Figure B-11B).

Figure B-10: Locations of the three sampling sites offshore from the Burdekin River mouth out to Old Reef where surface and depth water quality samples were taken on 15 Feb 2019.

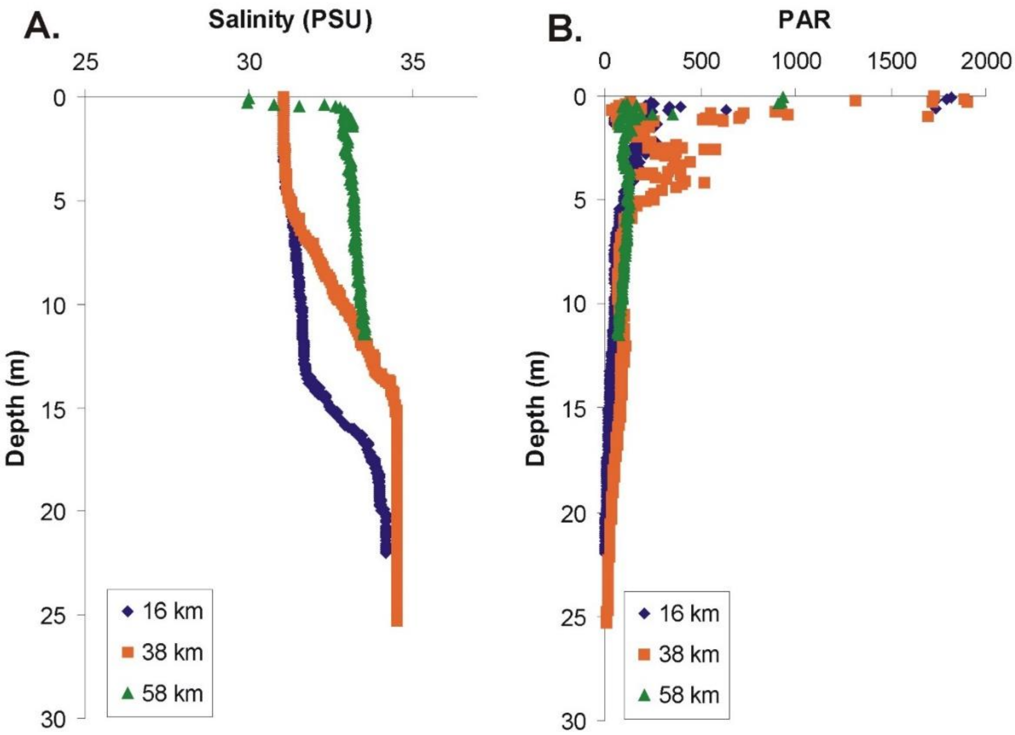

Figure B-11: Seabird CTD cast salinity (A) and PAR (B) data from a transect of MMP sites sampled on 15 February 2019 with increasing distance directly seaward from the Burdekin River mouth out to Old Reef on the mid-shelf (given in km offshore). The Old Reef site is the cast taken 58 km from the Burdekin mouth.

B-4 Discussion

Plume spatial extents

It has been well-established that the movement of flood plumes in the Reef is predominantly controlled by the wind speed and direction which has been shown in direct (aerial mapping) observations (e.g. Devin et al., 2001; Devlin and Brodie, 2005), satellite imagery (e.g. Devlin and Schaffelke 2009; Brodie et al., 2010), and hydrodynamic modelling (King et al., 2002; Xiao et al., 2019). During periods of low (or slight northerly) winds, river flood plumes may extend great distances seaward and impinge on the mid- and outer shelves. Multiple lines of evidence on the recurrence interval of plume extents which reach the mid-shelf show broad agreement with regional variations which are related to the cross-shelf distance. In that regard, the river plumes of the Wet Tropics more regularly impinge on the mid- and outer shelves as the continental shelf is much narrower in this region.

Hydrodynamic modelling covering the period 1973–1998 suggests that the closest mid-shelf reefs to the mainland in the Wet Tropics region are influenced by plumes nearly every year while sites further seaward receive plume waters on a 1-in-5 to 1-in-10-year period (King et al., 2002). A coral core from Batt Reef on the mid-shelf of the northern Wet Tropics region recorded luminescent lines (i.e. proxy of river plumes) once every 1.2 years (Lough et al., 2002). In addition, Devlin and Schaffelke (2009) presented aerial mapping and satellite images from the Wet Tropics plumes which show they impinged on mid- and outer shelf on three occasions in the 11 events examined from 1994–2008.

In contrast, a Burdekin plume recurrence interval of 1-in-5 to 1-in-10-years for the Old Reef mid-shelf area and a 1-in-3 to 1-in-5-year interval for the mid-shelf reefs further north of the Burdekin (e.g. Britomart and Rib Reefs) have been estimated by the King et al. (2002) hydrodynamic model. The coral luminescent line records from Rib Reef suggested a plume once every 2.6 years (Lough et al., 2002); however, for Britomart Reef a recurrence frequency for Burdekin plume waters was estimated to be once every 12.5 years over the 20th Century (Lough et al., 2015). Importantly, the recurrence frequency of the Burdekin plume at Britomart Reef has increased considerably with increasing and more frequent Burdekin flow events (Lough et al., 2015).

While recurrence intervals of plume waters from the Wet Tropics and Burdekin regions reaching the mid-shelf (and outer shelf for the Wet Tropics) show broad agreement across different methods of investigation, what is less known is the frequency of exposure for primary, secondary and tertiary waters at these locations. Indeed, the return interval for primary plume waters to reach the middle shelf across both the Burdekin and Wet Tropics regions would be much longer than the recurrence intervals presented above for 'all plume waters' (Petus et al., 2014b). The water quality of the primary (or brownish) and secondary (or greenish) plume water types exceed guideline values and have mean (± standard deviation) SPM concentrations of 8.23 (± 6.46) and 5.76 (± 4.28) mg L^{-1}, respectively (Petus et al., 2018).

Plume salinity and SPM mixing and sediment budgets

Our data indicate that the mixing of the plume freshwater lens in the water column does not vary significantly with wind speed but is rather controlled by discharge volume, wind direction and distance offshore. These findings are broadly consistent with previous analysis in the Reef and elsewhere (e.g. Dagg et al., 2004; Devlin and Brodie, 2005). The SPM concentrations throughout the water column in plumes are more variable ranging from being more concentrated at the surface, well-mixed throughout the water column and concentrated in the higher salinity bottom waters. Generally, with increasing distance offshore, it appears the Burdekin and Tully plumes become more consistently mixed through the water column consistent with the international examples presented in Geyer et al. (2004). This finding has important implications for our understanding of terrigenous sediment dispersal in the Reef and the degree of direct sediment exposure at coral reef and seagrass meadow sites.

Our new data allows us to revise the first-order estimates of the terrigenous sediment carried in river plumes first demonstrated in Larcombe and Woolfe (1999). In that study, the assumption was made that the plume SPM was solely concentrated in the surface 2 m of the water column based on the measurements of Taylor (1996) in the Barron River plume (1995) and the mass of sediment estimated was used to compare with potential wind-driven sediment resuspension masses. Our motivation for these budgets is different in that we wanted to provide a first-order approximation of the SPM travelling further in the plumes and the mass that could potentially reach the mid-shelf during moderate to large discharge events from both the Burdekin and Tully Rivers.

Based on satellite images, we estimated the area influenced by the Burdekin River plume in 2019 to be 7,700 km^2. Assuming an average depth of 20 m and a SPM concentration of 3 mg L^{-1} we estimate the plume sediment mass to be in the order of 460,000 tonnes. This mass is ~5% of the total sediment load estimated from the Burdekin River over the 2018–19 water year of 8.3 million tonnes (Gruber et al., 2019) and is lower than the 10% of load estimated to move beyond the Burdekin mouth by Lewis et al. (2014) and the ~20% estimated in the modelling of the 2007 plume (Delandmeter et al., 2015). Indeed, our estimated mass does not take into account the 'cumulative SPM' in the Burdekin plume that is delivered over the plume period and would replenish the existing SPM that settled onto the seafloor. Further, the SPM concentrations used are conservative based on measurements in the plume (our mean for the middle and outer reaches of the Burdekin plume was in the order of 5 mg L^{-1}); however, the lower concentration used was an attempt to only consider the terrigenous sediment delivered from the Burdekin River and not the 'new organic' sediment (i.e. diatoms and the organic component of flocs) created in the plume waters. In any case, this approximation largely supports the sediment budgets produced by various modelling exercises (Delandmeter et al., 2015; Margvelashvili et al., 2018).

When the same approach is applied to only examine the period when the Burdekin plume moved out towards and over Old Reef on the mid-shelf, we estimate a mass in the order of 100,000 tonnes. This mass is likely much less than 5% of the load delivered by the Burdekin during this period of peak discharge but could be considered a conservative estimation of the SPM delivered to the mid-shelf in 2019. More sophisticated modelling will help provide a better quantification of the total terrigenous sediment mass reaching the mid-shelf.

Using a similar approach for the 2018 Tully plume (1,200 km^2 area by 20 m depth and SPM of 3 mg L^{-1}) which impinged on the mid-shelf, we estimated a terrigenous sediment mass of 72,000 tonnes. While this mass is much lower than the 2019 Burdekin plume, it represents a much higher proportion of the sediment load delivered from the Tully River in the 2017–18 water year (110,000 tonnes). This finding provides additional evidence to support that a much lower proportion of terrigenous sediment is deposited near the mouth of the Tully River compared to the Burdekin. We note that as for the Burdekin, this calculation only provides a first-order estimate and modelling would provide a better quantification of the sediment mass as well as separating out potential contributions of the neighbouring Wet Tropics rivers (in this case particularly the Herbert and Murray Rivers).

Light reduction in flood plumes

Our data show that for the period of the flood plume, the euphotic depth is reduced considerably by several metres at locations 10's to 100's of km offshore from the river mouth compared to measurements taken in ambient conditions (Figures B-9, B-11). This has implications for benthic phototrophs such as corals and seagrasses that have specific light requirements such that long periods of exposure may lead to a reduction in depth or spatial distributions (e.g. Petus et al., 2014a).

Importantly, the reduction in euphotic depth shown in this study commonly coincides with SPM concentrations in the plume of <5 mg L^{-1} which have previously been dismissed as 'low' (e.g. Orpin and Ridd, 2012). Hence this finding should prompt a reconsideration on the influence of flood plumes.

Future work will examine the relative (to ambient conditions) reductions in euphotic depth under primary, secondary and tertiary plume colour class conditions (e.g. Petus et al., 2018). There is a need for research efforts to provide empirical data on the influence of SPM carried in river plumes on more offshore parts of the Reef. Furthermore, the influence of what has previously been considered 'low concentrations' (i.e. <5 mg L^{-1}) of SPM in river plumes (e.g. Larcombe and Woolfe, 1999; Orpin and Ridd, 2012) on light availability need additional examination. Indeed Wolanski et al. (2008) reported that fringing reefs below 4 m depth offshore from the Tully River received no light for 10 days during the 2007 plume event.

Broader implications of the results

Until the recent work of Fabricius et al. (2014, 2016) and Margvelashvili et al. (2018), it was generally thought that SPM delivered in river plumes had little effect on the mid- and outer shelves of the Reef. Indeed, there were only a few accounts of plumes reaching these areas prior to satellite imagery (see Devlin et al., 2001). Sedimentology studies showed that the Reef mid-shelf is a sediment-starved system containing old remnant sediments (Belperio, 1983), and sediment cores from the mid- and outer shelf reefs revealed little to no evidence of fine-grained terrigenous sediment accumulation (e.g. Davies and Hopley, 1983). On reflection, these reef sediment cores were collected via the rotary coring method which allows very limited recovery of any fine grained terrigenous sediments which may (or may not) be present (see Ryan et al., 2018). While it is clear that the mid-shelf of the Reef is a zone of very limited new terrigenous sediment accumulation, it is possible that the quantification of terrigenous sediment has been underestimated.

Our first-order estimates of the mass of terrigenous sediment that may reach mid-shelf areas of the Reef suggest unsurprisingly that the Burdekin plume carries more sediment in large events because of its larger discharge (and coverage of a greater area) and its higher sediment loads. However, when the recurrence intervals of such events are considered, the mass of terrigenous sediment delivered to the section of mid-shelf influenced by the Wet Tropics rivers may be similar to the Burdekin. Indeed, the mid-shelf reefs may represent preferential sediment accumulation areas for SPM carried in flood plumes due to their baffling effect. New investigations in these areas should employ coring techniques that are conducive to recovering fine grained terrigenous sediments. Only then will we have a more complete picture on the influence of terrigenous sediment on the mid-shelf.

The most critical question that needs to be resolved (at least on a finer scale) is to quantify the influence of SPM that is considered anthropogenic across the Reef. Our first-order sediment budget estimates provide some guidance for future modelling approaches to help answer this question. For example, the loads of terrigenous sediment delivered from the Burdekin River have increased by 5-to-10-fold since European settlement (Kroon et al., 2012; Lewis et al., 2014). If we assume that this increase is in proportion to the amount of sediment transported beyond the initial deposition zone near the mouth of the river then our first approximation would be that 360–410 kt of the 460 kt would be anthropogenic (back calculations produce an anthropogenic SPM concentration of 2.3–2.7 mg L^{-1}). In addition, the evidence of larger Burdekin flood events in the past 50 years compared to the ~350 year record (Lough et al., 2015) would not only coincide with higher sediment loadings but also result in a greater plume extent in the Reef (and hence increase the frequency of influence on the mid-shelf).

We note that these are very preliminary estimates and the dynamics of SPM behaviour in the estuarine mixing zone are not fully understood (e.g. Geyer et al., 2004); for example, additional sediment concentrations in the water column from increased loadings would provide more opportunity for the collision of individual particles to form more flocs leading to increased sediment deposition at the mouth. Because of this lack of knowledge, we do not want to speculate the potential effects of the anthropogenic sediment that travels further afield, other than point out that our data suggest that even a small increase in SPM concentrations (e.g., 2–3 mg L^{-1}) is enough to result in considerable reductions in light availability for several metres in the water column.

Conclusions

This case study examined the dispersal of the freshwater lens and SPM within river plumes over the estuarine mixing zone under different environmental conditions. We show that the dispersal of the freshwater lens varies with river discharge, distance offshore, and wind direction. The dispersal of SPM was more variable but generally mixed throughout the water column with increasing distance offshore.

SPM concentrations previously considered 'low' in some studies (e.g., <5 mg L^{-1}) had a considerable influence on light attenuation in the water column.

First-order estimates of the mass of sediment transported further seaward from plumes suggest that while the Burdekin carries more sediment, the level of exposure on the mid-shelf may be similar to the Wet Tropics plumes due to the difference in plume recurrence intervals in these regions (i.e. more frequent in the Wet Tropics) as well as the distances to the mid-shelf reefs.

Further sediment coring of mid-shelf reefs would better quantify the level of terrigenous sediment exposure. Our first-order sediment budget estimates provide some insights, but a more sophisticated modelling approach is required to better understand the potential impacts of newly-delivered anthropogenic terrigenous sediment on the mid-shelf.

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Appendix C: Water quality site locations and frequency of monitoring

Table C-1 lists all the sites included in the MMP, distinguishing the ambient and event sampling sites. The proposed number of visits to each site in the program design is shown in each column, with the number of actual visits shown in brackets in red text. The Cape York sampling program did not commence formally until April 2017 (due to delayed contracting arrangements with the Authority), although sampling commenced earlier where possible. Weather conditions also restricted access to the Normanby-Kennedy and Pascoe transects during the wet season.

Table C-1: Description of the water quality sites sampled by AIMS, JCU and CYWMP during 2018–19. 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 grab samples at fixed sites (proposed and actual)		Reactive event 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
Cape York					
Normanby-Kennedy transect					* (specific sites TBD)
Kennedy mouth				4 (Sampling 2 depths) (4)	1
Kennedy inshore				4 (Sampling 2 depths) (4)	
Cliff Islands				4 (Sampling 2 depths) (4)	1
Bizant River mouth				4 (Sampling 1 depth) (4)	
Normanby River mouth				4 (Sampling 2 depths) (4)	1
Normanby inshore				4 (Sampling 2 depths) (4)	
NR-03				4 (Sampling 2 depths) (4)	
NR-04				4 (Sampling 2 depths) (4)	
NR-05				4 (Sampling 2 depths) (3)	
Corbett Reef				4 (Sampling 2 depths) (3)	
Additional sites/ event samples					3
Pascoe transect					* (specific sites TBD)
Pascoe mouth north				5 (Sampling 2 depths) (4)	
Pascoe mouth south				5 (Sampling 2 depths) (4)	
PR-N2				5 (Sampling 2 depths) (4)	
PR-N3				5 (Sampling 2 depths) (3)	
PR-N5				5 (Sampling 2 depths) (1)	
PR-N6					1
PR-S2.5				5 (Sampling 2 depths) (4)	
Middle Reef				5 (Sampling 2 depths) (4)	
PR-S5				5 (Sampling 2 depths) (3)	
Additional sites/ event samples					2
Annan and Endeavour transect					* (specific sites TBD)
Annan mouth				5 (Sampling 2 depths) (4)	(3)
Walker Bay				5 (Sampling 2 depths) (4)	(2)
Dawson Reef	√			5 (Sampling 2 depths) (4)	(1)
Endeavour mouth				5 (Sampling 2 depths) (4)	(3)
Endeavour north shore				5 (Sampling 2 depths) (3)	(3)
Endeavour offshore				5 (Sampling 2 depths) (4)	(2)
Egret and Boulder Reef				5 (Sampling 2 depths) (3)	(2)
Additional sites/ event samples					(10)

Site Location	Logger Deployment		Ambient grab samples at fixed sites (proposed and actual)		Reactive event 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
Stewart transect					* (specific sites TBD)
Stewart mouth				5 (Sampling 2 depths) (5)	1
SR-02				5 (Sampling 2 depths) (5)	
SR-03				5 (Sampling 2 depths) (5)	
SR-04				5 (Sampling 2 depths) (5)	
Hannah Island				5 (Sampling 2 depths) (4)	
Additional site					2
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	√		6 (Sampling 2 depths) (6)		
RM2					** (Surface sampling only) (4)
RM3			6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (5)	
RM4					** (Surface sampling only) (5)
High Island East					** (Surface sampling only) (6)
Normanby Island					** (Surface sampling only) (6)
Frankland Group West (Russell Island)	√		6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
High Island West	√	√	6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
Palmer Point					** (Surface sampling only) (6)
Russell-Mulgrave River mouth mooring	√	√	6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
Russell-Mulgrave River mouth					** (Surface sampling only) (6)
Russell-Mulgrave junction [River]					** (Surface sampling only) (6)
Tully Focus Area					
King Reef					** (Surface sampling only) (1)
East Clump Point			6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (5)	
Dunk Island North	√	√	6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
South Mission Beach					** (Surface sampling only) (6)
Dunk Island South East			6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
Between Tam O'Shanter and Timana			6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
Hull River mouth					** (Surface sampling only) (6)
Bedarra Island			6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
Triplets					** (Surface sampling only) (5)
Tully River mouth mooring	√	√	6 (Sampling 2 depths) (6)	6 (Sampling 2 depths) (6)	
Tully River					** (Surface sampling only) (5)
Burdekin					
Burdekin Focus Area					
Pelorus and Orpheus Island West	√		4 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (6)	
Pandora Reef	√		4 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (6)	
Cordelia Rocks					** (Surface sampling only) (3)
Magnetic Island (Geoffrey Bay)	√		3 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (6)	

Site Location	Logger Deployment		Ambient grab samples at fixed sites (proposed and actual)		Reactive event 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
Inner Cleveland Bay					** (Surface sampling only) (6)
Cape Cleveland					** (Surface sampling only) (5)
Haughton 2			2 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (6)	
Haughton River mouth					** (Surface sampling only) (5)
Barratta Creek					** (Surface sampling only) (6)
Yongala IMOS NRS	√	√	11 (Sampling 2 depths) (12)		
Cape Bowling Green					** (Surface sampling only) (3)
Plantation Creek					** (Surface sampling only) (3)
Burdekin River mouth mooring	√	√	2 (Sampling 2 depths) (4)	5 (Sampling 2 depths) (6)	
Burdekin Mouth 2					** (Surface sampling only) (3)
Burdekin Mouth 3					** (Surface sampling only) (3)
Mackay-Whitsunday					
Whitsunday focus area					
Double Cone Island	√		5 (Sampling 2 depths) (5)		
Hook Island W					** (Surface sampling only)
North Molle Island					** (Surface sampling only)
Pine Island	√		5 (Sampling 2 depths) (5)		
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					** (Surface sampling only)
Brampton Island					** (Surface sampling only)
Sand Bay					** (Surface sampling only)
Pioneer River mouth					** (Surface sampling only)

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Appendix D: Water quality monitoring methods

D-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 D-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 program design prior to 2015 included sites in the open coastal and mid-shelf water bodies. The MMP program 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 Table E-9.

Table D-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.

		Enclosed coastal		Open coastal		Mid-shelf		Offshore	
Parameter	Unit	Wet Tropics	Central Coast	Wet Tropics	Central Coast	Wet Tropics	Central Coast	Wet Tropics	Central Coast
Chlorophyll *a**	$\mu g\ L^{-1}$	2.0	2.0	0.45	0.45	0.45	0.45	0.40	0.40
Particulate nitrogen*	$\mu g\ L^{-1}$	n/a	n/a	20.0	20.0	20.0	20.0	17.0	17.0
Particulate phosphorus*	$\mu g\ L^{-1}$	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	$\mu g\ L^{-1}$	10.0 QLD	3.0 QLD	0.35***	0.35***	0.35***	0.35***	2.0 QLD	2.0 QLD
PO_4	$\mu g\ L^{-1}$	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 D-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 GVs (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 GVs for open coastal and mid-shelf sites provided by the Authority

D-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).

A recent project completed a proof-of-concept for an integrated assessment framework for the reporting of Reef water quality using a spatio-temporal statistical process model that combines all MMP water quality data and discussed reasons for differences between the different measurement approaches (manual sampling, *in situ* data loggers, remote sensing; Brando et al., 2014). However, for this report, the focus is on interpreting trends in site-specific water quality.

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 80^{th} 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 (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 D-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, etc.).

2. Calculate the proportional deviations (ratios) of these running mean values (*V*) from the associated guideline value (*GV*) (Table D-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) were capped at 1 to bind the WQ Index scales to the region -1 to 1.

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

5. The WQ Index for each site per four-year period was 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) were 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 (e.g., all sites in the Tully focus region) were averaged and converted into the colour scheme as above. For regional summaries, the Index scores of all sampling locations within a region (e.g., all sites in the Wet Tropics region) were 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 E-9). 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 E-9).

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) were capped at 1 to bind the WQ Index scales to the region -1 to 1.

5. Ratios of several indicators were 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 was 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) were 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 (e.g., all sites in the Tully focus region) were averaged and converted into the colour scheme as above. For regional summaries, the Index scores of all sampling locations within a region (e.g., all sites in the Wet Tropics region) were 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 was 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 yielded 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.

Comparison of WQ Index values due to changes made in 2018–19 report

Several revisions were made to the WQ Index published in the 2018–19 report to make it more clear, robust, and comparable across regions. These revisions are described below and can be compared in Figure D-1 (version from 2017–18 report) and Figure D-2 (version from 2018–19 report).

<u>Long-term trend</u>:

- Reports for the 2017–18 water year and earlier used an 80th percentile GV for NO_x (2 µg L^{-1} for the Wet Tropics and 3 µg L^{-1} for other regions), which was based on the Queensland Water Quality Guidelines (Department of Environment and Resource Management, 2009). This value was determined to be too high and not reflective of NO_x concentrations in the Reef lagoon. From the 2018–19 report onwards, a revised

NO_x GV of 0.35 µg L^{-1} was used for this version of the Index (provided by the Authority). This change has caused the long-term version of the Index to decline in magnitude (i.e., scoring water quality as poorer), but retain the same trends over time (Figures D-1, D-2).

Annual condition:

- Reports for the 2017–18 water year and earlier used all MMP sites monitored in the current design, including enclosed coastal sites. It was determined that enclosed coastal sites are not representative of conditions experienced by most seagrass or coral reef communities. Additionally, GVs are not presently defined for all indicators at enclosed coastal sites. For reports 2018–19 and onwards, the annual condition Index only includes MMP sites from the open coastal and mid-shelf water bodies. This change has caused the annual condition version of the Index to increase in magnitude slightly in the Wet Tropics and Burdekin regions; the Index for the Mackay-Whitsunday region remained unchanged, as this region has very few enclosed coastal sites (Figures D-1, D-2).
- Reports for the 2017–18 water year and earlier used the same indicator weighting as the long-term Index whereby the following indicators are weighted evenly: water clarity (combined ratio for Secchi depth, TSS, and turbidity), NO_x, Chl-*a*, PN, and PP. It was thought that the Index would be more robust if similar indicators were grouped together. An alternative approach was tried for reports from 2018–19 onwards that gives a hierarchical weighting of indicators whereby the following indicators are weighted evenly: water clarity (combined ratio for Secchi depth, TSS, and turbidity), productivity (combined ratio for Chl-*a* and NO_x), and particulate nutrients (combined ratio for PN and PP). This change had very little effect on the Index (Figures D-1, D-2), which suggests that indicators grouped together were already behaving similarly with respect to GVs.

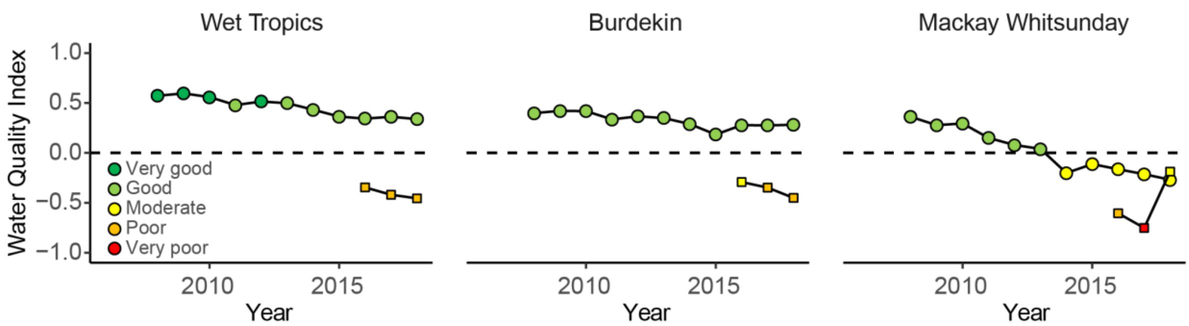

Figure D-1: Water Quality Index scores from 2006 to 2018 published in the 2017–18 report. The long-term version of the Index uses an 80th percentile NO_x GV (2 µg L^{-1} for the Wet Tropics and 3 µg L^{-1} for other regions). The annual condition version uses enclosed coastal, open coastal, and mid-shelf sites. The annual condition version uses a non-hierarchical classification of water quality indicators (water clarity, Chl-*a*, NO_x, PN, and PP are weighted equally).

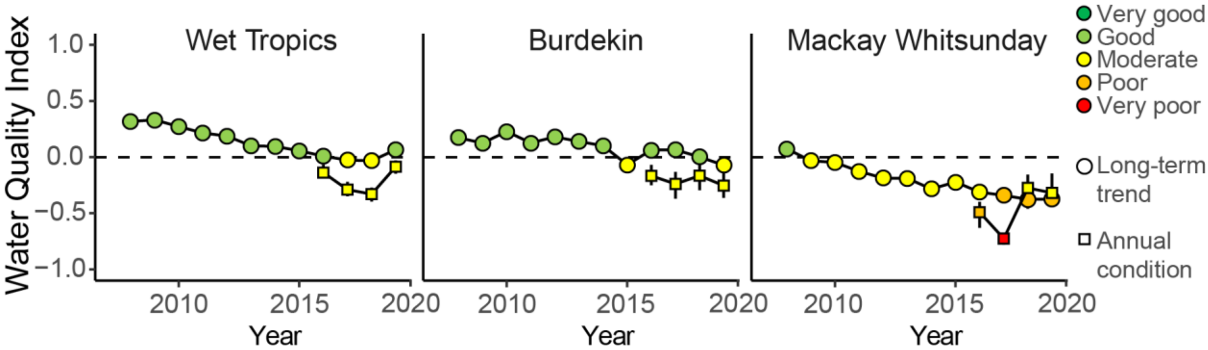

Figure D-2: Water Quality Index scores from 2006 to 2019 published in the 2018–19 report. The long-term version of the Index uses a revised NO_x GV (0.35 µg L^{-1}). The annual condition version uses only open coastal and mid-shelf sites. The annual condition version uses a full hierarchical classification of water quality indicators (water clarity, productivity, and particulate nutrients are weighted equally).

D-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 are mapped using MODIS true colour (TC) 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 TC 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).

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

Product / analysis name	Management outcome	Refs	Data: Satellite data	Data: In-situ water quality	Data: Catchment load	Data: Ecosystem monitoring
a. WS maps	Weekly composite maps Illustrating (qualitative) the composition of nearshore waters in the GBR during the wet season as well as the movements of river flood plumes	Alvarez-Romero et al., 2013	●			
b. Frequency maps	Provide a broad scale approach to reporting contaminant concentrations in the GBR marine environment Help defining water quality target concentration for ecosystem conservation	Devlin et al., 2015 Waterhouse et al., 2017a, 2018 Petus et al., 2018	●	●		
c. Load maps	Model the transport of land-sourced pollutants	Waterhouse et al., 2017a, 2018	●	●	●	
d. Susceptibility assessment	Explain changes in ecosystem condition / health	Thompson et al., 2018, McKenzie, 2018 Collier et al., 2014 Petus et al., 2014a Wenger et al., 2016	●	●		●
e. Exposure / potential risk maps & assessment	Evaluate the risk of ecosystems from river flood plume exposure. Use established risk management approaches (magnitude x likelihood)	Petus et al., 2014b, 2016 Waterhouse et al., 2017a, 2018	●	●		●
f. Integrated monitoring	Use combination / all products defined above	Devlin et al., 2015a, b, 2017b, Lønborg et al., 2016; Waterhouse et al., 2017a, b, 2018	●	●	●	●

Satellite data In-situ water quality Catchment load Ecosystem monitoring

Figure D-3: 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 D-3). 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.

Supervised classification using spectral signatures

Daily MODIS Level-0 data are acquired from the NASA Ocean Colour website (http://oceancolour.gsfc.nasa.gov) and converted into true colour images with a spatial resolution of approximately 500 × 500 m using SeaWiFS Data Analysis System 7.4 (SeaDAS; Baith et al., 2001). The method assumes that fully accurate atmospheric corrections are less crucial for turbid (case 2) Reef flood waters than it would be for clear (case 1) waters, and MODIS true-colour images are produced using Rayleigh corrected reflectance of MODIS bands 1, 4 and 3 (without an aerosol removal step). MODIS-Terra true colour images are also occasionally downloaded from the National Aeronautics and Space Administration (NASA)'s EOSDIS worldview website and processed to daily water type maps. MODIS-Terra are only used when MODIS data are too cloudy or unavailable, and when satellite information are required in near-real-time (rapid response mapping of flood events).

The true-colour images are then 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 masses types (including river plumes) in the Reef lagoon. The six colour classes are further reclassified into three wet season water types (primary, secondary and tertiary) corresponding to the three wet season water types, as described above and defined originally by Devlin and Schaffelke (2009) and Devlin et al. (2012). True-colour images for 2011 (very wet), 2016 and 2017 (dry) years, and from 2018 onward (2018 and 2019) are processed by BOM, while all other years were processed in-house by Tropwater.

Production of weekly wet season water type maps (Figure D-3, a)

This supervised classification is used to classify daily MODIS images. 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 minimum colour-class value of each cell/week is used to map the colour class with the maximum turbidity per pixel for each week of the wet season (i.e., assuming the colour classes represented a gradient in turbidity i.e., CC1 > CC2 > CC3 > CC4 > CC5 > CC6).

Production of annual, multi-annual and typical Wet and Dry wet season water type maps (Figure D-3, b)

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) all previous wet seasons (2003–18) 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. 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 (e.g. 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.

Table D-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

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.

Surface loading maps (Figure D-3, c)

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 D-3).

Susceptibility assessment (Figure D-3 d)

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 D-3d).

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

Additional information on wet season conditions are reported by characterising the mean long-term water quality concentrations across colour class and water types. 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, PO_4, PP, PN, TSS, Chl-

a, CDOM and K_D or Secchi depth. The mean, standard deviation, minimum, maximum and number of values for each pollutant across colour classes and water types are calculated using all surface data (<0.2 m) collected between November and April by JCU (since 2004), AIMS and the CYWMP (since 2016–17). Before 2016–17, the mean water quality concentrations were calculated using the JCU dataset only, assuming it was representative of high flow conditions.

Exposure maps and exposure assessment (Figure D-3, e)

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 (using all field data available during the December – April period, JCU: since 2004, AIMS and CYWMP since the wet season 2016–17) 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 D-3).

Table D-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 *a*	µg L^{-1}	0.63
Particulate nitrogen	µg L^{-1}	25
Particulate phosphorus	µg 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 D-4).

Table D-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:

$$Score\_expo = TSS.\mathrm{exp} + Chla.exp + PP.\mathrm{exp} + PN.exp$$

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 as chl 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 maximizing 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 WQ 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.

Finally, assessments of ecosystem exposure are made through the calculation of the areas (km^2) 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 the long-term mean and the difference in percentages between 2019 and in the long-term is also calculated. Figure D-4 presents the marine boundaries used for the Marine Park, each NRM region and the seagrass and coral reefs ecosystems. We assumed in this study that the 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.

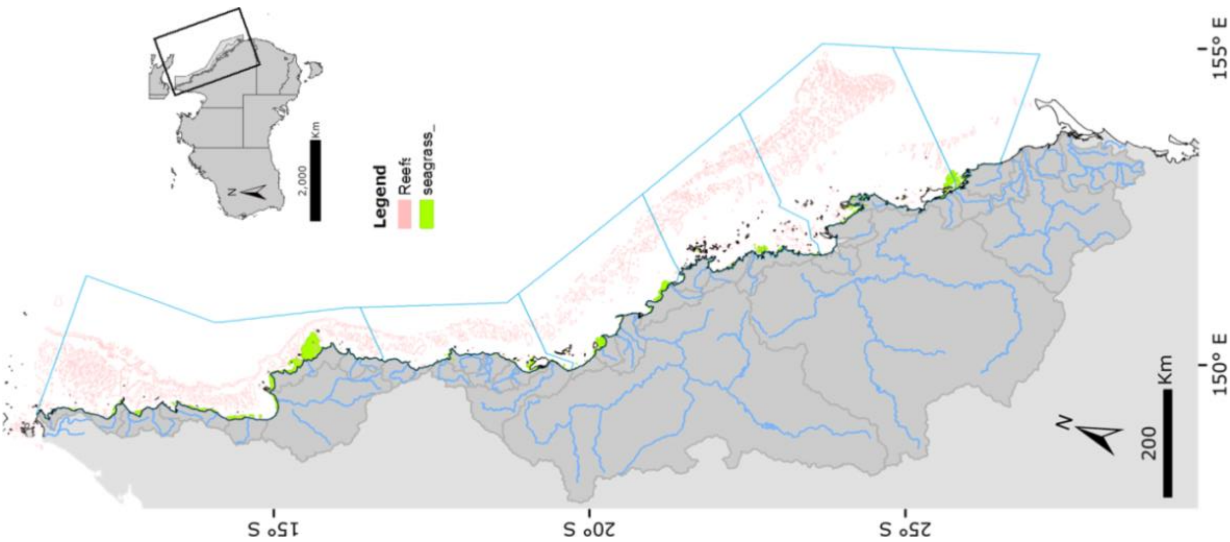

Figure D-4: Boundaries used for the Marine Park, each NRM region and the coral reefs and seagrass ecosystems. Coral reef and NRM layers derived from the Authority, supplied 2013. Seagrass layer is a composite of surveys conducted by Department of Agriculture and Fisheries, Qld.

D-4 References

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Appendix E: Additional information

E-1 Continuous FLNTU data

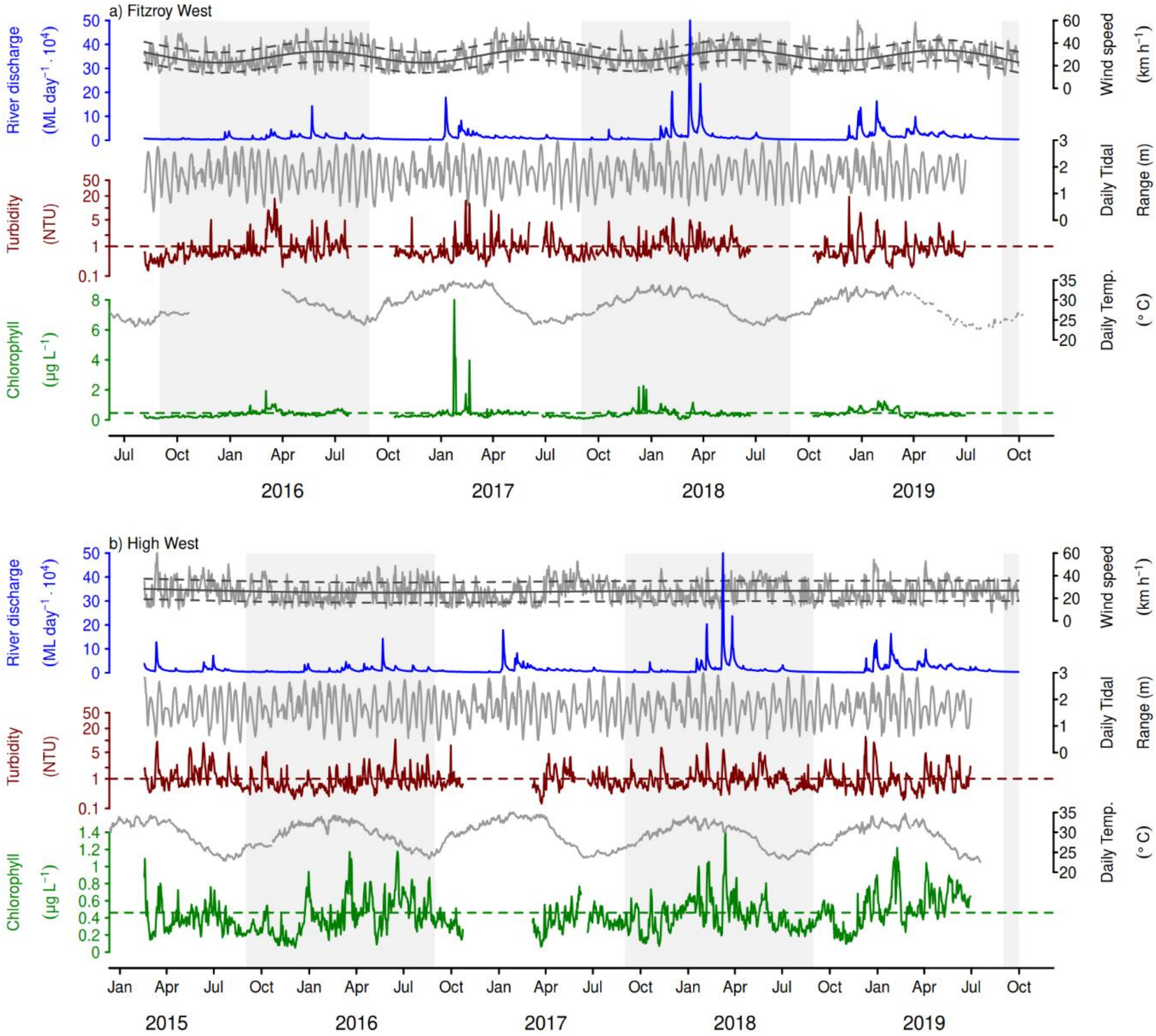
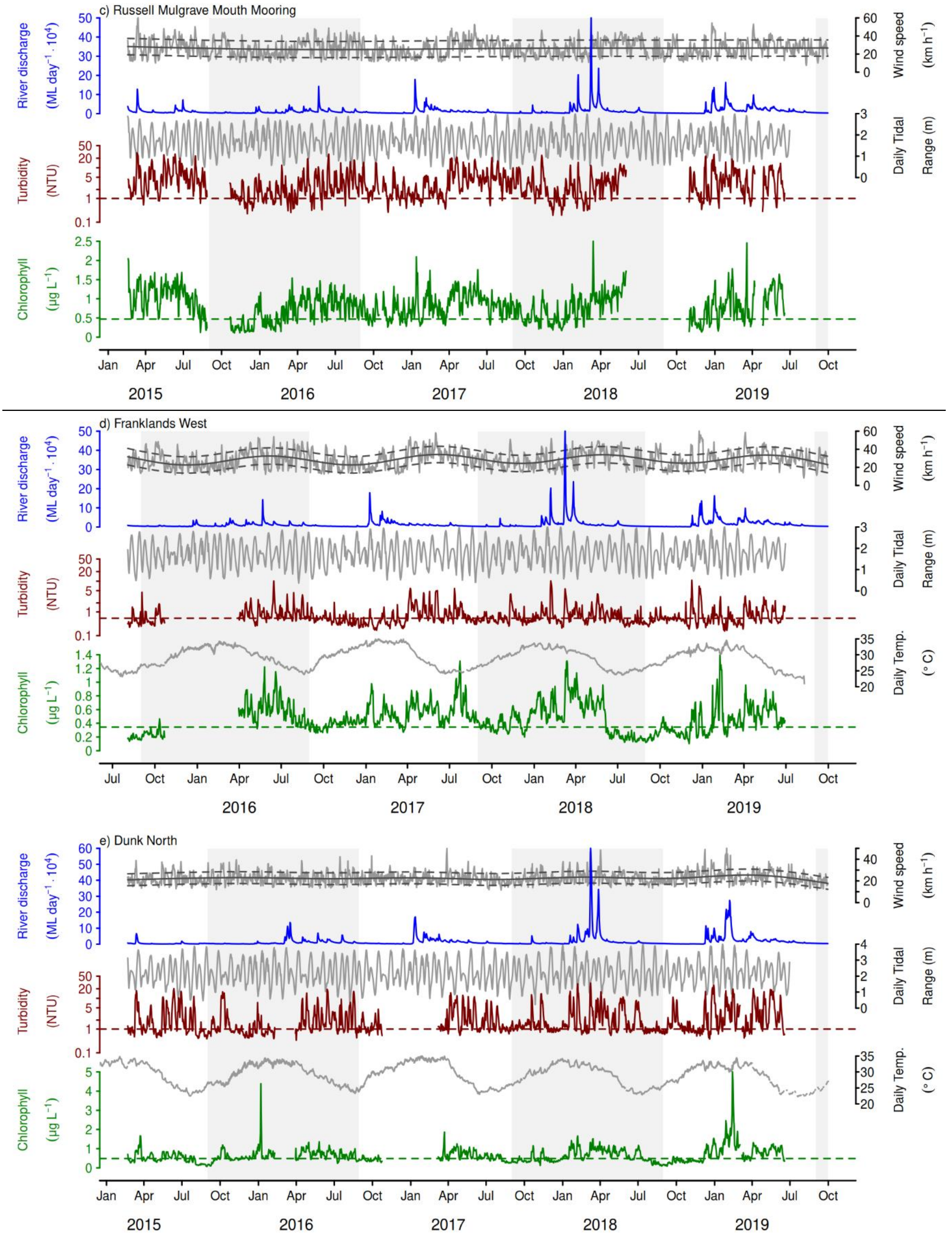
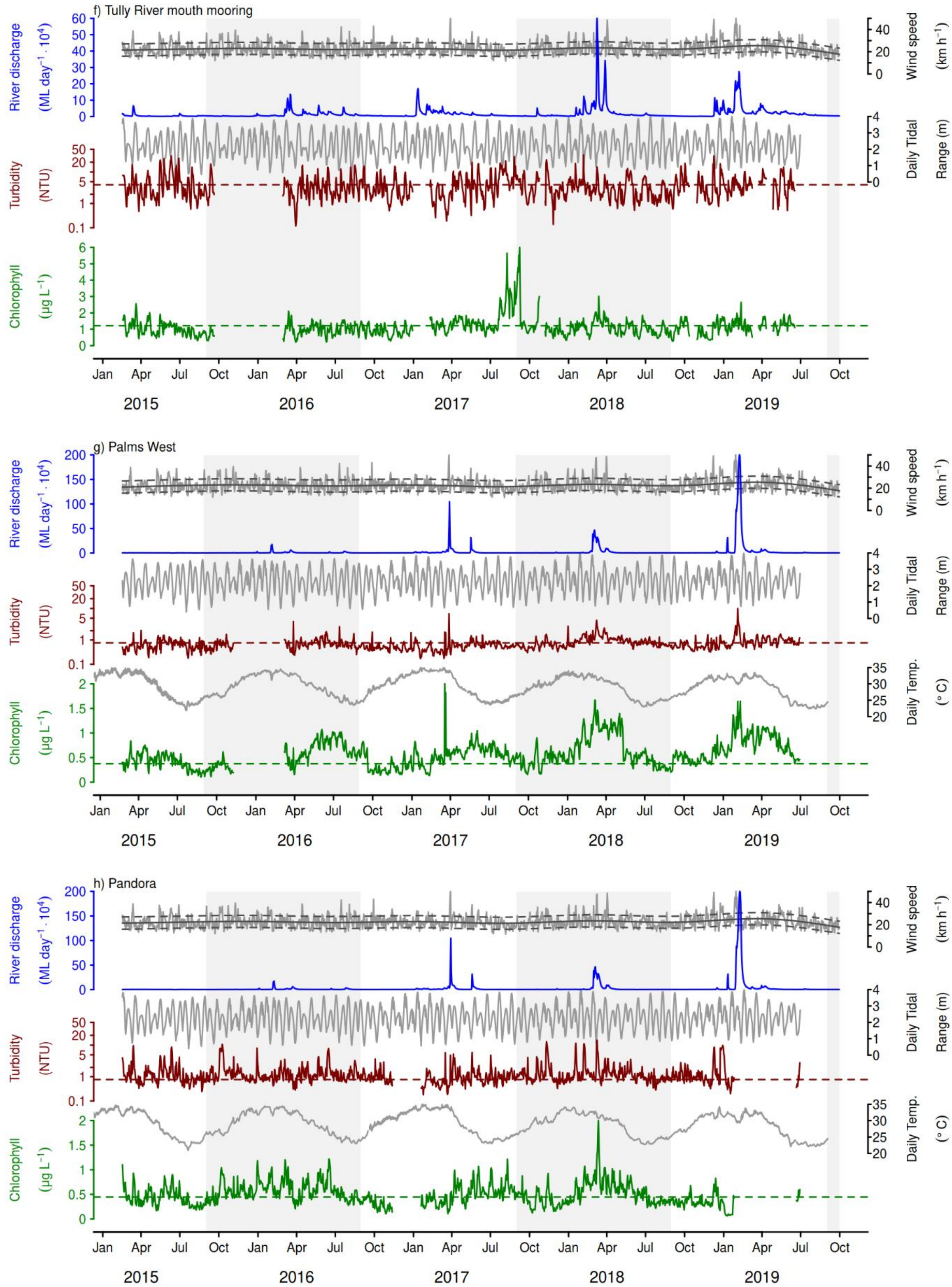
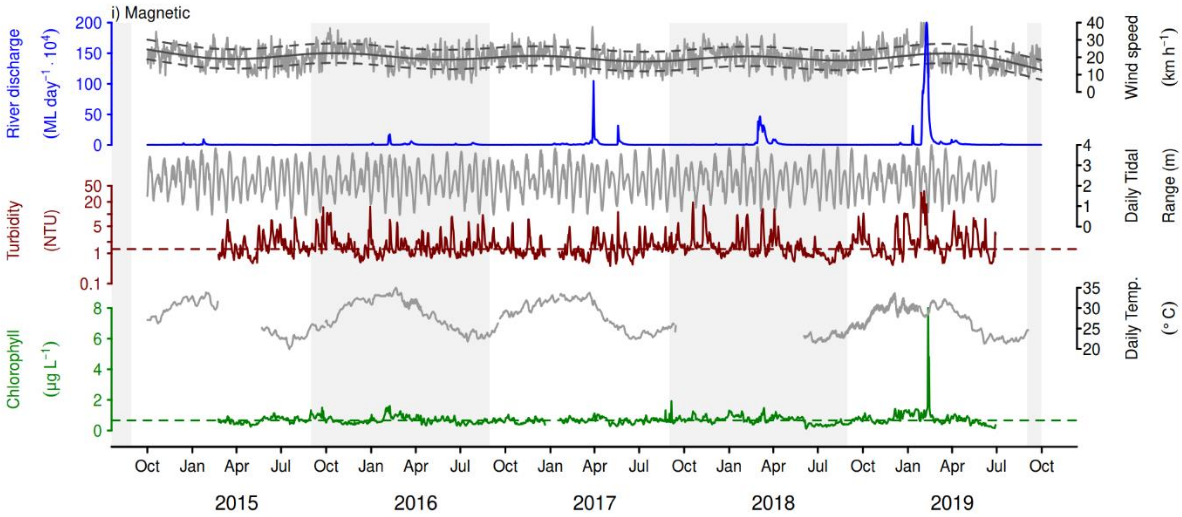


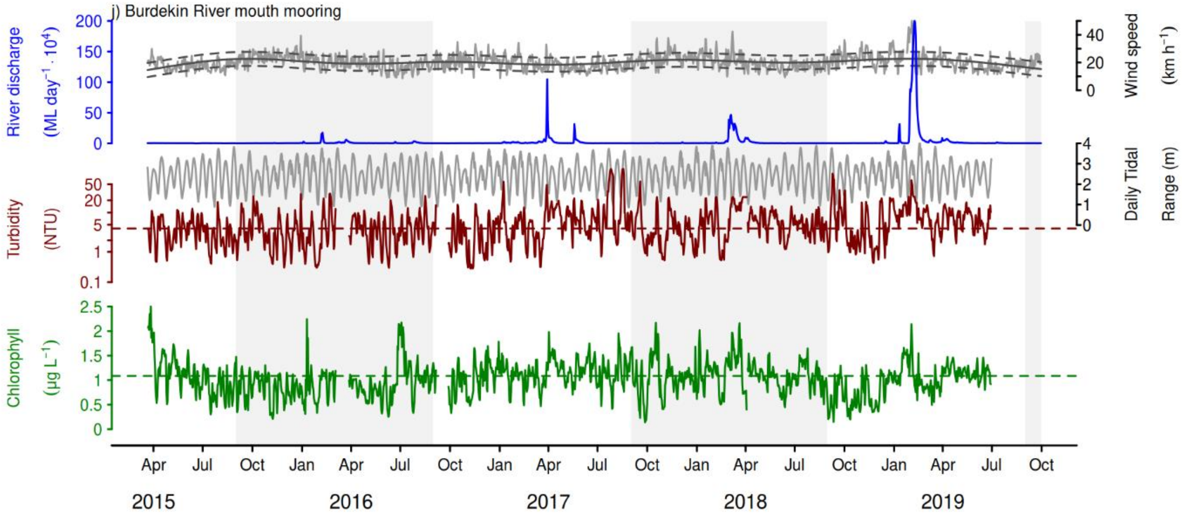
Figure E-1: Time-series of daily means of chlorophyll and turbidity collected by moored ECO FLNTUSB instruments; coloured dashed lines represent the Water Quality GVs. Daily river discharge from the nearest river, daily wind speeds from the nearest weather stations, daily tidal range from the nearest 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; and n) Repulse.


c) Russell Mulgrave Mouth Mooring
River discharge (ML day-1 . 104)
Wind speed (km h-1)
Daily Tidal Range (m)
Turbidity (NTU)
Chlorophyll (µg L-1)
Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2015 2016 2017 2018 2019
d) Franklands West
River discharge (ML day-1 . 104)
Wind speed (km h-1)
Daily Tidal Range (m)
Turbidity (NTU)
Chlorophyll (µg L-1)
Daily Temp. (° C)
Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2016 2017 2018 2019
e) Dunk North
River discharge (ML day-1 . 104)
Wind speed (km h-1)
Daily Tidal Range (m)
Turbidity (NTU)
Chlorophyll (µg L-1)
Daily Temp. (° C)
Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2015 2016 2017 2018 2019

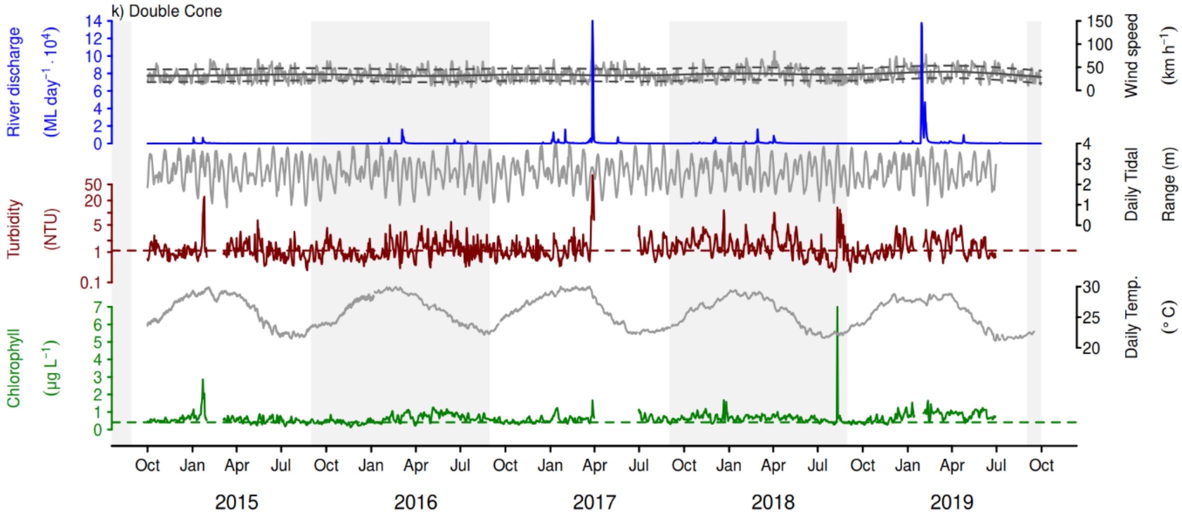

f) Tully River mouth mooring
g) Palms West
h) Pandora
River discharge (ML day⁻¹ . 10⁴)
Turbidity (NTU)
Chlorophyll (µg L⁻¹)
Wind speed (km h⁻¹)
Daily Tidal Range (m)
Daily Temp. (° C)
Jan Apr Jul Oct
2015 2016 2017 2018 2019



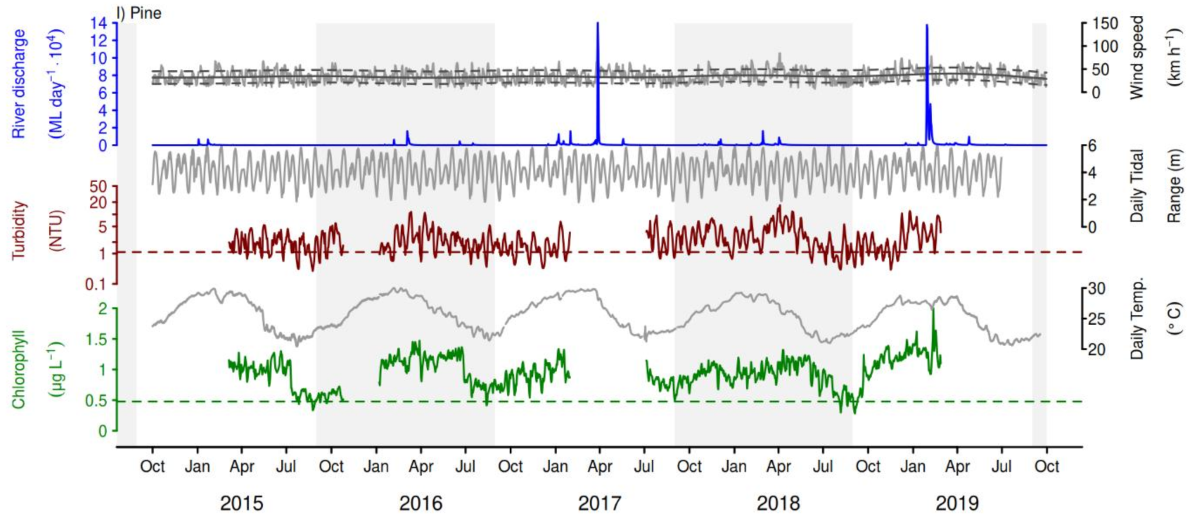
i) Magnetic
River discharge (ML day-1 . 104)
Turbidity (NTU)
Chlorophyll (µg L-1)
Wind speed (km h-1)
Daily Tidal Range (m)
Daily Temp. (° C)
Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2015 2016 2017 2018 2019

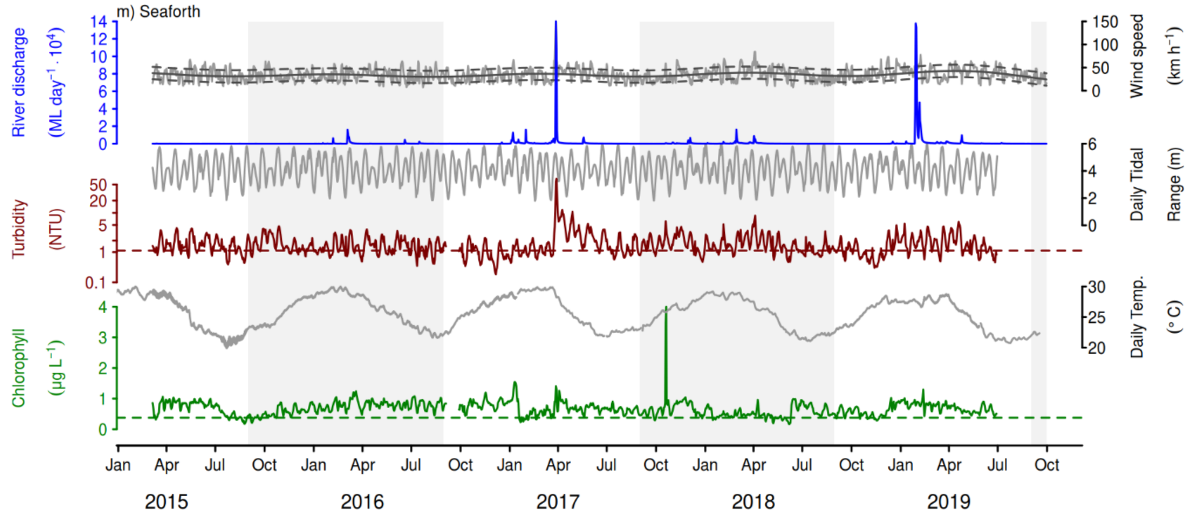


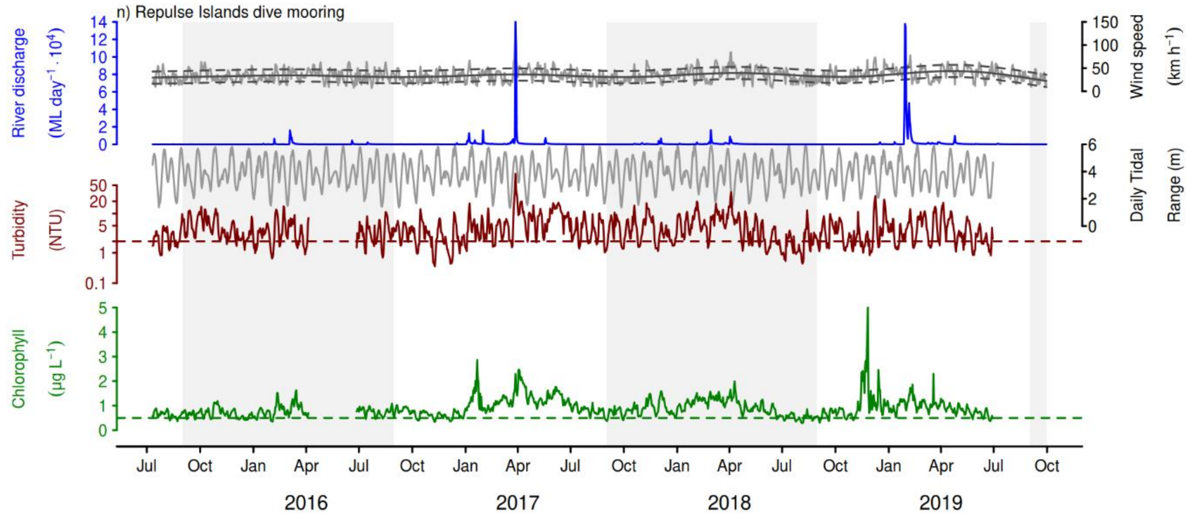
j) Burdekin River mouth mooring
River discharge (ML day-1 . 104)
Turbidity (NTU)
Chlorophyll (µg L-1)
Wind speed (km h-1)
Daily Tidal Range (m)
Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2015 2016 2017 2018 2019



k) Double Cone
River discharge (ML day-1 . 104)
Turbidity (NTU)
Chlorophyll (µg L-1)
Wind speed (km h-1)
Daily Tidal Range (m)
Daily Temp. (° C)
Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2015 2016 2017 2018 2019


l) Pine
River discharge
(ML day⁻¹ . 10⁴)
Turbidity
(NTU)
Chlorophyll
(µg L⁻¹)
Wind speed
(km h⁻¹)
Daily Tidal
Range (m)
Daily Temp.
(° C)
Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2015 2016 2017 2018 2019


m) Seaforth
River discharge
(ML day⁻¹ . 10⁴)
Turbidity
(NTU)
Chlorophyll
(µg L⁻¹)
Wind speed
(km h⁻¹)
Daily Tidal
Range (m)
Daily Temp.
(° C)
Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2015 2016 2017 2018 2019


n) Repulse Islands dive mooring
River discharge
(ML day⁻¹ . 10⁴)
Turbidity
(NTU)
Chlorophyll
(µg L⁻¹)
Wind speed
(km h⁻¹)
Daily Tidal
Range (m)
Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct
2016 2017 2018 2019

E-2 Continuous temperature and salinity

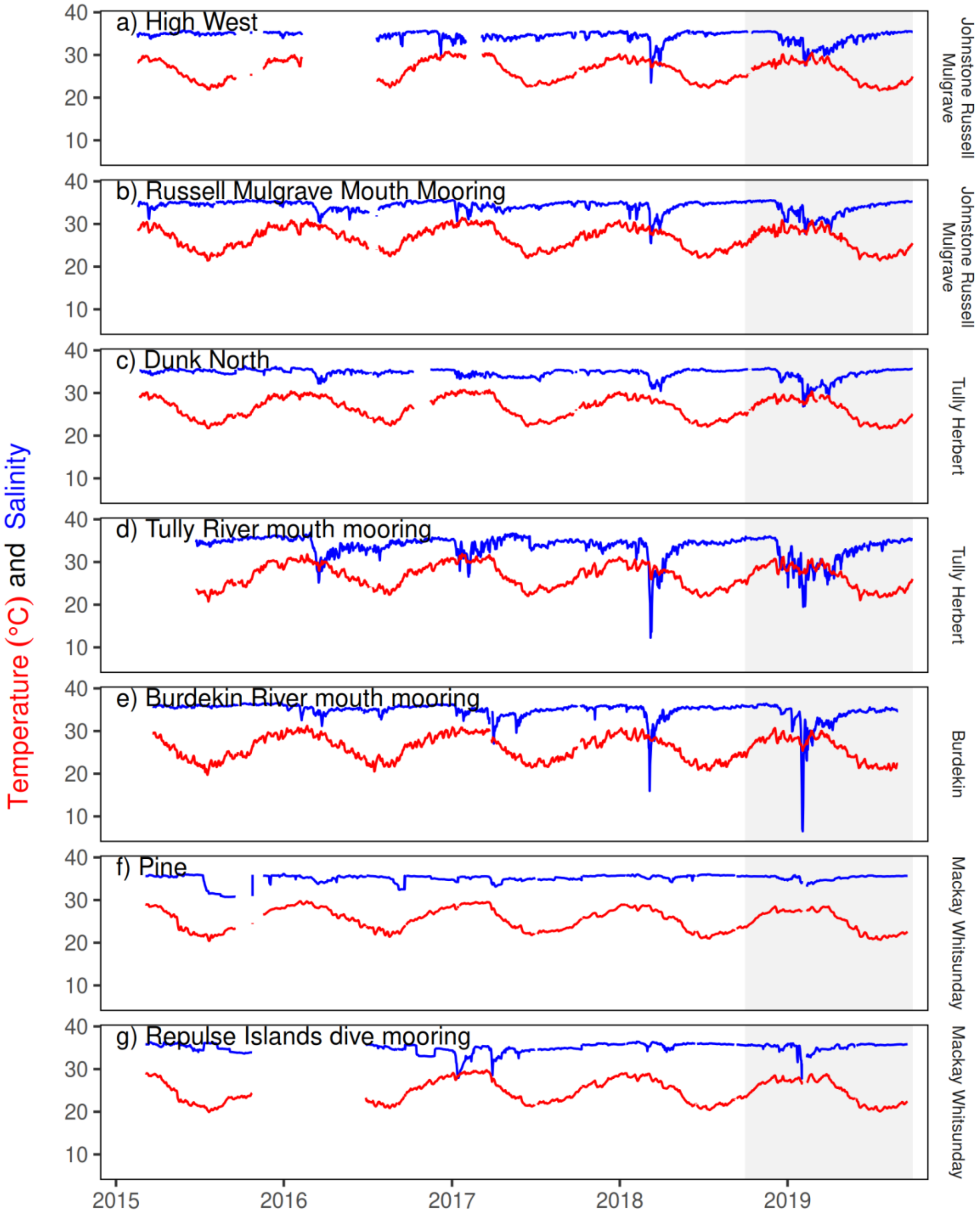


Figure E-2: Time series of daily means of temperature and salinity derived from moored Sea-Bird Electronics (SBE) CTDs. Sub-figures represent instrument locations at: a) High West, b) Russel Mulgrave Mouth Mooring, c) Dunk North, d) Tully River Mouth Mooring, e) Burdekin Mouth Mooring, f) Pine, and g) Repulse.

E-3 Summary statistics for all sites

Table E-1: Water quality results for Cape York sampling sites within the enclosed coastal (EC), open coastal (OC) and mid-shelf (MS) water bodies compared against the Draft Eastern Cape York Water Quality Guidelines (2019). Guidelines vary for each water body and focus region based on available data. For the EC water body, wet season GVs have been designated for each focus region, therefore the statistics are presented separately for dry season and wet season results. The EC guidelines have been updated since the 2017–18 MMP report with some revisions to the GVs. OC water body guidelines (all focus regions) include both wet season and dry season GVs except for NH_3 and Secchi depth which have annual GVs. As a result, the OC water body results for each focus region are presented in separate tables for the combined annual results, wet season and dry season. MS water body guidelines (all focus regions) are based on annual concentrations; therefore, only the annual (wet and dry season combined) results are presented for each focus region in this water body. Flood event sample results are not included in the statistics calculated for these tables. Results that exceed the relevant GVs are shaded in red.

ENCLOSED COASTAL DRY SEASON 2018 – 2019											
Region/ Water body	Site	Measure	N	Mean	Quantiles					Guidelines	
					Q5	Q20	Median	Q80	Q95	Statistic	Dry[1]
Cape York Enclosed Coastal Water body	Endeavour Basin	Secchi (m)[2]	3	NA	NA	NA	NA	NA	NA		--
		TSS (mgL⁻¹)	4	2.0	1.2	1.3	1.9	2.6	2.8		--
		TN (µgL⁻¹)	4	90	88	89	89	91	94		--
		NOx (µgL⁻¹)	4	4.7	2.9	3.9	5.0	5.6	6.1		--
		NH_3 (µgL⁻¹)	4	6	3	3	4	7	11		--
		DON (µgL⁻¹)	4	73	63	68	74	78	81		--
		PN (µgL⁻¹)	2	26	25	25	26	26	26		--
		TP (µgL⁻¹)	4	8	7	7	7	8	9		--
		PO4 (µgL⁻¹)	4	4.0	2.3	2.6	3.9	5.3	5.7		--
		DOP (µgL⁻¹)	4	4	2	3	4	4	5		--
		PP (µgL⁻¹)	1	10.9			10.9				--
		Chla (µgL⁻¹)	4	0.7	0.4	0.4	0.5	0.9	1.2		--
		DOC (µgL⁻¹)	0								--
	Normanby River	Secchi (m)	5	1.7	1.3	1.4	1.5	1.8	2.6		--
		TSS (mgL⁻¹)	5	3.8	2.2	3.0	3.5	4.6	5.6		--
		TN (µgL⁻¹)	5	190	167	178	194	205	207		--
		NOx (µgL⁻¹)	5	31.1	12.9	14.7	37.2	44.4	46.2		--
		NH_3 (µgL⁻¹)	5	3	1	1	2	4	8		--
		DON (µgL⁻¹)	5	122	106	108	118	131	147		--
		PN (µgL⁻¹)	5	44	29	34	44	55	60		--
		TP (µgL⁻¹)	5	7	5	6	8	8	8		--
		PO4 (µgL⁻¹)	5	3.9	2.3	2.9	3.4	5.1	5.7		--
		DOP (µgL⁻¹)	5	1	1	1	1	2	2		--
		PP (µgL⁻¹)	0								--
		Chla (µgL⁻¹)	5	2.0	1.4	1.8	2.0	2.1	2.5		--
		DOC (µgL⁻¹)	5	2.6	1.8	1.8	2.8	3.1	3.2		--
Cape York Enclosed Coastal	Stewart River	Secchi (m)	5	1.9	0.8	1.1	1.3	2.8	3.5		--
		TSS (mgL⁻¹)	6	7.5	2.6	3.0	5.2	7.0	18.3		--
		TN (µgL⁻¹)	6	123	100	116	124	139	141		--
		NOx (µgL⁻¹)	6	4.2	2.3	2.6	3.0	5.5	7.9		--
		NH_3 (µgL⁻¹)	6	8	5	6	9	11	12		--
		DON (µgL⁻¹)	6	87	79	80	86	94	97		--
		PN (µgL⁻¹)	3	57	46	48	53	66	72		--
		TP (µgL⁻¹)	5	10	9	9	10	11	12		--
		PO4 (µgL⁻¹)	6	4.1	2.6	2.9	4.5	5.1	5.2		--
		DOP (µgL⁻¹)	6	3	2	2	3	4	5		--

ENCLOSED COASTAL DRY SEASON 2018 – 2019											
Region/ Water body	Site	Measure	N	Mean	Quantiles					Guidelines	
					Q5	Q20	Median	Q80	Q95	Statistic	Dry[1]
Water body		PP (µgL^{-1})	3	8	4	5	7	11	14		--
		Chla (µgL^{-1})	6	1.7	1.0	1.0	1.4	2.6	2.6		--
		DOC (µgL^{-1})	3	1.9	1.7	1.7	1.7	2.1	2.2		--
	Pascoe River	Secchi (m)[2]	2	>3.5	NA	NA	NA	NA	NA		--
		TSS (mgL^{-1})	4	2.8	2.5	2.6	2.9	3.0	3.2		--
		TN (µgL^{-1})	4	119	88	90	93	138	187		--
		NH_3 (µgL^{-1})	4	16.7	5.5	11.9	18.8	22.3	24.9		--
		NOx (µgL^{-1})	4	2	1	2	2	3	3		--
		DON (µgL^{-1})	4	96	59	62	66	119	176		--
		PN (µgL^{-1})	0								--
		TP (µgL^{-1})	4	8	7	7	8	9	9		--
		PO4 (µgL^{-1})	4	4.5	2.7	2.7	4.3	6.1	6.6		--
		DOP (µgL^{-1})	4	2	1	1	2	3	3		--
		PP (µgL^{-1})	0								--
		Chla (µgL^{-1})	4	0.6	0.4	0.5	0.7	0.8	0.9		--
		DOC (µgL^{-1})	0								--

1 There are no annual or dry season guidelines for the Cape York enclosed coastal water body (wet season only)

2 Secchi depth exceeded water depth at some sites, therefore statistics could not be calculated

ENCLOSED COASTAL WET SEASON 2018 - 2019											
Region/ Water body	Site	Measure	N	Mean	Quantiles					Guidelines	
					Q5	Q20	Median	Q80	Q95	Statistic	Wet
Cape York Enclosed Coastal Water body	Endeavour Basin	Secchi (m)[1]	4	NA	NA	NA	NA	NA	NA	20th-50th-80th	1.8-3.0-4.4
		TSS (mgL^{-1})	4	2.8	1.3	1.9	2.5	3.6	4.7	20th-50th-80th	3-4-5
		TN (µgL^{-1})	4	135	119	120	130	147	159	20th-50th-80th	103-127-149
		NOx (µgL^{-1})	4	7.0	2.6	2.8	5.8	10.7	12.9	20th-50th-80th	1.5-2.5-9.6
		NH_3 (µgL^{-1})	4	4	2	3	4	5	6	20th-50th-80th	2-4-6
		DON (µgL^{-1})	4	96	80	84	91	106	118		
		PN (µgL^{-1})	4	31	23	24	31	38	38		
		TP (µgL^{-1})	4	7	6	6	7	7	7	20th-50th-80th	5-6.5-7
		PO4 (µgL^{-1})	4	4.4	3.2	3.3	4.4	5.5	5.8	20th-50th-80th	<2.0-2.0-3.4
		DOP (µgL^{-1})	4	1	1	1	1	1	1		
		PP (µgL^{-1})	1	6	6	6	6	6	6		
		Chla (µgL^{-1})	4	1.6	1.0	1.2	1.5	1.9	2.2	20th-50th-80th	0.2-0.6-0.8
		DOC (µgL^{-1})	2	1.6	1.5	1.5	1.6	1.7	1.8		
	Normanby River	Secchi (m)	4	0.8	0.5	0.7	0.9	1.0	1.0		1.0-1.5-2.6
		TSS (mgL^{-1})	5	33.6	9.6	10.6	16.0	58.2	73.8		4-6-13
		TN (µgL^{-1})	5	174	135	144	149	198	242		105-117-164
		NOx (µgL^{-1})	5	3.0	1.4	1.9	2.8	3.8	5.3		<1-1.0-4.0
		NH_3 (µgL^{-1})	5	4	1	1	4	6	9		2-4-6
		DON (µgL^{-1})	5	103	91	94	99	107	125		
		PN (µgL^{-1})	5	134	54	70	147	170	226		
		TP (µgL^{-1})	5	17	10	10	13	21	32		7-8-10
		PO4 (µgL^{-1})	4	6.2	5.5	5.6	6.1	6.8	7.1		<2-2.0-3.0
		DOP (µgL^{-1})	5	2	0	1	3	3	3		
		PP (µgL^{-1})	4	43	16	19	44	67	68		

Cape York Enclosed Coastal Water body		Chla (µgL⁻¹)	3	3.4	3.0	3.1	3.3	3.6	3.8		0.4-0.7-0.9
		DOC (µgL⁻¹)	0								
	Stewart River	Secchi (m)	4	2.8	1.1	1.1	2.6	4.4	4.8	20th-50th-80th	1.6-3.1-4.6
		TSS (mgL⁻¹)	6	11.3	1.5	1.6	10.8	20.0	22.3	20th-50th-80th	3-5-6
		TN (µgL⁻¹)	6	143	112	113	128	161	201	20th-50th-80th	113–130–
		NOx (µgL⁻¹)	6	3.2	1.1	1.4	2.8	3.8	6.4	20th-50th-80th	1.0-1.5-3.0
		NH_3 (µgL⁻¹)	6	4	1	2	2	4	13	20th-50th-80th	2-2-4
		DON (µgL⁻¹)	6	125	95	108	115	148	166		
		PN (µgL⁻¹)	6	60	19	30	64	94	95		
		TP (µgL⁻¹)	6	14	11	12	13	15	17	20th-50th-80th	5-7-10
		PO4 (µgL⁻¹)	6	2.5	1.9	2.5	2.6	2.8	2.9	20th-50th-80th	<2-2.0-3.0
		DOP (µgL⁻¹)	6	8	7	7	8	9	9		
		PP (µgL⁻¹)	6	7	1	3	4	8	17		
		Chla (µgL⁻¹)	6	1.6	0.5	0.8	1.4	2.6	2.9	20th-50th-80th	0.3-0.4-0.8
		DOC (µgL⁻¹)	6	1.6	1.5	1.5	1.6	1.6	1.7		
	Pascoe River	Secchi (m)[1]	4	>4.5	NA	NA	NA	NA	NA		2-3-5
		TSS (mgL⁻¹)	4	1.4	0.7	0.9	1.2	1.8	2.3	20th-50th-80th	4-4-8
		TN (µgL⁻¹)	4	135	121	129	136	142	147	20th-50th-80th	95-106-142
		NOx (µgL⁻¹)	4	2.4	0.6	0.8	1.2	3.6	5.9	20th-50th-80th	<1-1.5-4.0
		NH_3 (µgL⁻¹)	4	2	1	1	2	3	5	20th-50th-80th	2-2-3
		DON (µgL⁻¹)	4	114	90	96	114	132	138		
		PN (µgL⁻¹)	2	29	27	28	29	30	30		
		TP (µgL⁻¹)	4	9	6	6	9	11	11	20th-50th-80th	5-7-10
		PO4 (µgL⁻¹)	4	2.6	2.4	2.4	2.5	2.7	2.9	20th-50th-80th	2.0-3.0–3.5
		DOP (µgL⁻¹)	4	5	3	3	5	7	7		
		PP (µgL⁻¹)	2	7	1	3	7	12	14		
		Chla (µgL⁻¹)	4	1.3	0.6	0.8	1.4	1.8	1.9	20th-50th-80th	0.5–0.7-1.2
		DOC (µgL⁻¹)	2	1.4	1.4	1.4	1.4	1.4	1.4		

1 Secchi depth exceeded water depth at some sites, therefore statistics could not be calculated

OPEN COASTAL ANNUAL[1] (WET and DRY SEASON COMBINED) 2018–19											
Region/ Water body	Site	Measure	N	Mean	Quantiles					Guidelines	
					Q5	Q20	Median Q50	Q80	Q95	Statistic	Base Flow/ Annual
Cape York Open Coastal Water body	Endeavour Basin	Secchi (m)	15	6.5	4.8	5.5	6.6	7.6	8.2	Mean	▯10
		TSS (mgL^{-1})	33	1.5	0.1	0.4	1.2	2.4	3.8		
		TN (µgL^{-1})	30	102	82	86	94	113	138		
		NOx (µgL^{-1})	30	5.9	1.3	2.2	3.5	10.0	14.1	20th-50th-80th	0.14-0.35-1.05
		NH_3 (µgL^{-1})	30	4	2	2	3	5	8	20th-50th-80th	0-1-3
		DON (µgL^{-1})	30	79	61	69	78	84	96		
		PN (µgL^{-1})	22	28	14	17	23	40	51		
		TP (µgL^{-1})	30	8	6	7	8	9	10		
		PO4 (µgL^{-1})	30	4.3	2.2	2.6	4.5	5.6	6.3	20th-50th-80th	0.31-1.40-2.64
		DOP (µgL^{-1})	30	2	1	1	2	3	5		
		PP (µgL^{-1})	5	10	3	3	7	14	23		
		Chla (µgL^{-1})	30	1.0	0.1	0.2	1.0	1.4	2.0		
		DOC (µgL^{-1})	6	1.1	1.1	1.1	1.1	1.1	1.2		
	Normanby River	Secchi (m)	6	5.2	2.4	3.5	3.8	4.5	11.3	Mean	▯10
		TSS (mgL^{-1})	12	2.1	0.8	1.0	2.1	2.7	4.1		
		TN (µgL^{-1})	12	110	86	91	98	125	151		
		NOx (µgL^{-1})	12	7.1	1.4	2.5	5.4	11.2	15.4	20th-50th-80th	0.14-0.35-1.05
		NH_3 (µgL^{-1})	12	7	0	1	2	7	26	20th-50th-80th	0-1-3
		DON (µgL^{-1})	12	79	47	72	77	86	117		
		PN (µgL^{-1})	10	44	25	26	44	55	76		
		TP (µgL^{-1})	12	11	8	9	10	12	15		
		PO4 (µgL^{-1})	12	4.6	2.6	2.9	5.4	5.9	6.4	20th-50th-80th	0.31-1.40-2.64
		DOP (µgL^{-1})	12	4	2	3	4	7	8		
		PP (µgL^{-1})	9	15	2	2	5	25	56		
		Chla (µgL^{-1})	12	1.1	0.3	0.4	1.3	1.6	1.9		
		DOC (µgL^{-1})	6	1.4	0.9	1.0	1.3	1.6	2.3		
	Stewart River	Secchi (m)	8	5.4	3.5	3.5	4.0	7.8	9.7	Mean	▯10
		TSS (mgL^{-1})	16	2.7	0.4	0.7	1.9	4.6	9.0		
		TN (µgL^{-1})	16	110	91	94	111	119	137		
		NOx (µgL^{-1})	16	4.5	1.8	2.1	3.5	7.1	8.9	20th-50th-80th	0.14-0.35-1.05
		NH_3 (µgL^{-1})	16	4	1	2	3	6	10	20th-50th-80th	0-1-3
		DON (µgL^{-1})	16	87	67	76	84	98	109		
		PN (µgL^{-1})	12	36	21	27	34	41	59		
		TP (µgL^{-1})	16	10	8	8	11	12	13		
		PO4 (µgL^{-1})	16	3.6	1.9	2.3	3.3	5.3	5.9	20th-50th-80th	0.31-1.40-2.64
		DOP (µgL^{-1})	16	5	2	3	5	7	9		
		PP (µgL^{-1})	11	22	2	4	14	17	82		
		Chla (µgL^{-1})	16	1.0	0.2	0.4	0.7	1.6	2.7		
		DOC (µgL^{-1})	12	1.4	1.2	1.3	1.3	1.5	1.9		
	Pascoe River	Secchi (m)	10	4.7	3.6	3.9	4.3	5.5	6.5	Mean	▯10
		TSS (mgL^{-1})	19	2.0	0.8	1.4	1.8	2.5	3.1		
		TN (µgL^{-1})	19	118	96	101	118	139	144		
		NOx (µgL^{-1})	19	6.7	1.2	1.7	5.2	9.9	19.4	20th-50th-80th	0.14-0.35-1.05
		NH_3 (µgL^{-1})	19	3	1	2	2	4	6	20th-50th-80th	0-1-3
		DON (µgL^{-1})	19	92	69	75	92	104	124		
		PN (µgL^{-1})	6	36	30	31	34	41	45		

Cape York Open Coastal Water body	Pascoe River	TP (µgL^{-1})	19	10	7	9	10	11	12		
		PO4 (µgL^{-1})	19	3.4	1.9	2.5	3.0	4.1	5.6	20th-50th-80th	0.31-1.40-2.64
		DOP (µgL^{-1})	19	5	2	4	5	6	7		
		PP (µgL^{-1})	6	1	0	0	0	1	3		
		Chla (µgL^{-1})	19	1.0	0.3	0.5	0.8	1.6	2.3		
		DOC (µgL^{-1})	7	1.3	1.2	1.3	1.3	1.4	1.4		

1 Samples were collected between October 2018 and May 2019. This wet season bias is likely to contribute to exceedances of annual GVs

OPEN COASTAL DRY SEASON 2018–19											
Region/ Water body	Site	Measure	N	Mean	Quantiles					Guidelines	
					Q5	Q20	Median	Q80	Q95	Statistic	Dry
Cape York Open Coastal Water body	Endeavour Basin	Secchi (m)	8	6.8	5.5	6.2	7.1	7.4	7.7		
		TSS (mgL^{-1})	17	1.7	0.1	0.5	1.5	2.5	3.9	Mean	≤1.6
		TN (µgL^{-1})	16	95	81	86	92	101	116	20th-50th-80th	70–100–120
		NOx (µgL^{-1})	16	3.6	0.7	2.2	2.9	4.2	9.1	20th-50th-80th	0.14-0.32-1.05
		NH_3 (µgL^{-1})	16	4	2	3	4	5	6		
		DON (µgL^{-1})	16	77	61	70	78	84	89		
		PN (µgL^{-1})	8	36	19	24	37	49	53	Mean	≤16
		TP (µgL^{-1})	16	8	6	8	8	9	10	20th-50th-80th	8–10–16
		PO4 (µgL^{-1})	16	4.3	2.3	2.5	4.3	5.8	6.5	20th-50th-80th	0.62-1.86-2.74
		DOP (µgL^{-1})	16	3	2	2	3	4	5		
		PP (µgL^{-1})	3	32.6	12.5	17.1	26.1	46.9	57.3	mean	≤ 2.3
		Chla (µgL^{-1})	16	0.6	0.1	0.1	0.5	1.3	1.4	20th-50th-80th	0.16–0.25–0.46
		DOC (µgL^{-1})	0								
	Normanby River	Secchi (m)	1	4.0	4.0	4.0	4.0	4.0	4.0		
		TSS (mgL^{-1})	2	0.8	0.6	0.7	0.8	0.9	1.0	Mean	≤ 1.6
		TN (µgL^{-1})	2	120	117	118	120	122	123	20th-50th-80th	70–100–120
		NOx (µgL^{-1})	2	6.8	3.2	4.4	6.8	9.2	10.4	20th-50th-80th	0.14-0.32-1.05
		NH_3 (µgL^{-1})	2	6	6	6	6	6	6		
		DON (µgL^{-1})	2	93	87	89	93	97	99		
		PN (µgL^{-1})	0							Mean	≤16
		TP (µgL^{-1})	2	9	9	9	9	10	10	20th-50th-80th	8–10–16
		PO4 (µgL^{-1})	2	3.0	2.9	2.9	3.0	3.2	3.2	20th-50th-80th	0.62-1.86-2.74
		DOP (µgL^{-1})	2	5	4	5	5	5	5		
		PP (µgL^{-1})	0							mean	≤ 2.3
		Chla (µgL^{-1})	2	0.3	0.3	0.3	0.3	0.3	0.3	20th-50th-80th	0.16–0.25–0.46
		DOC (µgL^{-1})	2	1.5	1.4	1.4	1.5	1.5	1.5		
Cape York Open Coastal Water body	Stewart River	Secchi (m)	4	4.4	3.5	3.6	4.0	5.0	5.7		
		TSS (mgL^{-1})	8	2.2	0.5	0.7	1.8	3.8	4.9	Mean	≤1.6
		TN (µgL^{-1})	8	99	91	91	94	105	121	20th-50th-80th	70–100–120
		NOx (µgL^{-1})[2]	8	5.2	2.0	2.6	4.8	7.6	9.2	20th-50th-80th	0.14-0.32-1.05
		NH_3 (µgL^{-1})	8	5	2	4	6	7	8		
		DON (µgL^{-1})	8	75	67	69	76	79	81		
		PN (µgL^{-1})	4	47	33	35	39	56	73	Mean	≤ 16
		TP (µgL^{-1})	8	9	7	8	8	10	11	20th-50th-80th	8–10–16
		PO4 (µgL^{-1})	8	4.4	2.3	3.1	4.5	5.8	6.1	20th-50th-80th	0.62-1.86-2.74
		DOP (µgL^{-1})	8	3	1	2	3	4	5		
		PP (µgL^{-1})	3	55	10	33	79	82	84	mean	≤ 2.3
		Chla (µgL^{-1})	8	0.7	0.2	0.3	0.5	1.3	1.5	20th-50th-80th	0.16–0.25–0.46
		DOC (µgL^{-1})	4	1.4	1.3	1.3	1.4	1.4	1.5		
		Secchi (m)	3	NA	NA	NA	NA	NA	NA		

Cape York Open Coastal Water body	Pascoe River	TSS (mgL^{-1})	6	2.5	1.7	1.8	2.3	2.6	3.9	Mean	≤ 1.6
		TN (µgL^{-1})	6	109	91	97	104	122	134	20th-50th-80th	70–100–120
		NOx (µgL^{-1})	6	10.5	6.4	7.7	8.5	13.2	17.7	20th-50th-80th	0.14-0.32-1.05
		NH$_3$ (µgL^{-1})	6	3	2	2	3	4	4		
		DON (µgL^{-1})	6	77	66	70	76	86	91		
		PN (µgL^{-1})	0							Mean	≤16
		TP (µgL^{-1})	6	10	8	9	10	11	13	20th-50th-80th	8–10–16
		PO4 (µgL^{-1})	6	4.0	2.5	3.0	3.7	5.2	5.7	20th-50th-80th	0.62-1.86-2.74
		DOP (µgL^{-1})	6	4	2	2	4	5	6		
		PP (µgL^{-1})	0							mean	≤ 2.3
		Chla (µgL^{-1})	6	0.7	0.4	0.5	0.6	0.8	1.0	20th-50th-80th	0.16–0.25–0.46
		DOC (µgL^{-1})	3	NA	NA	NA	NA	NA	NA		

OPEN COASTAL WET SEASON 2018 - 2019											
Region/ Water body	Site	Measure	N	Mean	Quantiles					Guidelines	
					Q5	Q20	Median Q50	Q80	Q95	Statistic	Wet
Cape York Open Coastal Water body	Endeavour Basin	Secchi (m)	7	6.2	4.2	5.3	6.0	7.8	8.4		
		TSS (mgL^{-1})	17	1.1	0.1	0.4	0.8	1.7	2.8	20th-50th-80th	1.1-1.7-2.2
		TN (µgL^{-1})	14	110	83	85	104	126	159	20th-50th-80th	75–105–130
		NOx (µgL^{-1})	14	8.7	2.2	2.5	9.3	11.9	17.3	20th-50th-80th	0.20-0.45-0.98
		NH$_3$ (µgL^{-1})	14	3	1	2	3	4	9		
		DON (µgL^{-1})	14	81	61	66	77	85	116		
		PN (µgL^{-1})	14	23	13	16	20	29	39	20th-50th-80th	14-20-26
		TP (µgL^{-1})	14	7	5	6	7	8	8	20th-50th-80th	5–10–20
		PO4 (µgL^{-1})	14	4.2	2.2	2.7	4.5	5.5	5.9	20th-50th-80th	0.16-0.93-1.86
		DOP (µgL^{-1})	14	1	1	1	1	2	3		
		PP (µgL^{-1})	3	4	3	3	3	5	7	20th-50th-80th	2.2-3.0-3.9
		Chla (µgL^{-1})	14	1.3	0.1	0.8	1.3	1.8	2.4	20th-50th-80th	0.30-0.46-0.78
		DOC ((µgL^{-1})	6	1.1	1.1	1.1	1.1	1.1	1.2		
	Normanby River	Secchi (m)	5	5.4	2.3	3.2	3.5	6.3	11.7		
		TSS (mgL^{-1})	10	2.4	1.1	1.2	2.3	2.9	4.2	20th-50th-80th	1.1-1.7-2.2
		TN (µgL^{-1})	10	108	86	90	96	127	154	20th-50th-80th	75–105–130
		NOx (µgL^{-1})	10	7.2	1.4	2.3	5.4	12.2	15.4	20th-50th-80th	0.20-0.45-0.98
		NH$_3$ (µgL^{-1})	10	7	0	0	2	7	30		
		DON (µgL^{-1})	10	77	43	70	76	82	114		
		PN (µgL^{-1})	10	44	25	26	44	55	76	20th-50th-80th	14-20-26
		TP (µgL^{-1})	10	11	8	9	10	12	15	20th-50th-80th	5–10–20
		PO4 (µgL^{-1})	10	5.0	2.6	3.2	5.5	5.9	6.5	20th-50th-80th	0.16-0.93-1.86
		DOP (µgL^{-1})	10	4	2	2	3	8	8		
		PP (µgL^{-1})	9	15	2	2	5	25	56	20th-50th-80th	2.2-3.0-3.9
		Chla (µgL^{-1})	10	1.3	0.5	1.0	1.3	1.6	2.0	20th-50th-80th	0.30-0.46-0.78
		DOC (µgL^{-1})	4	1.4	0.9	0.9	1.1	1.7	2.3		
	Stewart River	Secchi (m)	4	6.5	3.5	3.5	6.3	9.4	9.9		
		TSS (mgL^{-1})	8	3.3	0.5	1.0	1.9	6.2	9.0	20th-50th-80th	1.1-1.7-2.2
		TN (µgL^{-1})	8	122	108	110	117	123	153	20th-50th-80th	75–105–130
		NOx (µgL^{-1})	8	3.7	1.6	2.0	3.0	5.0	7.5	20th-50th-80th	0.20-0.45-0.98
		NH$_3$ (µgL^{-1})	8	3	2	2	2	2	9		
		DON (µgL^{-1})	8	99	88	92	98	106	111		
		PN (µgL^{-1})	8	31	19	25	31	37	42	20th-50th-80th	14-20-26

Cape York Open Coastal Water body		TP (µgL⁻¹)	8	12	11	11	12	13	14	20th-50th-80th	5–10–20
		PO4 (µgL⁻¹)	8	2.9	1.9	2.2	2.7	3.4	4.5	20th-50th-80th	0.16-0.93-1.86
		DOP (µgL⁻¹)	8	7	6	6	7	8	10		
		PP (µgL⁻¹)	8	9	2	4	9	16	17	20th-50th-80th	2.2-3.0-3.9
		Chla (µgL⁻¹)	8	1.3	0.4	0.5	0.9	2.4	2.8	20th-50th-80th	0.30-0.46-0.78
		DOC (µgL⁻¹)	8	1.4	1.1	1.2	1.3	1.7	2.0		
	Pascoe River	Secchi (m)	7	4.3	3.6	3.9	4.0	4.9	5.3		
		TSS (mgL⁻¹)	13	1.7	0.8	1.2	1.6	2.2	2.8	20th-50th-80th	1.1-1.7-2.2
		TN (µgL⁻¹)	13	123	101	108	120	140	149	20th-50th-80th	75–105–130
		NOx (µgL⁻¹)	13	5.0	1.1	1.4	2.9	5.6	15.6	20th-50th-80th	0.20-0.45-0.98
		NH3 (µgL⁻¹)	13	3	1	2	2	4	6		
		DON (µgL⁻¹)	13	98	74	81	95	107	131		
		PN (µgL⁻¹)	6	36	30	31	34	41	45	20th-50th-80th	14-20-26
		TP (µgL⁻¹)	13	10	7	9	10	11	11	20th-50th-80th	5–10–20
		PO4 (µgL⁻¹)	13	3.2	1.9	2.4	3.0	3.9	4.6	20th-50th-80th	0.16-0.93-1.86
		DOP (µgL⁻¹)	13	5	3	4	6	6	7		
		PP (µgL⁻¹)	6	1	0	0	0	1	3	20th-50th-80th	2.2-3.0-3.9
		Chla (µgL⁻¹)	13	1.2	0.3	0.6	1.0	1.6	2.4	20th-50th-80th	0.30-0.46-0.78
		DOC (µgL⁻¹)	7	1.3	1.2	1.3	1.3	1.4	1.4		

MID-SHELF ANNUAL[1] (WET and DRY SEASON COMBINED) 2018–19

Region/ Water body	Site	Measure	N	Mean	Quantiles					Guidelines	
					Q5	Q20	Median Q50	Q80	Q95	Statistic	Base Flow/ Annual
Cape York Mid-shelf Water body	Endeavour Basin	Secchi (m)	6	8.1	6.0	6.9	7.0	8.5	12.0	Mean	▯10
		TSS (mgL⁻¹)	10	1.0	0.2	0.5	1.0	1.4	2.2	20th-50th-80th	0.9-1.5-2.3
		TN (µgL⁻¹)	10	89	78	84	89	94	100	20th-50th-80th	75–100–130
		NOx (µgL⁻¹)	10	4.8	1.4	2.5	4.1	7.7	8.7	20th-50th-80th	0.17-0.35-0.84
		NH3 (µgL⁻¹)	8	4	1	2	4	7	9	20th-50th-80th	0-1-3
		DON (µgL⁻¹)	10	73	61	67	74	79	83		
		PN (µgL⁻¹)	8	23	13	19	23	27	34	20th-50th-80th	14-18-22
		TP (µgL⁻¹)	8	8	6	7	8	10	11	20th-50th-80th	6–9–15
		PO4 (µgL⁻¹)	10	4.8	3.3	4.0	5.1	5.4	6.3	20th-50th-80th	0.16-0.62-2.02
		DOP (µgL⁻¹)	10	2	1	1	1	2	4		
		PP (µgL⁻¹)	2	2	2	2	2	3	3	20th-50th-80th	1.5-2.0-2.8
		Chla (µgL⁻¹)	10	0.9	0.1	0.2	1.0	1.3	1.7	20th-50th-80th	0.18-0.27-0.45
		DOC (µgL⁻¹)	4	1.1	1.0	1.0	1.1	1.1	1.2		
	Normanby Basin	Secchi (m)	3	13.2	7.9	10.6	16.0	16.3	16.5	Mean	▯10
		TSS (mgL⁻¹)	4	0.9	0.4	0.5	0.8	1.2	1.4	20th-50th-80th	0.9-1.5-2.3
		TN (µgL⁻¹)	4	92	90	90	92	93	93	20th-50th-80th	75–100–130
		NOx (µgL⁻¹)	4	4.9	1.7	2.0	4.1	7.5	9.4	20th-50th-80th	0.17-0.35-0.84
		NH3 (µgL⁻¹)	4	3	1	2	3	4	6	20th-50th-80th	0-1-3
		DON (µgL⁻¹)	4	78	74	75	77	80	82		
		PN (µgL⁻¹)	4	14	10	12	14	16	17	20th-50th-80th	14-18-22
		TP (µgL⁻¹)	4	10	9	9	10	10	10	20th-50th-80th	6–9–15
		PO4 (µgL⁻¹)	4	4.5	2.4	2.4	4.2	6.5	7.0	20th-50th-80th	0.16-0.62-2.02
		DOP (µgL⁻¹)	4	5	2	3	5	7	8		
		PP (µgL⁻¹)	3	20	2	4	10	33	45	20th-50th-80th	1.5-2.0-2.8
		Chla (µgL⁻¹)	4	0.9	0.1	0.3	1.0	1.6	1.6	20th-50th-80th	0.18-0.27-0.45

		DOC (µgL⁻¹)	2	1.2	1.1	1.2	1.2	1.2	1.3		
Cape York Mid-shelf Water body	Stewart River	Secchi (m)	4	4.7	3.8	3.8	4.5	5.6	6.1	Mean	10
		TSS (mgL⁻¹)	7	2.1	0.5	1.1	1.4	2.6	5.3	20th-50th-80th	0.9-1.5-2.3
		TN (µgL⁻¹)	7	103	91	93	96	113	125	20th-50th-80th	75–100–130
		NOx (µgL⁻¹)	7	5.2	1.4	2.0	2.8	6.5	14.0	20th-50th-80th	0.17-0.35-0.84
		NH_3 (µgL⁻¹)	7	6	2	3	5	10	12	20th-50th-80th	0-1-3
		DON (µgL⁻¹)	7	86	69	72	81	103	107		
		PN (µgL⁻¹)	4	33	21	25	33	41	45	20th-50th-80th	14-18-22
		TP (µgL⁻¹)	7	10	8	8	9	11	15	20th-50th-80th	6–9–15
		PO4 (µgL⁻¹)	7	3.7	2.5	2.7	3.3	4.7	5.5	20th-50th-80th	0.16-0.62-2.02
		DOP (µgL⁻¹)	7	5	3	4	4	7	8		
		PP (µgL⁻¹)	4	24	3	10	27	39	41	20th-50th-80th	1.5-2.0-2.8
		Chla (µgL⁻¹)	7	0.8	0.2	0.3	0.4	1.2	1.8	20th-50th-80th	0.18-0.27-0.45
		DOC (µgL⁻¹)	5	1.3	1.3	1.3	1.3	1.3	1.4		
	Pascoe River	Secchi (m)	6	7.0	4.6	6.5	6.8	8.0	9.5	Mean	10
		TSS (mgL⁻¹)	12	1.5	0.5	0.7	1.4	2.4	2.4	20th-50th-80th	0.9-1.5-2.3
		TN (µgL⁻¹)	12	101	88	90	95	117	128	20th-50th-80th	75–100–130
		NOx (µgL⁻¹)	12	6.3	0.8	1.6	4.4	11.5	14.6	20th-50th-80th	0.17-0.35-0.84
		NH_3 (µgL⁻¹)	12	3	2	2	2	4	5	20th-50th-80th	0-1-3
		DON (µgL⁻¹)	12	85	71	74	83	95	105		
		PN (µgL⁻¹)	4	24	18	18	23	29	31	20th-50th-80th	14-18-22
		TP (µgL⁻¹)	12	9	7	7	8	11	12	20th-50th-80th	6–9–15
		PO4 (µgL⁻¹)	12	3.4	2.2	2.5	3.2	4.3	5.1	20th-50th-80th	0.16-0.62-2.02
		DOP (µgL⁻¹)	12	4	1	2	4	6	7		
		PP (µgL⁻¹)	3	0	0	0	1	1	1	20th-50th-80th	1.5-2.0-2.8
		Chla (µgL⁻¹)	12	1.5	0.3	0.7	1.6	1.9	3.0	20th-50th-80th	0.18-0.27-0.45
		DOC (µgL⁻¹)	4	1.3	1.2	1.3	1.3	1.3	1.3		

1 Samples were collected between October 2018 and June 2019. This wet season bias is likely to contribute to exceedences of annual GV

Table E-2: Summary statistics for water quality parameters at individual monitoring sites (other than those in the Cape York region) from 1 October 2018 to 30 September 2019. N = number of sampling occasions. See Section 2 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.

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
Wet Tropics	Cape Tribulation(C1)	DIN ($\mu g\ L^{-1}$)	3	3.58	3.33	0.96	1.75	5.36	6.38				
		DOC ($\mu g\ L^{-1}$)	3	799	833	705	748	857	869				
		DON ($\mu g\ L^{-1}$)	3	72.26	72.21	67.04	68.77	75.74	77.50				
		DOP ($\mu g\ L^{-1}$)	3	4.46	4.34	3.57	3.82	5.08	5.45				
		Chl a ($\mu g\ L^{-1}$)	3	0.36	0.44	0.19	0.27	0.46	0.46	Mean	0.45		
		NO_x ($\mu g\ L^{-1}$)	3	0.69	0.28	0.28	0.28	1.02	1.38	Median	0.35		
		PN ($\mu g\ L^{-1}$)	3	10.09	10.54	8.87	9.43	10.85	11.00	Mean	20.00		
		PO_4 ($\mu g\ L^{-1}$)	3	1.24	1.55	0.64	0.94	1.59	1.62	Median	2.00		
		POC ($mg\ L^{-1}$)	3	74.68	76.55	68.14	70.95	78.78	79.90				
		PP ($\mu g\ L^{-1}$)	3	1.76	1.71	1.29	1.43	2.08	2.27	Mean	2.80		
		Secchi (m)	3	9.33	10.00	6.85	7.90	10.90	11.35	Mean	10.00		
		SiO_4	3	97.52	90.10	52.37	64.94	128.61	147.87				
		TSS ($mg\ L^{-1}$)	3	0.78	0.76	0.58	0.64	0.92	1.01	Mean	2.00		
	Port Douglas(C4)	DIN ($\mu g\ L^{-1}$)	3	3.17	4.38	1.07	2.17	4.42	4.44				
		DOC ($\mu g\ L^{-1}$)	3	822	826	763	784	862	880				
		DON ($\mu g\ L^{-1}$)	3	78.66	77.01	75.97	76.31	80.68	82.52				
		DOP ($\mu g\ L^{-1}$)	3	4.88	5.26	3.80	4.29	5.54	5.68				
		Chl a ($\mu g\ L^{-1}$)	3	0.34	0.29	0.27	0.28	0.40	0.45	Median	0.30	0.32	0.63
		NO_x ($\mu g\ L^{-1}$)	3	1.19	1.05	0.36	0.59	1.76	2.12	Median	0.31		
		PN ($\mu g\ L^{-1}$)	3	10.49	10.40	9.85	10.04	10.92	11.19	Median	14.00	16.00	25.00
		PO_4 ($\mu g\ L^{-1}$)	3	1.75	1.86	0.88	1.21	2.32	2.56	Median	2.00		
		POC ($mg\ L^{-1}$)	3	74.16	81.90	54.33	63.52	86.35	88.57				
		PP ($\mu g\ L^{-1}$)	3	2.21	2.95	0.95	1.62	2.95	2.95	Median	2.00	2.30	3.30
		Secchi (m)	3	10.67	10.50	7.80	8.70	12.60	13.65	Median	13.00		
		SiO_4	3	65.15	73.17	41.32	51.94	79.96	83.35				
		TSS ($mg\ L^{-1}$)	3	0.96	0.84	0.59	0.67	1.22	1.41	Median	1.20	1.60	2.40
	Double(C5)	DIN ($\mu g\ L^{-1}$)	3	2.14	2.66	1.12	1.63	2.74	2.79				
		DOC ($\mu g\ L^{-1}$)	3	907	898	750	799	1012	1069				
		DON ($\mu g\ L^{-1}$)	3	78.97	79.07	76.20	77.16	80.79	81.65				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		DOP (µg L^{-1})	3	4.83	4.96	3.63	4.07	5.61	5.93				
		Chl a (µg L^{-1})	3	0.28	0.29	0.20	0.23	0.33	0.35	Median	0.30	0.32	0.63
		NO_x (µg L^{-1})	3	0.51	0.28	0.28	0.28	0.70	0.91	Median	0.31		
		PN (µg L^{-1})	3	9.88	9.87	9.65	9.72	10.04	10.12	Median	14.00	16.00	25.00
		PO_4 (µg L^{-1})	3	1.68	1.86	1.02	1.30	2.09	2.21	Median	2.00		
		POC (mg L^{-1})	3	58.44	61.31	49.80	53.64	63.82	65.08				
		PP (µg L^{-1})	3	1.70	1.84	1.29	1.48	1.95	2.00	Median	2.00	2.30	3.30
		Secchi (m)	3	9.17	9.00	6.75	7.50	10.80	11.70	Median	13.00		
		SiO_4	3	90.15	88.34	49.03	62.14	117.80	132.52				
		TSS (mg L^{-1})	3	0.63	0.80	0.31	0.48	0.82	0.83	Median	1.20	1.60	2.40
	Green(C11)	DIN (µg L^{-1})	3	3.71	4.55	1.46	2.49	5.10	5.37				
		DOC (µg L^{-1})	3	865	876	813	834	898	910				
		DON (µg L^{-1})	3	86.72	85.69	85.43	85.52	87.72	88.74				
		DOP (µg L^{-1})	3	4.28	4.26	3.35	3.65	4.91	5.23				
		Chl a (µg L^{-1})	3	0.30	0.29	0.13	0.18	0.41	0.46	Median	0.30	0.32	0.63
		NO_x (µg L^{-1})	3	0.91	0.28	0.28	0.28	1.41	1.98	Median	0.31		
		PN (µg L^{-1})	3	9.56	9.11	7.81	8.24	10.79	11.63	Median	14.00	16.00	25.00
		PO_4 (µg L^{-1})	3	1.68	1.86	1.02	1.30	2.09	2.21	Median	2.00		
		POC (mg L^{-1})	3	55.66	52.08	50.66	51.13	59.46	63.16				
		PP (µg L^{-1})	3	1.79	1.78	1.47	1.58	2.00	2.11	Median	2.00	2.30	3.30
		Secchi (m)	3	11.00	11.00	10.10	10.40	11.60	11.90	Median	13.00		
		SiO_4	3	73.50	37.50	22.90	27.77	112.04	149.31				
		TSS (mg L^{-1})	3	0.51	0.62	0.28	0.39	0.64	0.66	Median	1.20	1.60	2.40
	Yorkey's Knob(C6)	DIN (µg L^{-1})	3	5.87	2.28	1.93	2.04	8.97	12.32				
		DOC (µg L^{-1})	3	945	911	771	818	1065	1143				
		DON (µg L^{-1})	3	83.66	80.72	78.48	79.22	87.50	90.89				
		DOP (µg L^{-1})	3	4.77	4.80	3.96	4.24	5.31	5.57				
		Chl a (µg L^{-1})	3	0.50	0.54	0.36	0.42	0.58	0.61	Mean	0.45		
		NO_x (µg L^{-1})	3	3.49	0.88	0.34	0.52	5.94	8.47	Median	0.35		
		PN (µg L^{-1})	3	15.75	14.69	14.01	14.24	17.05	18.23	Mean	20.00		
		PO_4 (µg L^{-1})	3	2.14	1.94	1.31	1.52	2.73	3.12	Median	2.00		
		POC (mg L^{-1})	3	121.65	118.09	108.54	111.73	130.86	137.24				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		PP (µg L⁻¹)	3	4.71	4.77	3.97	4.24	5.19	5.40	Mean	2.80		
		Secchi (m)	3	2.60	2.50	1.42	1.78	3.40	3.85	Mean	10.00		
		SiO_4	3	340.80	233.64	93.65	140.31	519.86	662.97				
		TSS (mg L⁻¹)	3	2.92	3.44	1.92	2.42	3.52	3.57	Mean	2.00		
	Fairlead Buoy (C8)	DIN (µg L⁻¹)	3	4.45	3.68	2.86	3.13	5.61	6.57				
		DOC (µg L⁻¹)	3	923	886	814	838	1001	1059				
		DON (µg L⁻¹)	3	75.68	77.81	66.47	70.25	81.53	83.39				
		DOP (µg L⁻¹)	3	4.85	4.80	3.96	4.24	5.45	5.78				
		Chl a (µg L⁻¹)	3	0.35	0.27	0.24	0.25	0.44	0.52	Mean	0.45		
		NO_x (µg L⁻¹)	3	1.16	0.49	0.30	0.36	1.81	2.47	Median	0.35		
		PN (µg L⁻¹)	3	14.58	16.25	10.91	12.69	16.81	17.09	Mean	20.00		
		PO_4 (µg L⁻¹)	3	1.57	1.47	1.33	1.38	1.75	1.89	Median	2.00		
		POC (mg L⁻¹)	3	105.15	121.10	76.10	91.10	122.38	123.02				
		PP (µg L⁻¹)	3	3.64	4.19	2.41	3.00	4.39	4.49	Mean	2.80		
		Secchi (m)	3	4.17	5.00	1.85	2.90	5.60	5.90	Mean	10.00		
		SiO_4	3	176.83	116.57	70.37	85.77	255.83	325.46				
		TSS (mg L⁻¹)	3	1.36	0.80	0.68	0.72	1.89	2.43	Mean	2.00		
	Fitzroy West (RM1)	DIN (µg L⁻¹)	5	3.35	3.61	1.51	2.69	4.03	4.89				
		DOC (µg L⁻¹)	5	895	891	801	848	947	987				
		DON (µg L⁻¹)	5	78.66	79.67	65.26	73.70	83.17	91.49				
		DOP (µg L⁻¹)	5	4.51	4.41	3.53	4.13	5.06	5.39				
		Chl a (µg L⁻¹)	5	0.35	0.37	0.20	0.23	0.48	0.49	Mean	0.45		
		NO_x (µg L⁻¹)	5	1.01	0.63	0.36	0.41	1.57	2.07	Median	0.35		
		PN (µg L⁻¹)	5	13.35	14.27	10.55	13.05	14.35	14.52	Mean	20.00		
		PO_4 (µg L⁻¹)	5	1.46	1.47	1.11	1.21	1.63	1.86	Median	2.00		
		POC (mg L⁻¹)	5	114.04	113.29	83.11	90.02	131.13	152.66				
		PP (µg L⁻¹)	5	2.17	2.25	1.30	1.42	2.56	3.34	Mean	2.80		
		Secchi (m)	5	7.60	8.00	5.40	6.60	8.40	9.60	Mean	10.00		
		SiO_4	5	122.99	80.48	59.83	69.94	147.47	257.23				
		TSS (mg L⁻¹)	5	0.54	0.47	0.21	0.38	0.78	0.84	Mean	2.00		
		DIN (µg L⁻¹)	3	10.77	6.32	2.91	4.05	16.60	21.74				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
	RM2 (RM2)	DOC (µg L⁻¹)	3										
		DON (µg L⁻¹)	3	83.41	82.98	61.00	68.32	98.40	106.12				
		DOP (µg L⁻¹)	3	0.93	0.90	0.85	0.87	0.98	1.02				
		Chl a (µg L⁻¹)	3	0.40	0.46	0.14	0.24	0.57	0.63	Median	0.30	0.32	0.63
		NO_x (µg L⁻¹)	3	8.15	6.07	2.23	3.51	12.37	15.52	Median	0.31		
		PN (µg L⁻¹)	3	30.27	32.00	25.16	27.44	33.44	34.16	Median	14.00	16.00	25.00
		PO_4 (µg L⁻¹)	3	4.67	5.15	3.74	4.21	5.22	5.25	Median	2.00		
		POC (mg L⁻¹)	3	185.24	199.38	158.67	172.24	201.06	201.90				
		PP (µg L⁻¹)	3	2.06	2.06	1.58	1.74	2.39	2.55	Median	2.00	2.30	3.30
		Secchi (m)	3	7.50	8.00	4.40	5.60	9.50	10.25	Median	13.00		
		SiO_4	3	640.00	700.00	538.00	592.00	700.00	700.00				
		TSS (mg L⁻¹)	3	0.87	0.83	0.33	0.49	1.23	1.43	Median	1.20	1.60	2.40
	RM3 (RM3)	DIN (µg L⁻¹)	8	7.49	5.64	1.53	3.21	10.32	16.94				
		DOC (µg L⁻¹)	8	959	976	874	900	1022	1025				
		DON (µg L⁻¹)	8	84.26	77.44	60.35	65.72	106.91	114.64				
		DOP (µg L⁻¹)	8	3.95	4.30	1.91	2.37	5.26	5.83				
		Chl a (µg L⁻¹)	8	0.59	0.59	0.37	0.47	0.71	0.82	Median	0.30	0.32	0.63
		NO_x (µg L⁻¹)	8	4.26	2.79	0.28	0.35	6.98	11.97	Median	0.31		
		PN (µg L⁻¹)	8	23.90	22.14	12.41	15.20	34.16	37.79	Median	14.00	16.00	25.00
		PO_4 (µg L⁻¹)	8	2.77	2.09	1.19	1.39	4.42	5.13	Median	2.00		
		POC (mg L⁻¹)	8	187.07	151.21	100.66	122.34	277.77	309.56				
		PP (µg L⁻¹)	8	3.97	2.80	1.34	2.06	6.46	8.41	Median	2.00	2.30	3.30
		Secchi (m)	8	7.56	8.00	4.05	6.00	9.80	10.00	Median	13.00		
		SiO_4	8	325.07	310.39	33.90	132.73	548.00	603.25				
		TSS (mg L⁻¹)	8	0.98	1.11	0.25	0.68	1.34	1.56	Median	1.20	1.60	2.40
	RM4 (RM4)	DIN (µg L⁻¹)	3	15.59	15.55	4.03	7.87	23.30	27.18				
		DOC (µg L⁻¹)	3										
		DON (µg L⁻¹)	3	82.58	95.46	57.10	69.88	97.86	99.06				
		DOP (µg L⁻¹)	3	1.36	1.50	1.09	1.23	1.52	1.53				
		Chl a (µg L⁻¹)	3	0.61	0.65	0.48	0.54	0.69	0.71	Mean	0.45		
		NO_x (µg L⁻¹)	3	10.69	7.87	2.79	4.48	16.34	20.57	Median	0.35		
		PN (µg L⁻¹)	3	33.07	34.80	29.40	31.20	35.28	35.52	Mean	20.00		

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		PO_4 (µg L⁻¹)	3	4.92	5.38	3.73	4.28	5.65	5.78	Median	2.00		
		POC (mg L⁻¹)	3	186.97	190.97	153.50	165.99	208.75	217.64				
		PP (µg L⁻¹)	3	4.28	2.75	2.63	2.67	5.59	7.01	Mean	2.80		
		Secchi (m)	3	6.17	6.00	2.85	3.90	8.40	9.60	Mean	10.00		
		SiO_4	3	1083.33	790.00	736.00	754.00	1354.00	1636.00				
		TSS (mg L⁻¹)	3	1.36	0.50	0.29	0.36	2.18	3.02	Mean	2.00		
		DIN (µg L⁻¹)	3	9.58	5.85	4.73	5.11	13.31	17.05				
		DOC (µg L⁻¹)	3										
		DON (µg L⁻¹)	3	80.82	78.00	63.88	68.59	92.49	99.74				
		DOP (µg L⁻¹)	3	1.10	1.30	0.53	0.78	1.45	1.52				
		Chl a (µg L⁻¹)	3	0.65	0.29	0.12	0.18	1.05	1.43	Median	0.30	0.32	0.63
		NO_x (µg L⁻¹)	3	7.23	5.60	4.48	4.86	9.28	11.13	Median	0.31		
	High East (RM5)	PN (µg L⁻¹)	3	35.20	33.20	24.92	27.68	42.32	46.88	Median	14.00	16.00	25.00
		PO_4 (µg L⁻¹)	3	4.79	5.18	3.99	4.38	5.27	5.31	Median	2.00		
		POC (mg L⁻¹)	3	205.39	188.17	164.39	172.32	235.02	258.44				
		PP (µg L⁻¹)	3	3.46	2.78	1.32	1.81	4.97	6.06	Median	2.00	2.30	3.30
		Secchi (m)	3	5.67	6.50	2.90	4.10	7.40	7.85	Median	13.00		
		SiO_4	3	1006.67	1190.00	614.00	806.00	1244.00	1271.00				
		TSS (mg L⁻¹)	3	1.54	1.20	0.96	1.04	1.98	2.37	Median	1.20	1.60	2.40
		DIN (µg L⁻¹)	8	9.05	7.65	1.97	2.48	15.89	18.45				
		DOC (µg L⁻¹)	8	937	968	816	868	1001	1033				
		DON (µg L⁻¹)	8	80.83	83.67	63.45	67.88	92.19	95.59				
		DOP (µg L⁻¹)	8	3.49	3.91	1.07	1.59	5.14	5.57				
		Chl a (µg L⁻¹)	8	0.47	0.48	0.19	0.27	0.60	0.78	Mean	0.45		
		NO_x (µg L⁻¹)	8	4.81	3.65	0.28	1.05	8.77	11.95	Median	0.35		
	High West (RM8)	PN (µg L⁻¹)	8	22.67	17.76	9.92	14.34	34.52	39.46	Mean	20.00		
		PO_4 (µg L⁻¹)	8	2.90	1.82	1.55	1.70	4.56	5.81	Median	2.00		
		POC (mg L⁻¹)	8	172.08	179.47	73.69	142.83	212.39	248.75				
		PP (µg L⁻¹)	8	3.44	2.37	1.03	1.44	4.00	9.05	Mean	2.80		
		Secchi (m)	8	6.38	6.25	3.38	5.40	7.00	9.60	Mean	10.00		
		SiO_4	8	433.78	409.76	44.05	175.79	563.02	956.25				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		TSS (mg L^{-1})	8	1.25	1.01	0.44	0.69	1.54	2.56	Mean	2.00		
	Palmer Point (RM9)	DIN (µg L^{-1})	3	21.80	25.25	8.15	13.85	30.44	33.03				
		DOC (µg L^{-1})	3										
		DON (µg L^{-1})	3	69.98	75.12	58.95	64.34	76.64	77.40				
		DOP (µg L^{-1})	3	0.76	0.68	0.56	0.60	0.91	1.02				
		Chl a (µg L^{-1})	3	0.64	0.65	0.39	0.48	0.81	0.88	Mean	0.45		
		NO_x (µg L^{-1})	3	18.91	18.59	6.89	10.79	26.97	31.16	Median	0.35		
		PN (µg L^{-1})	3	33.34	31.20	24.00	26.40	39.84	44.16	Mean	20.00		
		PO_4 (µg L^{-1})	3	4.73	5.18	3.74	4.22	5.32	5.39	Median	2.00		
		POC (mg L^{-1})	3	224.21	195.38	143.49	160.79	281.86	325.10				
		PP (µg L^{-1})	3	6.27	5.41	4.14	4.56	7.80	9.00	Mean	2.80		
		Secchi (m)	3	4.83	5.50	2.35	3.40	6.40	6.85	Mean	10.00		
		SiO_4	3	1793.33	860.00	410.00	560.00	2840.00	3830.00				
		TSS (mg L^{-1})	3	1.94	2.00	0.68	1.12	2.78	3.17	Mean	2.00		
	Normanby Island (RM6)	DIN (µg L^{-1})	3	10.45	4.21	1.53	2.42	17.23	23.74				
		DOC (µg L^{-1})	3										
		DON (µg L^{-1})	3	80.72	79.18	73.97	75.71	85.43	88.55				
		DOP (µg L^{-1})	3	1.45	0.92	0.87	0.89	1.91	2.40				
		Chl a (µg L^{-1})	3	0.91	0.85	0.32	0.50	1.32	1.55	Median	0.30	0.32	0.63
		NO_x (µg L^{-1})	3	7.87	3.96	1.28	2.17	12.79	17.20	Median	0.31		
		PN (µg L^{-1})	3	33.47	31.60	30.88	31.12	35.44	37.36	Median	14.00	16.00	25.00
		PO_4 (µg L^{-1})	3	4.79	4.97	4.14	4.41	5.19	5.31	Median	2.00		
		POC (mg L^{-1})	3	203.79	198.98	187.09	191.06	215.56	223.85				
		PP (µg L^{-1})	3	5.41	4.78	3.33	3.81	6.88	7.93	Median	2.00	2.30	3.30
		Secchi (m)	3	7.67	8.00	4.40	5.60	9.80	10.70	Median	13.00		
		SiO_4	3	896.67	840.00	471.00	594.00	1188.00	1362.00				
		TSS (mg L^{-1})	3	1.03	1.20	0.57	0.78	1.32	1.38	Median	1.20	1.60	2.40
	Russell-Mulgrave Mouth Mooring (RM10)	DIN (µg L^{-1})	8	16.82	9.66	2.35	5.18	25.48	45.70				
		DOC (µg L^{-1})	8	1018	1011	936	990	1056	1096				
		DON (µg L^{-1})	8	93.34	93.78	65.71	78.15	109.66	120.32				
		DOP (µg L^{-1})	8	3.29	4.22	0.94	0.99	4.97	5.03				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		Chl a (µg L^{-1})	8	0.64	0.63	0.32	0.42	0.77	1.10	Mean	0.45		
		NO_x (µg L^{-1})	8	12.56	5.43	0.34	1.91	21.08	38.96	Median	0.35		
		PN (µg L^{-1})	8	38.00	31.64	17.74	22.43	51.60	72.33	Mean	20.00		
		PO_4 (µg L^{-1})	8	3.19	2.52	1.53	1.63	4.79	6.14	Median	2.00		
		POC (mg L^{-1})	8	324.86	252.95	163.48	197.40	394.83	621.88				
		PP (µg L^{-1})	8	6.17	4.15	2.77	3.22	10.40	12.02	Mean	2.80		
		Secchi (m)	8	4.12	4.00	1.70	3.20	5.60	6.32	Mean	10.00		
		SiO_4	8	1087.86	491.01	62.09	166.76	2191.00	3338.00				
		TSS (mg L^{-1})	8	2.67	1.89	0.66	1.24	4.42	6.38	Mean	2.00		
	Russell Mulgrave Mouth (RM11)	DIN (µg L^{-1})	3	97.30	97.30	97.28	97.29	97.32	97.32				
		DOC (µg L^{-1})	3										
		DON (µg L^{-1})	3	82.71	82.71	81.79	82.09	83.32	83.63				
		DOP (µg L^{-1})	3	1.14	0.78	0.71	0.73	1.47	1.82				
		Chl a (µg L^{-1})	3	0.92	1.17	0.38	0.64	1.25	1.30				
		NO_x (µg L^{-1})	3	118.11	90.91	87.41	88.58	142.21	167.85				
		PN (µg L^{-1})	3	58.80	60.00	54.60	56.40	61.44	62.16				
		PO_4 (µg L^{-1})	3	5.00	5.32	4.07	4.49	5.57	5.69				
		POC (mg L^{-1})	3	450.95	454.82	434.64	441.36	461.30	464.55				
		PP (µg L^{-1})	3	18.34	17.32	13.29	14.63	21.85	24.12				
		Secchi (m)	3	1.17	1.50	0.60	0.90	1.50	1.50				
		SiO_4	3	8306.67	8510.00	7178.00	7622.00	9032.00	9293.00				
		TSS (mg L^{-1})	3	3.40	3.50	2.33	2.72	4.10	4.40				
	Franklands West (RM7)	DIN (µg L^{-1})	8	7.96	7.03	1.75	3.35	8.89	19.14				
		DOC (µg L^{-1})	8	987	971	874	943	1049	1098				
		DON (µg L^{-1})	8	82.87	81.86	64.02	74.90	92.63	101.63				
		DOP (µg L^{-1})	8	3.67	3.99	1.33	2.27	4.96	5.36				
		Chl a (µg L^{-1})	8	0.52	0.46	0.20	0.30	0.67	0.97	Median	0.30	0.32	0.63
		NO_x (µg L^{-1})	8	4.58	2.61	0.39	0.97	5.91	13.74	Median	0.31		
		PN (µg L^{-1})	8	24.14	20.77	12.15	15.29	34.96	40.61	Median	14.00	16.00	25.00
		PO_4 (µg L^{-1})	8	2.74	1.97	1.19	1.39	4.42	5.22	Median	2.00		
		POC (mg L^{-1})	8	183.06	187.67	97.31	129.43	224.21	270.22				
		PP (µg L^{-1})	8	4.25	3.14	1.54	1.75	7.32	8.23	Median	2.00	2.30	3.30

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		Secchi (m)	8	8.56	8.75	5.53	6.70	10.60	11.32	Median	13.00		
		SiO_4	8	268.40	280.00	98.86	179.43	306.22	499.60				
		TSS (mg L^{-1})	8	1.16	0.80	0.22	0.42	1.35	3.07	Median	1.20	1.60	2.40
	Russell Mulgrave Junction (RM12)	DIN (µg L^{-1})	3	165.37	145.28	111.11	122.50	204.22	233.68				
		DOC (µg L^{-1})	3										
		DON (µg L^{-1})	3	34.31	50.69	-3.47	14.58	57.32	60.63				
		DOP (µg L^{-1})	3	0.82	0.74	0.14	0.34	1.29	1.57				
		Chl a (µg L^{-1})	3	0.63	0.72	0.42	0.52	0.76	0.77	Median	2.00		
		NO_x (µg L^{-1})	3	149.43	135.86	100.90	112.55	183.59	207.45	Median	15.00		
		PO_4 (µg L^{-1})	3	4.81	5.24	3.83	4.30	5.41	5.49	Median	3.00		
		POC (mg L^{-1})	3	414.51	419.18	353.60	375.46	454.50	472.15				
		Secchi (m)	3	1.67	1.50	1.05	1.20	2.10	2.40	Median	1.50		
		SiO_4	3	9613.33	9170.00	8270.00	8570.00	10568.00	11267.00				
		TSS (mg L^{-1})	3	3.07	4.00	0.85	1.90	4.42	4.63	Median	7.00		
	King (TUL1)	DIN (µg L^{-1})											
		DOC (µg L^{-1})											
		DON (µg L^{-1})											
		DOP (µg L^{-1})											
		Chl a (µg L^{-1})								Mean	0.45		
		NO_x(µg L^{-1})								Median	0.35		
		PN (µg L^{-1})								Mean	20.00		
		PO_4(µg L^{-1})								Median	2.00		
		POC (mg L^{-1})											
		PP (µg L^{-1})								Mean	2.80		
		Secchi (m)								Mean	10.00		
		SiO_4											
		TSS (mg L^{-1})								Mean	2.00		
	Clump Point East (TUL2)	DIN (µg L^{-1})	7	3.24	2.35	1.20	1.25	5.04	6.64				
		DOC (µg L^{-1})	7	982	991	903	948	1011	1056				
		DON (µg L^{-1})	7	88.61	79.53	74.00	74.97	107.18	118.29				
		DOP (µg L^{-1})	7	3.63	4.18	1.67	2.17	4.85	4.99				
		Chl a (µg L^{-1})	7	0.67	0.54	0.19	0.24	0.92	1.53	Median	0.30	0.32	0.63

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		NO$_x$ (μg L^{-1})	7	1.89	1.36	0.28	0.32	2.92	4.85	Median	0.31		
		PN (μg L^{-1})	7	23.07	19.34	11.31	13.23	27.05	43.78	Median	14.00	16.00	25.00
		PO$_4$ (μg L^{-1})	7	2.49	1.86	1.16	1.30	3.59	5.04	Median	2.00		
		POC (mg L^{-1})	7	184.56	157.77	100.74	116.24	195.01	344.79				
		PP (μg L^{-1})	7	3.95	2.38	1.54	1.92	4.65	10.01	Median	2.00	2.30	3.30
		Secchi (m)	7	8.79	9.00	4.90	7.40	10.80	11.35	Median	13.00		
		SiO$_4$	7	275.72	245.37	39.28	47.32	517.24	535.96				
		TSS (mg L^{-1})	7	0.49	0.30	0.07	0.16	0.76	1.23	Median	1.20	1.60	2.40
	Dunk North (TUL3)	DIN (μg L^{-1})	7	8.38	4.37	1.28	2.04	9.82	24.65				
		DOC (μg L^{-1})	7	1012	1036	830	879	1153	1165				
		DON (μg L^{-1})	7	89.68	83.84	55.27	76.28	116.81	122.37				
		DOP (μg L^{-1})	7	3.90	4.34	1.89	2.40	5.06	5.40				
		Chl a (μg L^{-1})	7	0.50	0.36	0.29	0.32	0.72	0.88	Mean	0.45		
		NO$_x$ (μg L^{-1})	7	4.62	3.12	0.28	0.29	4.81	15.19	Median	0.35		
		PN (μg L^{-1})	7	22.46	18.62	13.72	14.30	31.45	40.34	Mean	20.00		
		PO$_4$ (μg L^{-1})	7	3.32	2.94	1.18	1.46	5.34	6.44	Median	2.00		
		POC (mg L^{-1})	7	177.66	183.14	120.63	135.39	207.06	242.80				
		PP (μg L^{-1})	7	3.67	2.75	2.04	2.52	5.23	6.59	Mean	2.80		
		Secchi (m)	7	4.76	6.00	2.59	2.94	6.00	6.35	Mean	10.00		
		SiO$_4$	7	392.92	456.74	81.92	157.67	588.26	644.85				
		TSS (mg L^{-1})	7	2.45	0.76	0.62	0.63	1.94	8.18	Mean	2.00		
	Mission Beach South (TUL4)	DIN (μg L^{-1})	2	11.35	11.35	8.00	9.12	13.58	14.70				
		DOC (μg L^{-1})	2										
		DON (μg L^{-1})	2	105.91	105.91	86.98	93.29	118.53	124.84				
		DOP (μg L^{-1})	2	1.47	1.47	0.95	1.12	1.82	2.00				
		Chl a (μg L^{-1})	2	0.73	0.73	0.49	0.57	0.90	0.98	Mean	0.45		
		NO$_x$ (μg L^{-1})	2	9.98	9.98	7.32	8.20	11.75	12.64	Median	0.35		
		PN (μg L^{-1})	2	35.20	35.20	25.84	28.96	41.44	44.56	Mean	20.00		
		PO$_4$ (μg L^{-1})	2	4.74	4.74	3.42	3.86	5.62	6.06	Median	2.00		
		POC (mg L^{-1})	2	248.83	248.83	219.82	229.49	268.17	277.83				
		PP (μg L^{-1})	2	3.24	3.24	2.83	2.97	3.51	3.65	Mean	2.80		

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		Secchi (m)	2	4.00	4.00	3.10	3.40	4.60	4.90	Mean	10.00		
		SiO_4	2	1210.00	1210.00	1192.00	1198.00	1222.00	1228.00				
		TSS (mg L^{-1})	2	0.61	0.61	0.42	0.49	0.74	0.81	Mean	2.00		
	Dunk South (TUL5)	DIN (µg L^{-1})	7	5.81	5.92	1.37	2.39	9.34	11.51				
		DOC (µg L^{-1})	7	1043	1016	895	959	1142	1203				
		DON (µg L^{-1})	7	93.68	84.22	65.21	76.83	116.13	119.42				
		DOP (µg L^{-1})	7	3.93	4.41	1.72	3.30	4.85	5.33				
		Chl a (µg L^{-1})	7	0.70	0.69	0.26	0.35	0.85	1.36	Mean	0.45		
		NO_x (µg L^{-1})	7	3.11	1.05	0.28	0.35	5.78	7.65	Median	0.35		
		PN (µg L^{-1})	7	24.79	21.01	12.01	13.68	31.30	47.08	Mean	20.00		
		PO_4 (µg L^{-1})	7	2.50	2.25	1.26	1.36	2.76	4.85	Median	2.00		
		POC (mg L^{-1})	7	211.05	182.70	105.48	127.91	217.34	415.98				
		PP (µg L^{-1})	7	3.86	3.99	1.69	2.57	5.53	5.66	Mean	2.80		
		Secchi (m)	7	5.29	5.50	3.65	4.00	6.80	7.00	Mean	10.00		
		SiO_4	7	445.72	371.00	68.27	111.97	797.24	913.21				
		TSS (mg L^{-1})	7	2.45	1.87	0.58	1.32	3.69	4.70	Mean	2.00		
	Between Tam O'Shanter and Timana (TUL6)	DIN (µg L^{-1})	7	11.52	5.77	1.27	2.33	24.18	30.15				
		DOC (µg L^{-1})	7	1185	1234	887	912	1431	1461				
		DON (µg L^{-1})	7	103.69	105.74	55.30	82.70	128.69	147.13				
		DOP (µg L^{-1})	7	3.97	3.95	1.83	2.53	4.80	6.18				
		Chl a (µg L^{-1})	7	0.78	0.61	0.32	0.39	0.99	1.48	Mean	0.45		
		NO_x (µg L^{-1})	7	8.29	4.88	0.36	1.01	16.03	23.00	Median	0.35		
		PN (µg L^{-1})	7	32.18	31.61	14.78	18.45	44.12	48.16	Mean	20.00		
		PO_4 (µg L^{-1})	7	3.15	2.79	1.31	1.49	4.23	6.29	Median	2.00		
		POC (mg L^{-1})	7	259.92	275.45	141.06	160.73	333.78	402.60				
		PP (µg L^{-1})	7	3.84	2.69	2.15	2.48	5.62	6.34	Mean	2.80		
		Secchi (m)	7	3.21	3.50	2.00	2.10	4.00	4.35	Mean	10.00		
		SiO_4	7	818.98	875.00	105.06	293.25	1226.29	1363.76				
		TSS (mg L^{-1})	7	2.50	1.94	0.99	1.28	3.78	4.77	Mean	2.00		
	Hull Mouth (TUL7)	DIN (µg L^{-1})	2	13.12	13.12	9.01	10.38	15.86	17.23				
		DOC (µg L^{-1})	2										

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		DON (µg L⁻¹)	2	135.39	135.39	123.75	127.63	143.15	147.03				
		DOP (µg L⁻¹)	2	0.64	0.64	0.62	0.63	0.66	0.67				
		Chl a (µg L⁻¹)	2	1.15	1.15	1.14	1.15	1.16	1.17	Median	1.10		
		NO_x (µg L⁻¹)	2	11.25	11.25	7.55	8.78	13.71	14.94	Median	3.00		
		PO_4 (µg L⁻¹)	2	4.81	4.81	4.59	4.66	4.96	5.03	Median	3.00		
		POC (mg L⁻¹)	2	329.10	329.10	329.10	329.10	329.10	329.10				
		Secchi (m)	2	1.50	1.50	1.50	1.50	1.50	1.50	Median	1.60		
		SiO_4	2	1655.00	1655.00	1587.50	1610.00	1700.00	1722.50				
		TSS (mg L⁻¹)	2	7.60	7.60	2.74	4.36	10.84	12.46	Median	5.00		
	Bedarra (TUL8)	DIN (µg L⁻¹)	7	7.40	4.83	0.92	1.02	9.86	22.57				
		DOC (µg L⁻¹)	7	1130	1109	859	952	1307	1421				
		DON (µg L⁻¹)	7	105.75	85.72	57.05	83.25	124.80	173.52				
		DOP (µg L⁻¹)	7	3.99	4.41	2.16	2.86	4.88	5.44				
		Chl a (µg L⁻¹)	7	0.78	0.56	0.31	0.38	0.84	1.78	Mean	0.45		
		NO_x (µg L⁻¹)	7	5.56	0.32	0.28	0.28	10.61	18.61	Median	0.35		
		PN (µg L⁻¹)	7	26.67	24.80	12.83	14.30	40.89	44.76	Mean	20.00		
		PO_4 (µg L⁻¹)	7	2.86	2.01	1.08	1.36	4.22	5.38	Median	2.00		
		POC (mg L⁻¹)	7	207.02	198.57	120.79	137.66	258.76	324.84				
		PP (µg L⁻¹)	7	4.74	4.15	1.83	2.75	4.78	10.15	Mean	2.80		
		Secchi (m)	7	4.50	4.50	2.80	3.70	5.00	6.05	Mean	10.00		
		SiO_4	7	582.46	516.36	84.72	155.25	994.00	1300.12				
		TSS (mg L⁻¹)	7	2.31	2.30	0.83	1.76	3.32	3.56	Mean	2.00		
	Tully River (TUL11)	DIN (µg L⁻¹)	2	183.90	183.90	108.66	133.74	234.06	259.14				
		DOC (µg L⁻¹)	2										
		DON (µg L⁻¹)	2	119.12	119.12	109.76	112.88	125.37	128.49				
		DOP (µg L⁻¹)	2	1.02	1.02	0.70	0.81	1.24	1.34				
		Chl a (µg L⁻¹)	2	0.46	0.46	0.40	0.42	0.49	0.51	Median	2.00		
		NO_x (µg L⁻¹)	2	172.26	172.26	101.39	125.01	219.50	243.12	Median	15.00		
		PO_4 (µg L⁻¹)	2	5.44	5.44	3.66	4.26	6.63	7.23	Median	3.00		
		POC (mg L⁻¹)	2	532.69	532.69	462.96	486.21	579.17	602.41				
		Secchi (m)	2	0.50	0.50	0.50	0.50	0.50	0.50	Median	1.50		

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		SiO_4	2	11100.00	11100.00	10470.00	10680.00	11520.00	11730.00				
		TSS (mg L^{-1})	2	9.80	9.80	6.92	7.88	11.72	12.68	Median	7.00		
	Tully Mouth Mooring (TUL10)	DIN (µg L^{-1})	7	11.70	10.44	0.88	2.03	20.67	23.37				
		DOC (µg L^{-1})	7	1215	1274	881	980	1463	1477				
		DON (µg L^{-1})	7	109.06	107.88	53.05	83.10	147.52	155.24				
		DOP (µg L^{-1})	7	4.05	3.87	2.55	3.06	5.05	5.57				
		Chl a (µg L^{-1})	7	1.32	1.11	0.30	0.53	1.78	2.69	Median	1.10		
		NO_x (µg L^{-1})	7	8.63	5.68	0.28	0.81	17.03	17.36	Median	3.00		
		PO_4 (µg L^{-1})	7	2.80	2.40	1.18	1.25	3.96	5.30	Median	3.00		
		POC (mg L^{-1})	7	298.68	291.53	147.72	181.60	400.94	443.86				
		Secchi (m)	7	2.79	2.50	0.80	1.60	3.40	5.60	Median	1.60		
		SiO_4	7	1040.78	1270.51	108.55	316.28	1635.89	1696.21				
		TSS (mg L^{-1})	7	3.54	3.50	1.41	2.53	4.51	5.86	Median	5.00		
	Triplets (TUL9)	DIN (µg L^{-1})	1	18.54	18.54	18.54	18.54	18.54	18.54				
		DOC (µg L^{-1})	1										
		DON (µg L^{-1})	1	144.47	144.47	144.47	144.47	144.47	144.47				
		DOP (µg L^{-1})	1	0.57	0.57	0.57	0.57	0.57	0.57				
		Chl a (µg L^{-1})	1	0.75	0.75	0.75	0.75	0.75	0.75	Mean	0.45		
		NO_x (µg L^{-1})	1	17.95	17.95	17.95	17.95	17.95	17.95	Median	0.35		
		PN (µg L^{-1})	1	46.80	46.80	46.80	46.80	46.80	46.80	Mean	20.00		
		PO_4 (µg L^{-1})	1	5.08	5.08	5.08	5.08	5.08	5.08	Median	2.00		
		POC (mg L^{-1})	1	262.64	262.64	262.64	262.64	262.64	262.64				
		PP (µg L^{-1})	1	7.39	7.39	7.39	7.39	7.39	7.39	Mean	2.80		
		Secchi (m)	1	5.50	5.50	5.50	5.50	5.50	5.50	Mean	10.00		
		SiO_4	1	2270.00	2270.00	2270.00	2270.00	2270.00	2270.00				
		TSS (mg L^{-1})	1	0.05	0.05	0.05	0.05	0.05	0.05	Mean	2.00		
Burdekin	Palms West (BUR1)	DIN (µg L^{-1})	6	9.60	8.23	2.06	2.35	15.75	19.77				
		DOC (µg L^{-1})	6	983	983	843	903	1091	1106				
		DON (µg L^{-1})	6	87.68	81.66	74.62	75.12	89.94	114.93				
		DOP (µg L^{-1})	6	3.39	3.42	1.45	1.88	5.03	5.21				
		Chl a (µg L^{-1})	6	0.58	0.57	0.30	0.51	0.72	0.84	Median	0.35	0.32	0.63

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		NO_x (µg L^{-1})	6	6.03	2.27	0.46	0.98	10.61	17.47	Median	0.28		
		PN (µg L^{-1})	6	36.14	29.04	14.27	17.70	61.40	65.23	Median	12.00	16.00	25.00
		PO_4 (µg L^{-1})	6	2.73	2.71	0.48	1.01	4.02	5.22	Median	1.00		
		POC (mg L^{-1})	6	322.96	259.33	113.03	124.57	583.73	597.16				
		PP (µg L^{-1})	6	3.29	3.92	1.77	2.13	4.24	4.40	Median	2.20	2.30	3.30
		Secchi (m)	6	6.37	5.10	3.50	3.50	7.00	12.25	Mean	10.00		
		SiO_4	6	135.15	131.25	25.65	43.61	200.14	263.79				
		TSS (mg L^{-1})	6	0.86	0.79	0.34	0.63	1.20	1.43	Median	1.20	1.60	2.40
	Pandora (BUR2)	DIN (µg L^{-1})	6	8.55	6.59	2.80	3.54	14.52	16.75				
		DOC (µg L^{-1})	6	1096	1095	963	971	1179	1252				
		DON (µg L^{-1})	6	93.54	92.06	78.80	79.77	105.50	111.42				
		DOP (µg L^{-1})	6	3.18	3.46	1.10	1.30	4.57	5.09				
		Chl a (µg L^{-1})	6	0.50	0.53	0.28	0.35	0.64	0.66	Median	0.35	0.32	0.63
		NO_x (µg L^{-1})	6	5.44	2.58	0.28	0.28	10.42	14.98	Median	0.28		
		PN (µg L^{-1})	6	65.88	42.19	18.74	24.86	99.01	152.50	Median	12.00	16.00	25.00
		PO_4 (µg L^{-1})	6	3.15	2.84	1.03	1.32	5.03	5.73	Median	1.00		
		POC (mg L^{-1})	6	441.72	373.25	127.29	176.34	550.37	937.22				
		PP (µg L^{-1})	6	6.22	5.67	1.74	1.80	9.77	12.13	Median	2.20	2.30	3.30
		Secchi (m)	6	5.70	4.00	2.67	3.20	9.50	10.62	Mean	10.00		
		SiO_4	6	240.28	198.75	58.71	68.61	382.66	498.79				
		TSS (mg L^{-1})	6	1.79	1.38	0.46	0.59	3.20	3.61	Median	1.20	1.60	2.40
	Magnetic (BUR4)	DIN (µg L^{-1})	6	11.63	8.49	2.73	3.89	19.45	25.21				
		DOC (µg L^{-1})	6	1098	1082	969	1008	1214	1238				
		DON (µg L^{-1})	6	81.12	82.01	61.39	68.08	92.87	100.14				
		DOP (µg L^{-1})	6	3.29	3.22	1.43	2.00	4.49	5.30				
		Chl a (µg L^{-1})	6	1.13	0.75	0.46	0.51	0.83	2.82	Median	0.59	0.32	0.63
		NO_x (µg L^{-1})	6	8.95	4.97	1.07	2.38	18.25	21.42	Median	0.28		
		PN (µg L^{-1})	6	48.95	47.80	16.28	23.68	70.93	84.98	Median	17.00	16.00	25.00
		PO_4 (µg L^{-1})	6	3.23	2.71	1.45	1.63	4.12	6.14	Median	1.00		
		POC (mg L^{-1})	6	424.40	394.15	127.17	177.82	634.61	785.22				
		PP (µg L^{-1})	6	6.56	5.02	2.85	2.96	9.54	12.43	Mean	2.80		

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		Secchi (m)	6	3.35	3.30	2.12	2.50	4.50	4.50	Median	4.00		
		SiO_4	6	287.81	271.25	82.34	104.57	399.86	553.72				
		TSS (mg L^{-1})	6	2.77	2.67	1.16	1.65	3.40	4.76	Median	1.90	1.60	2.40
	Cape Cleveland (BUR6)	DIN (µg L^{-1})	3	15.34	17.90	10.71	13.11	18.09	18.19				
		DOC (µg L^{-1})	3	1178	1131	1095	1107	1239	1293				
		DON (µg L^{-1})	3	92.53	99.10	76.24	83.86	102.51	104.22				
		DOP (µg L^{-1})	3	1.67	1.69	1.10	1.29	2.05	2.23				
		Chl a (µg L^{-1})	3	3.33	0.72	0.59	0.64	5.50	7.89	Mean	0.45		
		NO_x (µg L^{-1})	3	11.51	13.74	4.56	7.62	15.85	16.90	Median	1.00		
		PN (µg L^{-1})	3	92.26	66.67	62.11	63.63	115.77	140.31	Median	13.00	16.00	25.00
		PO_4 (µg L^{-1})	3	4.01	3.66	3.01	3.22	4.72	5.25	Median	2.00		
		POC (mg L^{-1})	3	712.98	678.62	574.13	608.96	810.12	875.87				
		PP (µg L^{-1})	3	15.63	15.63	6.00	9.21	22.05	25.25	Median	2.10	2.30	3.30
		Secchi (m)	3	2.50	2.50	2.05	2.20	2.80	2.95	Mean	10.00		
		SiO_4	3	240.00	200.00	92.00	128.00	344.00	416.00				
		TSS (mg L^{-1})	3	7.07	3.50	1.88	2.42	11.00	14.75	Median	1.20	1.60	2.40
	Cleveland Bay (BUR5)	DIN (µg L^{-1})	3	14.76	16.08	11.75	13.19	16.59	16.85				
		DOC (µg L^{-1})	3	1244	1251	1062	1125	1365	1422				
		DON (µg L^{-1})	3	105.55	115.74	85.35	95.48	117.65	118.61				
		DOP (µg L^{-1})	3	2.72	3.02	2.07	2.39	3.10	3.15				
		Chl a (µg L^{-1})	3	0.73	0.85	0.18	0.40	1.09	1.21	Median	0.60	0.32	0.63
		NO_x (µg L^{-1})	3	12.16	12.74	8.91	10.19	14.25	15.00	Median	0.50		
		PN (µg L^{-1})	3	70.37	59.93	58.22	58.79	79.87	89.83	Mean	20.00		
		PO_4 (µg L^{-1})	3	4.11	3.55	3.25	3.35	4.75	5.35	Median	2.00		
		POC (mg L^{-1})	3	521.58	496.52	416.89	443.43	594.72	643.83				
		PP (µg L^{-1})	3	6.34	6.34	6.34	6.34	6.34	6.34	Mean	2.80		
		Secchi (m)	3	1.33	1.20	0.84	0.96	1.68	1.92	Median	3.00		
		SiO_4	3	416.67	330.00	249.00	276.00	540.00	645.00				
		TSS (mg L^{-1})	3	4.55	4.25	2.14	2.84	6.20	7.17	Median	5.00	1.60	2.40
	Haughton (BUR7)	DIN (µg L^{-1})	5	11.01	6.65	3.16	5.20	17.88	22.14				
		DOC (µg L^{-1})	5	1101	1126	1013	1051	1141	1171				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		DON (µg L⁻¹)	5	95.89	90.48	86.51	87.29	105.05	110.11				
		DOP (µg L⁻¹)	5	3.10	2.49	1.06	1.17	5.36	5.40				
		Chl a (µg L⁻¹)	5	0.98	0.94	0.40	0.55	1.21	1.79	Mean	0.45		
		NO_x (µg L⁻¹)	5	8.12	2.80	0.74	2.12	16.14	18.80	Median	1.00		
		PN (µg L⁻¹)	5	74.06	77.68	33.10	47.45	102.12	109.96	Median	13.00	16.00	25.00
		PO_4 (µg L⁻¹)	5	3.06	3.25	0.94	1.46	4.32	5.34	Median	2.00		
		POC (mg L⁻¹)	5	659.81	578.08	288.22	388.07	898.86	1145.84				
		PP (µg L⁻¹)	5	4.50	4.06	2.63	3.36	5.46	6.97	Median	2.10	2.30	3.30
		Secchi (m)	5	3.40	3.10	2.52	2.88	3.80	4.70	Mean	10.00		
		SiO_4	5	219.05	280.83	62.54	86.88	304.00	361.00				
		TSS (mg L⁻¹)	5	2.49	2.61	1.36	2.29	2.83	3.37	Median	1.20	1.60	2.40
	Yongala (BUR10)	DIN (µg L⁻¹)	8	4.02	4.11	1.73	2.77	4.66	6.81				
		DOC (µg L⁻¹)	8	998	992	789	925	1086	1184				
		DON (µg L⁻¹)	8	107.12	100.42	77.88	82.51	136.33	139.43				
		DOP (µg L⁻¹)	8	5.57	5.57	3.98	5.06	6.35	6.62				
		Chl a (µg L⁻¹)	8	0.31	0.24	0.14	0.18	0.39	0.64	Median	0.33	0.32	0.63
		NO_x (µg L⁻¹)	8	0.84	0.58	0.28	0.28	1.06	2.16	Median	0.28		
		PN (µg L⁻¹)	8	16.58	15.46	11.63	13.03	20.19	23.13	Median	14.00	16.00	25.00
		PO_4 (µg L⁻¹)	8	1.55	1.59	0.67	0.81	2.18	2.60	Median	1.00		
		POC (mg L⁻¹)	8	144.51	145.96	89.03	100.65	170.69	211.23				
		PP (µg L⁻¹)	8	1.64	1.60	1.23	1.36	1.91	2.16	Median	2.00	2.30	3.30
		Secchi (m)	8	11.00	12.00	5.90	8.60	13.00	14.40	Mean	10.00		
		SiO_4	8	79.47	34.59	16.18	25.30	76.38	272.92				
		TSS (mg L⁻¹)	8	0.73	0.23	0.03	0.12	0.90	2.55	Median	0.80	1.60	2.40
	Haughton River Mouth (BUR8)	DIN (µg L⁻¹)	2	11.85	11.85	7.09	8.67	15.02	16.61				
		DOC (µg L⁻¹)	2	1221	1221	1176	1191	1251	1266				
		DON (µg L⁻¹)	2	84.21	84.21	83.00	83.40	85.01	85.41				
		DOP (µg L⁻¹)	2	1.90	1.90	1.05	1.33	2.46	2.74				
		Chl a (µg L⁻¹)	2	0.78	0.78	0.61	0.67	0.90	0.96	Median	1.00		
		NO_x (µg L⁻¹)	2	7.80	7.80	1.10	3.34	12.27	14.51	Median	4.00		
		PO_4 (µg L⁻¹)	2	3.90	3.90	2.92	3.24	4.56	4.89	Median	1.00		
		POC (mg L⁻¹)	2	819.70	819.70	684.08	729.29	910.11	955.32				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		Secchi (m)	2	1.15	1.15	1.10	1.12	1.18	1.20	Median	1.50		
		SiO_4	2	525.00	525.00	466.50	486.00	564.00	583.50				
		TSS (mg L^{-1})	2	6.40	6.40	3.97	4.78	8.02	8.83	Median	2.00		
	Barratta Creek (BUR9)	DIN (µg L^{-1})	3	16.37	15.50	6.28	9.36	23.21	27.07				
		DOC (µg L^{-1})	3	1615	1732	1272	1425	1828	1876				
		DON (µg L^{-1})	3	130.64	106.51	103.13	104.25	152.20	175.05				
		DOP (µg L^{-1})	3	2.26	2.13	1.17	1.49	3.00	3.44				
		Chl a (µg L^{-1})	3	1.62	1.75	1.35	1.49	1.78	1.79	Median	1.00		
		NO_x (µg L^{-1})	3	13.15	11.86	1.50	4.95	21.10	25.71	Median	4.00		
		PO_4 (µg L^{-1})	3	4.71	4.93	3.32	3.86	5.61	5.95	Median	1.00		
		POC (mg L^{-1})	3	952.84	902.03	842.68	862.46	1033.06	1098.58				
		Secchi (m)	3	0.87	1.10	0.38	0.62	1.16	1.19	Median	1.50		
		SiO_4	3	1296.67	1110.00	462.00	678.00	1878.00	2262.00				
		TSS (mg L^{-1})	3	16.00	6.20	5.84	5.96	24.08	33.02	Median	2.00		
	Burdekin River Mouth Mooring (BUR13)	DIN (µg L^{-1})	6	9.27	6.58	2.55	3.36	15.16	20.03				
		DOC (µg L^{-1})	6	1174	1176	985	1149	1271	1324				
		DON (µg L^{-1})	6	98.92	98.74	77.42	84.18	117.35	118.85				
		DOP (µg L^{-1})	6	3.59	3.20	1.60	2.14	5.57	5.92				
		Chl a (µg L^{-1})	6	1.56	1.16	0.74	1.04	2.12	2.95	Median	1.00		
		NO_x (µg L^{-1})	6	6.52	3.03	0.58	1.47	11.13	17.91	Median	4.00		
		PO_4 (µg L^{-1})	6	3.19	3.02	2.11	2.40	3.48	4.78	Median	1.00		
		POC (mg L^{-1})	6	660.00	725.18	255.77	315.38	846.98	1045.27				
		Secchi (m)	6	1.62	1.75	0.77	1.00	2.00	2.38	Median	1.50		
		SiO_4	6	433.56	222.33	101.25	165.00	366.71	1250.43				
		TSS (mg L^{-1})	6	9.06	6.04	3.16	4.70	12.85	19.75	Median	2.00		
Mackay-Whitsunday	Double Cone (WHI1)	DIN (µg L^{-1})	4	4.46	2.49	1.30	1.63	6.50	10.39				
		DOC (µg L^{-1})	4	884	865	849	850	910	946				
		DON (µg L^{-1})	4	85.98	84.64	76.28	80.39	91.04	97.58				
		DOP (µg L^{-1})	4	5.83	4.96	4.14	4.49	6.81	8.73				
		Chl a (µg L^{-1})	4	0.64	0.65	0.51	0.56	0.73	0.77	Median	0.36	0.32	0.63
		NO_x (µg L^{-1})	4	2.66	0.44	0.30	0.36	4.07	8.13	Median	1.00		
		PN (µg L^{-1})	4	18.54	17.28	15.83	16.57	20.00	23.01	Mean	14.00		

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		PO_4 (µg L⁻¹)	4	1.39	1.39	0.81	0.91	1.87	1.98	Median	1.00		
		POC (mg L⁻¹)	4	167.82	166.23	145.74	151.27	183.74	192.12				
		PP (µg L⁻¹)	4	3.53	3.49	2.78	3.12	3.92	4.33	Median	2.30	2.30	3.30
		Secchi (m)	4	4.88	4.25	3.15	3.60	5.90	7.47	Mean	10.00		
		SiO_4	4	63.61	56.53	36.40	38.36	86.03	100.72				
		TSS (mg L⁻¹)	4	2.41	1.58	0.80	1.20	3.28	5.16	Median	1.40	1.60	2.40
	Pine (WHI4)	DIN (µg L⁻¹)	4	9.25	8.28	3.92	5.09	13.02	15.93				
		DOC (µg L⁻¹)	4	928	948	815	864	1000	1014				
		DON (µg L⁻¹)	4	72.88	73.10	66.91	69.81	76.05	78.55				
		DOP (µg L⁻¹)	4	3.79	3.56	3.43	3.50	4.00	4.48				
		Chl a (µg L⁻¹)	4	0.66	0.65	0.44	0.53	0.79	0.89	Median	0.36	0.32	0.63
		NO_x (µg L⁻¹)	4	5.15	4.15	1.42	2.11	7.78	10.27	Median	1.00		
		PN (µg L⁻¹)	4	19.01	16.54	11.68	12.97	24.06	29.80	Mean	14.00		
		PO_4 (µg L⁻¹)	4	3.00	3.06	2.21	2.56	3.47	3.71	Median	1.00		
		POC (mg L⁻¹)	4	180.92	149.43	95.17	117.38	231.86	310.75				
		PP (µg L⁻¹)	4	4.95	4.92	2.38	3.72	6.17	7.56	Median	2.30	2.30	3.30
		Secchi (m)	4	3.75	2.75	1.57	1.80	5.30	7.32	Mean	10.00		
		SiO_4	4	90.75	87.57	76.43	76.49	103.74	109.52				
		TSS (mg L⁻¹)	4	6.57	3.99	1.34	2.47	9.63	15.40	Median	1.40	1.60	2.40
	Seaforth (WHI5)	DIN (µg L⁻¹)	4	8.54	7.98	4.37	4.87	11.98	13.50				
		DOC (µg L⁻¹)	4	881	893	818	854	913	926				
		DON (µg L⁻¹)	4	76.49	78.30	56.50	67.25	86.46	93.94				
		DOP (µg L⁻¹)	4	3.99	3.91	3.43	3.50	4.44	4.65				
		Chl a (µg L⁻¹)	4	0.71	0.69	0.48	0.59	0.83	0.97	Median	0.36	0.32	0.63
		NO_x (µg L⁻¹)	4	2.34	1.59	0.57	0.83	3.55	5.14	Median	1.00		
		PN (µg L⁻¹)	4	18.65	17.97	14.98	15.94	21.09	23.27	Mean	14.00		
		PO_4 (µg L⁻¹)	4	2.56	2.40	2.04	2.11	2.94	3.29	Median	1.00		
		POC (mg L⁻¹)	4	167.20	166.23	120.38	133.69	200.33	215.40				
		PP (µg L⁻¹)	4	3.85	4.35	2.47	3.44	4.46	4.54	Median	2.30	2.30	3.30
		Secchi (m)	4	4.25	3.25	2.57	2.80	5.30	7.32	Mean	10.00		
		SiO_4	4	81.18	73.74	56.99	59.83	99.55	115.79				

						Quantiles				Guidelines			
Region	Site	Measure	N	Mean	Median	Q5	Q20	Q80	Q95	Statistic	Annual	Dry	Wet
		TSS (mg L⁻¹)	4	3.26	2.86	1.00	1.98	4.38	6.07	Median	1.40	1.60	2.40
	O'Connell River Mouth (WHI6)	DIN (µg L⁻¹)	4	25.81	5.34	2.75	3.35	40.08	77.54				
		DOC (µg L⁻¹)	4	1648	1291	1115	1120	2033	2680				
		DON (µg L⁻¹)	4	106.46	91.90	77.14	83.11	123.99	156.17				
		DOP (µg L⁻¹)	4	3.52	3.76	0.97	2.26	4.88	5.75				
		Chl a (µg L⁻¹)	4	0.73	0.50	0.41	0.42	0.94	1.36	Median	1.30		
		NO_x (µg L⁻¹)	4	17.72	1.93	0.43	0.87	28.25	57.13	Median	4.00		
		PO_4 (µg L⁻¹)	4	9.48	5.30	3.82	4.58	12.71	21.01	Median	3.00		
		POC (mg L⁻¹)	4	384.88	290.03	162.90	167.66	564.16	739.66				
		Secchi (m)	4	2.30	2.00	0.39	0.98	3.50	4.62	Median	1.60		
		SiO_4	4	797.07	490.70	363.62	389.95	1081.65	1659.44				
		TSS (mg L⁻¹)	4	9.51	4.86	0.95	1.69	15.47	24.57	Median	5.00		
	Repulse Islands dive mooring (WHI7)	DIN (µg L⁻¹)	4	13.42	6.07	5.13	5.40	18.51	32.01				
		DOC (µg L⁻¹)	4	1122	1003	906	935	1261	1503				
		DON (µg L⁻¹)	4	106.94	101.82	70.97	78.50	133.33	150.07				
		DOP (µg L⁻¹)	4	8.54	5.77	4.90	4.97	10.99	16.05				
		Chl a (µg L⁻¹)	4	0.82	0.87	0.46	0.61	1.05	1.10	Mean	0.45		
		NO_x (µg L⁻¹)	4	6.34	1.59	0.98	0.98	9.79	18.33	Median	0.25		
		PN (µg L⁻¹)	4	29.78	27.59	13.96	17.18	41.51	48.69	Median	18.00	16.00	25.00
		PO_4 (µg L⁻¹)	4	4.51	3.25	2.53	2.91	5.61	8.25	Median	2.00		
		POC (mg L⁻¹)	4	284.18	277.71	121.90	160.64	405.13	455.51				
		PP (µg L⁻¹)	4	6.93	6.98	4.05	5.34	8.53	9.73	Median	2.10	2.30	3.30
		Secchi (m)	4	2.38	1.75	1.07	1.30	3.20	4.55	Mean	10.00		
		SiO_4	4	236.25	183.71	115.78	128.58	322.91	430.29				
		TSS (mg L⁻¹)	4	14.44	8.98	1.87	3.23	23.47	34.65	Median	1.60	1.60	2.40

Table E-3: Summary of turbidity measurements from moored loggers in all regions except Cape York (site locations in Section 5) for the last 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 values above the site-specific water quality guideline values (Table E-9). Red shading indicates the annual means or medians that exceeded guidelines. '% 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.

		October 2016–September 2017						October 2017–September 2018						October 2018–September 2019					
Region	Reef	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
Johnstone Russell Mulgrave	Fitzroy West	332	1.14	0.08	0.80	30.21	1.81	264	1.32	0.05	1.03	50.76	1.14	264	1.18	0.09	0.81	32.95	1.89
	Franklands West	365	0.94	0.05	0.66	59.18	1.37	365	0.97	0.05	0.68	65.21	1.37	272	1.01	0.06	0.69	66.54	1.47
	High West	231	1.12	0.04	0.92	40.38	0.00	365	1.28	0.06	0.95	44.93	1.92	272	1.30	0.08	0.89	42.28	2.21
	Russell Mulgrave Mouth Mooring	365	4.31	0.22	2.74	91.04	28.01	244	3.47	0.22	2.16	79.51	21.31	231	5.02	0.31	3.36	84.98	37.56
Tully Herbert	Dunk North	231	2.60	0.18	1.36	83.98	14.72	365	3.00	0.20	1.38	76.44	16.44	261	4.25	0.31	1.80	78.60	26.85
	Tully Mouth Mooring	325	4.61	0.23	3.31	41.23	32.92	365	3.86	0.18	2.90	32.39	20.74	260	4.92	0.24	4.03	51.17	33.80
Burdekin	Burdekin Mouth Mooring	365	10.38	1.00	5.23	58.36	52.33	365	7.80	0.49	5.42	60.99	53.30	272	8.58	0.48	6.76	67.65	60.66
	Magnetic	337	1.75	0.07	1.38	57.57	2.08	365	2.18	0.13	1.45	58.63	7.12	272	3.16	0.27	1.74	66.18	16.18
	Palms West	365	0.73	0.02	0.67	24.93	0.27	365	1.01	0.02	0.91	63.56	0.00	272	1.03	0.04	0.90	58.82	0.37
	Pandora	298	1.18	0.05	0.98	69.46	1.01	365	1.65	0.10	1.12	85.48	4.38	126	1.78	0.19	1.02	73.81	8.73
Mackay-Whitsunday	Double Cone	275	2.12	0.39	1.16	53.45	2.55	365	1.83	0.09	1.38	65.48	3.84	272	1.68	0.06	1.31	61.42	0.00
	Pine	210	2.34	0.11	1.80	76.67	9.05	365	3.35	0.13	2.56	85.21	19.45	149	3.18	0.21	2.23	84.56	20.81
	Repulse	365	6.10	0.36	4.42	81.10	45.75	365	5.01	0.21	3.79	74.52	39.18	272	4.64	0.25	3.26	71.32	31.62
	Seaforth	365	2.50	0.27	1.42	65.75	7.40	365	1.86	0.05	1.53	80.55	1.64	272	1.78	0.07	1.48	69.85	1.84

E-4 Data used to generate remote sensing maps

Table E-4: 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. Samples were collected between December–April by AIMS and CYWMP since 2016–17 and by JCU since 2003–04. No Data = nd.

				TSS (mg L^{-1})	Chla (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	multi-annual	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
	2018-19	CC1	mean	85.88	1.62	2.23	1.24	39.59	6.71	64.14	138.95
			SD	155.74	1.02	1.02	1.36	30.83	6.15	65.61	131.35
			min	0.50	0.29	0.07	0.00	2.24	1.72	0.20	8.00
			max	590.00	4.57	3.98	5.00	108.84	25.00	165.00	532.25
			count	28.00	28.00	24.00	27.00	27.00	28.00	8.00	26.00
	multi-annual	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
	2018-19	CC2	mean	15.23	2.16	0.56	1.47	16.52	6.91	13.70	62.59
			SD	21.07	1.29	0.53	1.03	13.58	10.27	12.20	52.40
			min	1.00	0.41	0.08	0.20	3.36	1.60	1.00	13.00
			max	79.00	5.41	2.07	3.50	56.25	46.00	40.70	244.00
			count	17.00	16.00	15.00	17.00	17.00	16.00	9.00	16.00
	multi-annual	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
			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
	2018-19	CC3	mean	9.85	2.60	0.80	1.63	13.92	3.84	13.37	60.38
			SD	15.45	1.20	0.35	0.70	6.76	1.56	11.64	45.29
			min	0.80	0.65	0.23	0.50	4.33	1.55	1.90	3.00
			max	53.00	4.30	1.29	2.80	21.98	7.19	28.77	152.00
			count	9.00	9.00	8.00	9.00	9.00	9.00	4.00	8.00
	multi-annual	CC4	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
	2018-19	CC4	mean	4.08	1.48	0.58	3.04	18.95	4.33	8.59	35.59
			SD	6.46	1.24	0.56	2.12	25.56	3.68	9.71	35.41
			min	0.05	0.10	0.02	0.25	2.80	0.93	0.30	2.00
			max	36.00	6.89	3.45	11.50	145.27	30.00	37.90	216.00
			count	60.00	60.00	52.00	56.00	58.00	60.00	35.00	48.00
	multi-annual	P	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
	2018-	P	mean	26.07	1.69	0.99	2.24	23.06	5.23	17.38	68.83
			SD	84.73	1.24	0.98	1.91	26.24	5.74	32.53	87.32

		min	0.05	0.10	0.02	0.00	2.24	0.93	0.20	2.00
		max	590.00	6.89	3.98	11.50	145.27	46.00	165.00	532.25
		count	115.00	114.00	100.00	110.00	112.00	114.00	57.00	99.00
multi-annual	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
2018-19	S (or CC5)	mean	3.21	0.96	0.30	4.26	14.52	3.33	1.97	26.03
		SD	6.59	1.18	0.50	2.81	19.40	1.61	1.10	22.70
		min	0.03	0.10	0.00	0.20	0.70	0.31	0.48	0.50
		max	60.00	8.69	2.53	16.00	131.25	7.36	5.76	99.50
		count	112.00	111.00	96.00	111.00	111.00	112.00	45.00	76.00
multi-annual	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
2018-19	T (or CC6)	mean	1.82	0.86	0.20	6.12	10.59	4.53	1.20	21.08
		SD	2.84	0.52	0.44	3.16	8.93	1.45	0.97	19.28
		min	0.05	0.10	0.00	0.80	0.70	0.93	0.04	0.00
		max	14.00	1.95	2.00	16.00	29.84	7.14	3.70	75.50
		count	31.00	30.00	20.00	31.00	31.00	31.00	16.00	27.00

Table E-5: 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. Samples were collected between December and April by CYWMP since 2016-17. No Data = nd.

				TSS (mg L^{-1})	Chla (µg L^{-1})	CDOM (m^{-1})	SDD (m)	DIN (µg L^{-1})	DIP (µg L^{-1})	PP (µg L^{-1})	PN (µg L^{-1})
Cape York	multi-annual	CC1	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
	2018-19	CC1	mean	36.85	1.89	2.50	1.22	31.48	4.44	nd	123.76
			SD	61.41	1.07	0.89	1.08	14.17	2.73		114.86
			min	0.50	0.32	0.94	0.10	14.91	1.72		37.75
			max	250.00	4.57	3.98	4.15	83.18	11.00		532.25
			count	19.00	19.00	17.00	18.00	19.00	19.00		18.00
	multi-annual	CC2	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
	2018-19	CC2	mean	14.61	2.06	0.78	1.99	18.49	3.47	nd	76.31
			SD	26.49	1.14	0.63	0.98	16.45	1.93		71.41
			min	1.00	0.64	0.17	0.50	3.67	1.60		21.50
			max	79.00	3.90	2.07	3.30	56.25	6.48		244.00
			count	7.00	6.00	6.00	7.00	7.00	6.00		7.00
	multi-	CC3	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
		count	7	9	9	6	9	9	4	8
2018-19	CC3	mean	15.38	2.60	0.95	1.93	12.99	4.03	nd	76.00
		SD	21.77	1.13	0.33	0.64	7.30	1.83		45.06
		min	0.80	1.24	0.47	1.00	4.33	2.71		34.00
		max	53.00	4.25	1.29	2.80	21.83	7.19		152.00
		count	4.00	4.00	4.00	4.00	4.00	4.00		4.00
multi-annual	CC4	mean	5.44	1.14	1.21	3.02	20.91	3.26	2.94	50.61
		SD	5.54	1.00	1.20	2.14	17.64	1.79	1.94	58.97
		min	0.10	0.10	0.00	0.25	2.80	1.00	0.00	2.00
		max	34.00	5.18	3.71	9.50	73.00	11.00	7.00	318.00
		count	44	49	31	36	49	49	33	48
2018-19	CC4	mean	4.22	1.39	0.74	3.61	17.97	3.23	nd	52.10
		SD	7.80	0.68	0.83	2.29	15.22	1.28		46.78
		min	0.10	0.10	0.08	0.25	2.80	1.69		15.00
		max	34.00	2.94	3.45	9.00	52.75	5.41		216.00
		count	16.00	16.00	15.00	14.00	16.00	16.00		15.00
multi-annual	P	mean	19.13	1.36	1.49	2.03	26.72	3.98	6.22	66.59
		SD	38.36	1.30	1.53	1.94	20.47	2.34	7.56	77.80
		min	0.10	0.10	0.00	0.10	2.10	1.00	0.00	0.00
		max	250.00	8.82	6.03	12.00	89.00	12.00	35.00	532.25
		count	125	136	101	109	138	137	91	135
2018-19	P	mean	20.25	1.80	1.48	2.19	23.20	3.84	nd	87.44
		SD	44.01	1.03	1.16	1.86	16.11	2.20		90.20
		min	0.10	0.10	0.08	0.10	2.80	1.60		15.00
		max	250.00	4.57	3.98	9.00	83.18	11.00		532.25
		count	46.00	45.00	42.00	43.00	46.00	45.00		44.00
multi-annual	S (or CC5)	mean	4.47	0.68	0.48	4.51	13.71	2.99	1.79	24.80
		SD	7.06	0.60	0.78	2.63	15.36	1.40	2.31	29.75
		min	0.10	0.07	0.00	0.20	2.32	1.00	0.00	0.00
		max	60.00	3.26	3.25	16.00	131.25	8.00	13.00	179.00
		count	124	132	51	120	131	132	98	131
2018-19	S (or CC5)	mean	4.62	1.24	0.77	4.54	23.61	3.86	nd	40.20
		SD	10.80	0.81	0.80	3.36	25.79	1.23		23.30
		min	0.10	0.10	0.10	0.20	2.32	1.90		10.50
		max	60.00	3.26	2.53	16.00	131.25	5.79		99.50
		count	34.00	33.00	25.00	33.00	33.00	34.00		33.00
multi-annual	T (or CC6)	mean	2.48	0.45	0.17	8.01	12.27	2.93	1.60	17.22
		SD	2.37	0.46	0.42	4.08	13.99	1.47	1.51	19.40
		min	0.10	0.02	0.00	0.80	2.94	1.00	0.00	0.00
		max	14.00	1.95	2.00	17.40	104.00	7.14	5.00	84.00
		count	61	61	25	47	63	63	52	63
2018-19	T (or CC6)	mean	2.47	1.26	0.73	5.58	10.40	5.25	nd	33.01
		SD	4.27	0.44	0.77	3.93	8.89	0.95		19.85
		min	0.10	0.45	0.07	0.80	2.94	2.93		9.50
		max	14.00	1.95	2.00	16.00	29.84	7.14		75.50
		count	11.00	11.00	4.00	11.00	11.00	11.00		11.00

Table E-6: 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. No Data = nd.

				TSS (mg L^{-1})	Chla (µg L^{-1})	CDOM (m^{-1})	SDD (m)	DIN (µg L^{-1})	DIP (µg L^{-1})	PP (µg L^{-1})	PN (µg L^{-1})
Wet Tropics	multi-annual	CC1	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
	2018-19	CC1	mean	1.50	4.50	0.29	0.94	nd	5.33	2.62	8.00
			SD	0.00	0.00	0.00	0.00		0.00	0.00	0.00
			min	1.50	4.50	0.29	0.94		5.33	2.62	8.00
			max	1.50	4.50	0.29	0.94		5.33	2.62	8.00
			count	1.00	1.00	1.00	1.00		1.00	1.00	1.00
	multi-annual	CC2	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
	2018-19	CC2	mean	nd							
			SD								
			min								
			max								
			count								
	multi-annual	CC3	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
			count	7	38	37	34	30	30	26	28
	2018-19	CC3	mean	2.50	3.78	2.83	0.65	21.98	1.55	nd	nd
			SD	0.00	0.00	0.00	0.00	0.00	0.00		
			min	2.50	3.78	2.83	0.65	21.98	1.55		
			max	2.50	3.78	2.83	0.65	21.98	1.55		
			count	1.00	1.00	1.00	1.00	1.00	1.00		
	multi-annual	CC4	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
	2018-19	CC4	mean	3.50	2.74	1.40	0.56	32.63	4.54	2.41	22.75
			SD	2.45	3.70	0.80	0.30	39.41	1.86	1.95	19.10
			min	0.50	0.05	0.36	0.19	3.18	0.93	0.53	4.00
			max	11.50	16.00	2.86	1.54	145.27	8.40	6.53	67.00
			count	20.00	20.00	20.00	20.00	18.00	20.00	14.00	12.00
	multi-annual	P	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	164.00	375.00	368.00	357.00	321.00	324.00	301.00	309.00
	2018-19	P	mean	3.36	2.87	1.42	0.58	32.07	4.44	2.42	21.62
			SD	2.38	3.56	0.86	0.30	38.43	1.89	1.89	18.76
			min	0.50	0.05	0.29	0.19	3.18	0.93	0.53	4.00
			max	11.50	16.00	2.86	1.54	145.27	8.40	6.53	67.00
			count	22.00	22.00	22.00	22.00	19.00	22.00	15.00	13.00

multi-annual	S (or CC5)	mean	4.09	5.09	0.79	0.29	26.12	5.89	3.25	23.92
		SD	2.34	5.20	0.70	0.40	34.99	4.74	3.63	30.47
		min	0.50	0.00	0.02	0.00	0.08	0.00	0.00	0.00
		max	13.00	33.00	11.24	2.74	369.00	22.00	29.00	372.00
		count	289	482	495	438	475	476	446	447
2018-19	S (or CC5)	mean	5.25	1.62	0.54	0.15	11.21	2.93	1.72	10.34
		SD	2.20	2.36	0.43	0.14	19.77	1.83	1.22	8.31
		min	0.50	0.03	0.10	0.02	0.70	0.47	0.55	2.00
		max	10.00	13.00	2.28	0.78	108.05	7.36	5.76	34.00
		count	36.00	36.00	36.00	36.00	36.00	36.00	20.00	20.00
multi-annual	T (or CC6)	mean	7.33	4.42	0.55	0.14	18.03	4.68	2.14	18.32
		SD	3.85	5.79	0.60	0.19	16.56	4.18	2.56	23.40
		min	0.50	0.00	0.02	0.00	0.04	0.03	0.00	0.00
		max	19.00	31.00	5.34	1.38	82.00	21.00	17.00	174.00
		count	121	172	172	141	169	169	166	167
2018-19	T (or CC6)	mean	6.81	1.02	0.64	0.08	11.35	4.29	1.24	13.73
		SD	2.60	0.82	0.43	0.05	9.54	1.23	0.98	13.86
		min	2.50	0.05	0.10	0.01	0.70	1.40	0.04	2.20
		max	11.00	3.30	1.63	0.19	28.47	5.83	3.70	56.70
		count	16.00	16.00	16.00	13.00	16.00	16.00	15.00	15.00

Table E-7: 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. Samples were collected between December and April by AIMS since 2016–17 and JCU since 2003–04. No Data = nd.

				TSS (mg L^{-1})	Chla (µg L^{-1})	CDOM (m^{-1})	SDD (m)	DIN (µg L^{-1})	DIP (µg L^{-1})	PP (µg L^{-1})	PN (µg L^{-1})
Burdekin	multi-annual	CC1	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
	2018-19	CC1	mean	212.51	1.15	1.66	1.24	58.85	12.26	72.93	196.71
			SD	231.02	0.54	1.06	1.91	46.94	8.46	65.59	154.21
			min	1.35	0.49	0.07	0.00	2.24	2.79	0.20	36.00
			max	590.00	1.92	2.62	5.00	108.84	25.00	165.00	432.00
			count	8.00	8.00	6.00	8.00	8.00	8.00	7.00	7.00
	multi-annual	CC2	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
	2018-19	CC2	mean	15.67	2.21	0.40	1.10	15.13	8.98	13.70	51.92
			SD	16.22	1.38	0.38	0.90	10.92	12.45	12.20	25.59
			min	1.00	0.41	0.08	0.20	3.36	2.38	1.00	13.00
			max	61.00	5.41	1.34	3.50	35.96	46.00	40.70	102.00
			count	10.00	10.00	9.00	10.00	10.00	10.00	9.00	9.00
	multi-annual	CC3	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
			count	14	13	7	6	12	12	12	12
	20	CC3	mean	5.85	2.55	0.65	1.13	12.84	4.23	13.37	44.75

		SD	2.80	1.40	0.35	0.41	5.59	0.81	11.64	39.79
		min	2.70	0.65	0.23	0.50	5.88	3.11	1.90	3.00
		max	10.00	4.30	1.08	1.50	20.75	5.38	28.77	106.00
		count	4.00	4.00	3.00	4.00	4.00	4.00	4.00	4.00
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
2018-19	CC4	mean	5.11	1.60	0.48	2.29	9.62	4.83	12.71	31.15
		SD	7.21	1.76	0.44	1.28	5.03	5.46	10.60	28.04
		min	0.05	0.29	0.02	0.30	2.80	2.00	0.30	2.00
		max	36.00	6.89	1.81	4.50	22.27	30.00	37.90	119.00
		count	23.00	23.00	17.00	21.00	23.00	23.00	21.00	21.00
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
2018-19	P	mean	43.45	1.72	0.66	1.75	19.63	6.94	22.73	63.94
		SD	124.10	1.55	0.73	1.43	27.44	8.37	36.41	90.91
		min	0.05	0.29	0.02	0.00	2.24	2.00	0.20	2.00
		max	590.00	6.89	2.62	5.00	108.84	46.00	165.00	432.00
		count	46.00	46.00	36.00	44.00	46.00	46.00	42.00	42.00
multi-annual	S (or CC5)	mean	4.86	0.74	0.13	3.68	15.15	3.55	2.90	24.65
		SD	9.64	0.90	0.24	2.08	21.61	3.51	4.20	23.98
		min	0.20	0.10	-0.02	0.20	0.00	0.01	0.00	0.00
		max	130.00	8.69	1.98	14.00	245.68	27.90	47.90	146.00
		count	188	187	132	146	187	187	177	176
2018-19	S (or CC5)	mean	2.82	1.19	0.11	3.36	10.96	3.42	2.17	19.35
		SD	2.82	1.85	0.09	2.58	6.64	1.64	0.96	17.80
		min	0.20	0.10	-0.02	0.80	0.84	0.31	0.48	0.50
		max	16.00	8.69	0.35	14.00	24.86	6.74	4.71	55.20
		count	34.00	34.00	31.00	34.00	34.00	34.00	25.00	23.00
multi-annual	T (or CC6)	mean	3.60	0.44	0.10	5.34	11.49	4.09	2.30	20.34
		SD	2.55	0.24	0.20	2.50	8.93	3.15	2.49	20.54
		min	0.15	0.17	-0.09	1.40	0.11	0.02	0.00	0.00
		max	12.00	1.14	1.11	13.00	40.00	12.00	11.00	80.96
		count	47	45	37	35	47	47	43	45
2018-19	T (or CC6)	mean	3.82	0.56	0.03	5.00	10.25	4.14	0.48	0.00
		SD	1.93	0.40	0.03	2.12	4.44	2.32	0.00	0.00
		min	1.30	0.17	0.00	3.50	4.06	0.93	0.48	0.00
		max	6.00	0.96	0.05	8.00	14.28	6.36	0.48	0.00
		count	3.00	2.00	2.00	3.00	3.00	3.00	1.00	1.00

Table E-8: 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. Samples were collected between December and April by AIMS since 2016–17 and JCU since 2003–04. No Data = nd.

				TSS (mg L^{-1})	Chla (µg L^{-1})	CDOM (m^{-1})	SDD (m)	DIN (µg L^{-1})	DIP (µg L^{-1})	PP (µg L^{-1})	PN (µg L^{-1})
Macka	multi-	CC1	mean	73.00	3.69	1.13	0.35	44.00	13.67	25.67	73.67
			SD	36.12	2.26	0.44	0.12	26.99	8.38	7.72	40.20

		min	24.00	1.42	0.76	0.20	15.00	5.00	15.00	32.00
		max	110.00	6.78	1.75	0.50	80.00	25.00	33.00	128.00
		count	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
2018-19	CC1	mean	nd							
		SD								
		min								
		max								
		count								
multi-annual	CC2	mean	22.35	0.92	0.11	nd	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		22.00	6.00	5.00	5.00
		max	39.00	1.56	0.14		33.00	10.00	24.00	59.00
		count	2.00	2.00	2.00		2.00	2.00	2.00	2.00
2018-19	CC2	mean	nd							
		SD								
		min								
		max								
		count								
multi-annual	CC3	mean	14.00	1.35	0.14	nd	58.50	8.00	12.50	15.00
		SD	0.00	0.05	0.00		25.50	6.00	3.50	5.00
		min	14.00	1.30	0.14		33.00	2.00	9.00	10.00
		max	14.00	1.40	0.15		84.00	14.00	16.00	20.00
		count	2.00	2.00	2.00		2.00	2.00	2.00	2.00
2018-19	CC3	mean	nd							
		SD								
		min								
		max								
		count								
multi-annual	CC4	mean	8.19	1.35	0.24	0.84	28.04	13.29	12.41	35.76
		SD	7.09	1.01	0.13	0.38	9.08	5.30	8.28	44.60
		min	1.00	0.27	0.03	0.35	2.80	2.00	3.00	2.00
		max	22.00	4.81	0.45	1.50	40.00	23.00	30.00	169.00
		count	19.00	16.00	18.00	6.00	19.00	19.00	17.00	17.00
2018-19	CC4	mean	5.03	1.47	nd	1.50	2.80	6.51	nd	nd
		SD	0.00	0.00		0.00	0.00	0.00		
		min	5.03	1.47		1.50	2.80	6.51		
		max	5.03	1.47		1.50	2.80	6.51		
		count	1.00	1.00		1.00	1.00	1.00		
multi-annual	P	mean	17.21	1.62	0.32	0.68	32.18	12.52	14.25	38.46
		SD	25.10	1.44	0.35	0.39	16.74	5.96	9.13	43.40
		min	1.00	0.27	0.03	0.20	2.80	2.00	3.00	2.00
		max	110.00	6.78	1.75	1.50	84.00	25.00	33.00	169.00
		count	26.00	23.00	25.00	9.00	26.00	26.00	24.00	24.00
2018-19	P	mean	5.03	1.47	nd	1.50	2.80	6.51	nd	nd
		SD	0.00	0.00		0.00	0.00	0.00		
		min	5.03	1.47		1.50	2.80	6.51		
		max	5.03	1.47		1.50	2.80	6.51		
		count	1.00	1.00		1.00	1.00	1.00		
multi-annual	S (or CC5)	mean	6.75	1.02	0.17	2.73	15.95	4.95	4.89	21.37
		SD	7.89	0.61	0.17	1.44	14.39	3.75	5.16	17.24
		min	0.10	0.24	0.01	0.40	0.00	0.00	0.10	0.00
		max	41.00	3.88	0.88	6.00	64.00	15.00	37.00	85.00
		count	86.00	81.00	53.00	34.00	86.00	86.00	77.00	78.00

2018-19	S (or CC5)	mean	6.04	0.70	0.09	2.44	7.06	2.44	nd	nd
		SD	4.93	0.16	0.04	1.18	5.78	0.79		
		min	0.89	0.40	0.06	1.00	2.59	1.09		
		max	16.32	0.92	0.16	5.00	21.21	3.41		
		count	8.00	8.00	4.00	8.00	8.00	8.00		
multi-annual	T (or CC6)	mean	1.88	0.67	0.03	4.89	4.77	1.89	2.33	16.46
		SD	2.70	0.21	0.01	1.05	8.08	1.79	2.33	9.99
		min	0.11	0.25	0.01	4.00	0.10	0.02	0.09	2.20
		max	12.00	1.19	0.05	7.00	35.00	7.00	10.00	36.87
		count	18.00	18.00	9.00	9.00	17.00	17.00	17.00	17.00
2018-19	T (or CC6)	mean	1.28	0.53	0.05	4.50	1.54	1.71	nd	nd
		SD	0.00	0.00	0.00	0.00	0.00	0.00		
		min	1.28	0.53	0.05	4.50	1.54	1.71		
		max	1.28	0.53	0.05	4.50	1.54	1.71		
		count	1.00	1.00	1.00	1.00	1.00	1.00		

E-5 Site-specific Guideline Values for MMP sites

Table E-9: Site-specific Guideline Values (GVs) used for comparison with water quality monitoring data. These GVs 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 D-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 D for details on Index calculation. DOF is direction of failure ('H' = high values fail, while 'L' = low values fail). Annual mean GVs are applied to annual mean values of monitoring data (and median GVs are applied to median data, etc.). Bold GVs are those applied to monitoring data.

					Annual		Dry	Wet
Group	**Site codes**	**Water Body**	**Measure**	**DOF**	**Mean**	**Median**	**Median**	**Median**
1	C1,C6,C8,RM1,RM4,RM8,TUL1	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.35**		
			Turbidity (NTU)	H		**1.00**		
			PN (µgL⁻¹)	H	20.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H	2.00		**1.60**	**2.40**
2	RM9,RM10,TUL3,TUL4,TUL5,TUL6,TUL8,TUL9	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.35**		
			Turbidity (NTU)	H		**1.00**		
			PN (µgL⁻¹)	H	20.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H	2.00		**1.60**	**2.40**
3	C4,C5,C11,RM2,RM3,RM5,RM6,RM7,TUL2	Mid-shelf waters	Chla (µgL⁻¹)	H		0.30	**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.31**		
			Turbidity (NTU)	H		**0.60**		
			PN (µgL⁻¹)	H		14.00	**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H		2.00	**2.30**	**3.30**
			Secchi (m)	L		**13.00**		
			TSS (mgL⁻¹)	H		1.20	**1.60**	**2.40**
4	RM12,TUL11	Mid-estuarine waters	Chla (µgL⁻¹)	H		**2.00**		
			NOx (µgL⁻¹)	H		**15.00**		
			Turbidity (NTU)	H		**5.00**		
			PN (µgL⁻¹)	H				
			PO4 (µgL⁻¹)	H		**3.00**		
			PP (µgL⁻¹)	H				
			Secchi (m)	L		**1.50**		
			TSS (mgL⁻¹)	H		**7.00**		
5	TUL7,TUL10	Lower estuarine waters	Chla (µgL⁻¹)	H		**1.10**		
			NOx (µgL⁻¹)	H		**3.00**		
			Turbidity (NTU)	H		**4.00**		

					Annual		Dry	Wet
Group	Site codes	Water Body	Measure	DOF	Mean	Median	Median	Median
			PN (µgL⁻¹)	H				
			PO4 (µgL⁻¹)	H		**3.00**		
			PP (µgL⁻¹)	H				
			Secchi (m)	L		**1.60**		
			TSS (mgL⁻¹)	H		**5.00**		
6	BUR1,BUR2	Open Coastal waters	Chla (µgL⁻¹)	H		0.35	**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.28**		
			Turbidity (NTU)	H		**0.80**		
			PN (µgL⁻¹)	H		12.00	**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**1.00**		
			PP (µgL⁻¹)	H		2.20	**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H		1.20	**1.60**	**2.40**
7	BUR3	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.28**		
			Turbidity (NTU)	H		**0.80**		
			PN (µgL⁻¹)	H	20.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**1.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H	2.00		**1.60**	**2.40**
8	BUR4	Open Coastal waters	Chla (µgL⁻¹)	H		0.59	**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.28**		
			Turbidity (NTU)	H		**1.30**		
			PN (µgL⁻¹)	H		17.00	**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**1.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L		**4.00**		
			TSS (mgL⁻¹)	H		1.90	**1.60**	**2.40**
9	BUR5	Open Coastal waters	Chla (µgL⁻¹)	H		0.60	**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.50**		
			Turbidity (NTU)	H		**3.00**		
			PN (µgL⁻¹)	H	20.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L		**3.00**		
			TSS (mgL⁻¹)	H		5.00	**1.60**	**2.40**
10	BUR6.BUR7	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**1.00**		
			Turbidity (NTU)	H	**2.00**			
			PN (µgL⁻¹)	H		13.00	**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H		2.10	**2.30**	**3.30**

Group	Site codes	Water Body	Measure	DOF	Annual Mean	Annual Median	Dry Median	Wet Median
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H		1.20	**1.60**	**2.40**
11	BUR8,BUR9	Enclosed Coastal waters	Chla (µgL⁻¹)	H		**1.00**		
			NOx (µgL⁻¹)	H		**4.00**		
			Turbidity (NTU)	H		**4.00**		
			PN (µgL⁻¹)	H				
			PO4 (µgL⁻¹)	H		**1.00**		
			PP (µgL⁻¹)	H				
			Secchi (m)	L		**1.50**		
			TSS (mgL⁻¹)	H		**2.00**		
12	BUR10	Mid-shelf waters	Chla (µgL⁻¹)	H		0.33	**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.28**		
			Turbidity (NTU)	H		**0.50**		
			PN (µgL⁻¹)	H		14.00	**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**1.00**		
			PP (µgL⁻¹)	H		2.00	**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H		0.80	**1.60**	**2.40**
13	BUR11,BUR12	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**1.00**		
			Turbidity (NTU)	H		**2.00**		
			PN (µgL⁻¹)	H	20.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H	2.00		**1.60**	**2.40**
14	BUR13,BUR14,BUR15	Enclosed Coastal waters	Chla (µgL⁻¹)	H		**1.00**		
			NOx (µgL⁻¹)	H		**4.00**		
			Turbidity (NTU)	H		**4.00**		
			PN (µgL⁻¹)	H				
			PO4 (µgL⁻¹)	H		**1.00**		
			PP (µgL⁻¹)	H				
			Secchi (m)	L		**1.50**		
			TSS (mgL⁻¹)	H		**2.00**		
15	WHI1,WHI2,WHI3,WHI4,WHI5	Open Coastal waters	Chla (µgL⁻¹)	H		0.36	**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**1.00**		
			Turbidity (NTU)	H		**1.10**		
			PN (µgL⁻¹)	H	14.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**1.00**		
			PP (µgL⁻¹)	H		2.30	**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H		1.40	**1.60**	**2.40**
16	WHI6	Enclosed Coastal waters	Chla (µgL⁻¹)	H		**1.30**		

					Annual		Dry	Wet
Group	Site codes	Water Body	Measure	DOF	Mean	Median	Median	Median
			NOx (µgL⁻¹)	H		**4.00**		
			Turbidity (NTU)	H		**4.00**		
			PN (µgL⁻¹)	H				
			PO4 (µgL⁻¹)	H		**3.00**		
			PP (µgL⁻¹)	H				
			Secchi (m)	L		**1.60**		
			TSS (mgL⁻¹)	H		**5.00**		
17	WHI7,WHI10	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.25**		
			Turbidity (NTU)	H	**2.00**			
			PN (µgL⁻¹)	H		18.00	**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H		2.10	**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H		1.60	**1.60**	**2.40**
18	WHI8,WHI11	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**1.00**		
			Turbidity (NTU)	H	**2.00**			
			PN (µgL⁻¹)	H	20.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H	2.00		**1.60**	**2.40**
19	WHI9	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**0.25**		
			Turbidity (NTU)	H	**1.00**			
			PN (µgL⁻¹)	H		18.00	**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H		2.10	**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H		1.60	**1.60**	**2.40**
20	WHI10.1,WHI10.2	Open Coastal waters	Chla (µgL⁻¹)	H	0.45		**0.32**	**0.63**
			NOx (µgL⁻¹)	H		**1.00**		
			Turbidity (NTU)	H			**2.00**	**12.00**
			PN (µgL⁻¹)	H	20.00		**16.00**	**25.00**
			PO4 (µgL⁻¹)	H		**2.00**		
			PP (µgL⁻¹)	H	2.80		**2.30**	**3.30**
			Secchi (m)	L	**10.00**			
			TSS (mgL⁻¹)	H	2.00		**1.60**	**2.40**

Appendix E References

Cooper TF, Uthicke S, Humphrey C, Fabricius KE (2007). Gradients in water column nutrients, sediment parameters, irradiance and coral reef development in the Whitsunday Region, central Great Barrier Reef. Estuarine, Coastal and Shelf Science 74:458-470.

Cooper TF, Ridd PV, Ulstrup KE, Humphrey C, Slivkoff M, Fabricius KE (2008). Temporal dynamics in coral bioindicators for water quality on coastal coral reefs of the Great Barrier Reef. Marine and Freshwater Research 59:703-716.

De'ath G and Fabricius KE (2008) Water quality of the Great Barrier Reef: distributions, effects on reef biota and trigger values for the protection of ecosystem health. Final Report to the Great Barrier Reef Marine Park Authority. Australian Institute of Marine Science, Townsville. 104 pp.

Department of Environment and Resource Management (DERM) (2009). Queensland Water Quality Guidelines, Version 3. 167 p. Available at www.derm.qld.gov.au. ISBN 978-0-9806986-0-2.

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Great Barrier Reef Marine Park Authority (2010). Water Quality Guidelines for the Great Barrier Reef Marine Park. Revised Edition 2010. Great Barrier Reef Marine Park Authority, Townsville. 100pp.

Appendix F. Quality assurance/quality control (QA/QC) information

F-1 Method performance and QA/QC information for water quality monitoring activities

Information pertaining to QA/QC generally includes the assessment of the limit of detection (LOD), measurements of accuracy (e.g. using reference materials to assess the recovery of a known amount of analyte) and precision (the repeated analyses of the same concentration of analyte to check for reproducibility).

F-2 Limits of detection

LOD or detection limit is the lowest concentration level that can be determined to be statistically different from a blank (99% confidence). LOD of water quality parameters sampled under the MMP are summarised below (Table F-1):

Table F-1: Limits of detection (LODs) for analyses of marine water quality parameters.

Parameter (analyte)	LOD
NO_2	0.28 µg L^{-1}*
NO_3+ NO_2	0.28 µg L^{-1}*
NH_3	0.84 µg L^{-1}*
NH_3 by OPA	0.28 µg L^{-1}
TDN	0.28 µg L^{-1}*
PN	1.0 µg $filter^{-1}$
PO_4	0.62 µg L^{-1}*
TDP	0.62 µg L^{-1}*
PP	0.09 µg L^{-1}
Si	1.9 µg L^{-1}*
DOC	0.1 mg L^{-1}
POC	1.0 µg $filter^{-1}$
Chl-*a*	0.004 µg L^{-1}
SS	0.15mg $filter^{-1}$
Salinity	0.03

*LOD for analysis of dissolved nutrients is estimated for each individual analytical batch, the range given is the range of LODs from batches analysed with samples collected in 2014/15.

F-3 Precision

The variation between results for replicate analyses of standards or reference material is used as a measure for the precision of an analysis. Reproducibility of samples was generally within a CV of 20%, with the majority of analyses delivering precision of results within 10% (Table F-2).

Table F-2: Summary of coefficients of variation (CV) of replicate measurements (N) of a standard or reference material.

Parameter (analyte)	CV (%)	N
PN	9–18*	53–68
PP	7	8
POC	8–13*	52–56
Chl-*a*	0.7	48
TSS	n/a**	
Salinity	<0.1	2–5

* Two different reference materials used in each batch

**No standard material exists for analysis of this parameter.

F-4 Accuracy

Analytical accuracy is measured as the recovery (%) of a known concentration of a certified reference material or analyte standard (where no suitable reference material is available, e.g., for PP), which is usually analysed interspersed between samples in each analytical run. The recovery of known amounts of reference material is expected to be within 90%–110% (i.e., the percent difference should be ≤20%) of their expected (certified) value for results to be considered accurate. The accuracy of analytical results for PN, PP, POC, Chl-*a*, TSS and salinity were generally within this limit (Table F-3). Analytical results for PP are adjusted using a batch-specific recovery factor that is determined with each sample batch.

Table F-3: Summary of average recovery of known analyte concentrations.

Parameter (analyte)	Average recovery (%)	N
PN	102–110	53–68
PP	92*	9
POC	105–109	53–56
Chl-*a*	99.5	24
TSS	n/a**	
Salinity	100	11

*Data are adjusted using a batch-specific efficiency factor (recovery)

**No suitable reference material exists for analysis of this parameter

F-5 Procedural blanks

Wet filter blanks (filter placed on filtration unit and wetted with filtered seawater, then further handled like samples) were prepared during the on-board sample preparation to measure contamination during the preparation procedure for PN, PP, POC and Chl-a. The instrument readings (or actual readings in the case of Chl-*a*) from these filters were compared to instrument readings from actual water samples. On average, the wet filter blank values were below 1% of the measured values for Chl-*a* (Table F-4) and we conclude that contamination due to handling was minimal.

Wet filter blanks (as well as filter blanks using pre-combusted filters) for PN, PP and POC generally returned measurable readings, which indicates that the filter material contains phosphorus and organic carbon. The blank values are relatively constant and were subtracted from sample results to adjust for the inherent filter component.

Wet filter blanks for TSS analysis (filter placed on filtration unit and wetted with filtered seawater, rinsed with distilled water, then further handled like samples) were prepared during the on-board sample preparation. The mean weight difference of these filter blanks (final weight - initial filter weight) was 0.00010 g (n = 32). This value indicated the average amount of remnant salt in the filters (‘salt blank’). The salt blank was approximately 3.5% of the average sample filter weight (Table F-4). This value was included in the calculation of the amount of TSS per litre of water by subtraction from the sample filter weight differences.

Table F-4: Comparison of instrument readings of wet filter blanks to actual sample readings.

	PP (absorbance readings)	**PN (instrument readings)**	**Chl-*a* (µg L^{-1})**	**TSS (mg $filter^{-1}$)**	**POC (µg $filter^{-1}$)**
Average of blank readings	0.007	1.09	0.005	0.08	7.43
N of blank readings	44	37	42	8	36
Average of sample readings	0.12	5.61	0.58	2.28	44.31
N of sample readings	510	494	638	572	493
Average of blanks as % of average sample readings	5.4%	19.36%	0.94%	3.51%	16.8%

Appendix G. Scientific publications and presentations associated with the program, 2018–19

G-1 Publications

Ceccarelli, D. M., Evans, R. D., Logan, M., Mantel, P., Puotinen, M., Petus, C., Russ, G. R., and Williamson, D. H. 2019. Long-term dynamics and drivers of coral and macroalgal cover on inshore reefs of the Great Barrier Reef Marine Park. *Ecological Applications*, 30(1), e02008. doi:10.1002/eap.2008.

Lønborg, C., Calleja, M. L., Fabricius, K. E., Smith, J. N., & Achterberg, E. P. 2019. The Great Barrier Reef: A source of CO_2 to the atmosphere. *Marine Chemistry*. doi:10.1016/j.marchem.2019.02.003.

Petus, C., Waterhouse, J., Lewis, S., Vacher, M., Tracey, D., Devlin, M. 2019. A flood of information: Using Sentinel-3 water colour products to assure continuity in the monitoring of water quality trends in the Great Barrier Reef (Australia). *Journal of Environmental Management*, 248, 109255.

Gruber R, Waterhouse J, Logan M, Petus C, Howley C, Lewis S, Tracey D, Langlois L, Tonin H, Skuza M, Costello P, Davidson J, Gunn K, Lefevre C, Shanahan M, Wright M, Zagorskis I, Kroon F, and Neilen A. 2019. Marine Monitoring Program: Annual Report for Inshore Water Quality Monitoring 2017-18. Report for the Great Barrier Reef Marine Park Authority, Great Barrier Reef Marine Park Authority, Townsville.

Brinkman R, Baird M, Boswood P, Fearns P, Gruber R, Holmes M, Honchin C, Johnson R, Lewis S, Lonborg C, Mueller J, Robillot C, Schroeder T, Steinberg C, and Treleaven J. 2019. Monitoring the marine physical and chemical environment within the Reef 2050 Integrated Monitoring and Reporting Program: Final Report of the Marine Physical and Chemical Environment Expert Group, Great Barrier Reef Marine Park Authority, Townsville.

G-2 Presentations

Gruber R, et al. *Inshore Water Quality 2018-19: Site-specific conditions and trends*. Presented at the Marine Monitoring Program Annual MERI Workshop, Townsville, QLD, November 2019.

Gruber R, et al. *Inshore Water Quality: 2018-19 results from the Marine Monitoring Program*. Presented at Great Barrier Reef Marine Park Authority lunchtime seminar, Townsville, QLD, Oct 2019.

Gruber R and R Brinkman. *Great Barrier Reef water quality.* Presented to Herbert River canegrowers at AIMS, Townsville, QLD, Oct 2019.

Gruber R, et al. *Water quality research and monitoring at AIMS*. Presented to South Cape York Partnerships and Cooktown Community Event at Cooktown, QLD, Sept 2019.

Gruber R and R Brinkman. *Great Barrier Reef water quality.* Presented to NQ Dry Tropics and Burdekin canegrowers at AIMS, Townsville, QLD, May 2019.

Howley C, et al. *Flood Event water quality monitoring by the Cape York Water Monitoring Partnership*. Presented at Cape York LMAC meeting, Cooktown, QLD, Feb 2019.

Howley C, et al. *Estuary and marine water quality monitoring by the Cape York Water Monitoring Partnership*. Presented at Cooktown Community meeting hosted by SCYC and CYWMP with AIMS. September 2019.

Howley C, et al. *Cape York flood events 2018-2019: Water quality monitoring by the Cape York Water Monitoring Partnership*. Presented to Lama Lama Rangers and community, Port Stewart, QLD, Oct 2019.

Howley C, et al. *Inshore Water Quality 2018-19: wet season monitoring in the Great Barrier Reef- Cape York Region*. Presented at the Marine Monitoring Program Annual MERI Workshop, Townsville, QLD, November 2019.

Kroon FJ, et al. *AIMS' GBR water quality monitoring and research*. Presented to Reef Trust 2050 Partnership at AIMS, Townsville, May 2019.

Kroon FJ. *Managing water quality in the Great Barrier Reef*. Keynote to 8th International Symposium on Gully Erosion, Townsville, QLD July 2019.

Kroon FJ and Robson B. *Managing water quality in the Great Barrier Reef*. Presentation to Nestle representative at AIMS, Townsville, QLD, August 2019.

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