Australian Government
Great Barrier Reef
Marine Park Authority

Queensland
Government

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

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 Islander Traditional Owners whose rich cultures, heritage values, enduring connections and shared efforts protect the Reef for future generations.

Published by the Great Barrier Reef Marine Park Authority

ISBN 9780648721437

A catalogue record for this publication is available from the National Library of Australia

This publication should be cited as:

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.

Front cover image: Crinoids. Photographed by Chris Jones.

DISCLAIMER

Australian Government
Great Barrier Reef
Marine Park Authority

Great Barrier Reef Marine Park Authority
280 Flinders Street Townsville | PO Box 1379 Townsville QLD 4810
Phone: (07) 4750 0700
Fax: 07 4772 6093
Email: info@gbrmpa.gov.au
www.gbrmpa.gov.au

Contents

List of Figures

List of Tables

1.0 Executive Summary

The physical and chemical environment of the Great Barrier Reef (the Reef) ultimately underpins all ecological processes and other cultural and human values associated with the Reef. Reef 'water quality' is also a value in itself, and a pressure on many ecological, cultural, social and economic values through a range of physical and chemical processes. As such, understanding the state and trajectory of key physical and chemical indicators is fundamental to many of the information needs and reporting requirements for management of the Reef.

Existing monitoring efforts and information sources related to describing the physical and chemical environment of the Reef are numerous. However, when evaluated as a collective, and viewed from the perspective of providing contextual information to support monitoring of other ecological and social values, and management of the Reef, the existing efforts:

- are inadequate in terms of key parameters and processes observed, monitored or inferred;
- do not provide sufficient geographical coverage; and
- are undertaken at a temporal frequency that is often a compromise between providing sufficient context to aid in the interpretation of ecological processes and responses associated with changes in water quality, and determining long-term trajectories of environmental change.

Outlook reporting requirements include the need to monitor and describe the state and trends in a range of physical and chemical parameters and processes. Specific reporting products to be delivered as part of the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP), in addition to the regular Great Barrier Reef Outlook Report (the Outlook Report) and Reef and Regional report cards, have yet to be comprehensively defined. However, the Outlook reporting requirements and suggested monitoring objectives have provided broad guidance for the identification of relevant indicators.

The following indicators are recommended as priority monitoring candidates as part of the physical and chemical environmental monitoring component of RIMReP.

Executive Summary Table 1. Priority indicators for monitoring the physical and chemical environment of the Reef.

Indicator Group	Priority Indicator	Justification for selection*	Related Reef 2050 Objective/Target
Nutrients	Nutrients (nitrogen and phosphorus species; silica as well as chlorophyll *a* as a proxy of nutrient enrichment) (dissolved and particulate)	Nutrient delivery and enrichment is an underpinning process for many components of benthic and pelagic ecosystems. Considered a key pressure on marine ecosystems — primarily inshore and some areas of mid-shelf.	WQO1, WQO2: species, speciation changes, trace nutrients, organic carbon; important for understanding management options and effectiveness (e.g. dissolved

		Measure/evaluate marine ecosystem response to changes in catchment loadings.	inorganic nitrogen versus organic matter); EH02 EB02
	Nutrients (carbon species)	As above.	
	Chlorophyll *a*	As a proxy for pelagic production and for dissolved inorganic nitrogen. Major controls on benthic light availability.	
	Nitrogen river-derived loading maps (use DIN and PN as proxies)	Maps of dissolved inorganic nitrogen exposure from rivers — useful spatial overlay.	
Sediment	Suspended sediment concentration (solids)	A key pressure on marine ecosystems — primarily inshore. Measure marine effects of actual catchment load reductions.	WQO1, WQO2 EH02, EB02 As Above As Above
	Turbidity	Lack of water clarity is a key indicator of poor water quality and is an essential environmental factor for phototrophic organisms that dominate coral reefs, seagrass meadows and the seafloor microphytobenthos.	
	Secchi depth	Lack of water clarity is a key indicator of poor water quality and is an essential environmental factor for phototrophic organisms that dominate coral reefs, seagrass meadows and the seafloor microphytobenthos.	
	Sediment river-derived loading maps	Model and remote sensing based — useful spatial overlay.	
Marine debris	Marine debris — density of plastics recovered (per unit effort) through beach cleanups.	Emerging contaminant of concern — broadscale ecosystem impacts unquantified at present. Measure of effectiveness of (terrestrial) waste management activities.	EH02, WQ02
	Microplastics — standardised density of microplastic particles	Emerging contaminant of concern — broadscale ecosystem impacts unquantified at present.	

Light	Vertical attenuation (spectrally resolved) Secchi depth Benthic PAR	Light is an essential environmental factor for phototrophic organisms that dominate coral reefs, seagrass meadows and the seafloor microphytobenthos. Light availability (integrated through time) is a key pressure for phototrophic organisms. Measure marine effects of actual catchment load reductions.	WQ02, EH02, EB02
Temperature	Sea surface temperature *In situ* water column temp — fixed sites Water column temperature (3D maps - modelled)	Priority pressure on marine ecosystems. Coral bleaching indicator and predictor of thermal stress. Significant contributor to cumulative impacts. Informs tactical monitoring and deployment of field teams to assess bleaching damage. In a predictive capacity can inform strategic planning (e.g. zoning, resilience mapping).	EH02, EB02
Salinity	*In situ* water column salinity Water column Salinity (3D maps - modelled)	Pressure on marine ecosystems. Useful indicator of river plume extent. Indicator of circulation.	EH02, EB02
Ocean currents	*In situ* water column current observations - fixed sites. Water column Salinity (3D maps - modelled)	Underpins understanding of connectivity and residence times. Can inform strategic planning for management response (e.g. zoning, approvals, resilience mapping). Tactical information required for operational activities (maritime operations) and response (maritime incident) operations.	EH02, EB02
Ocean acidification	Operational pCO_2 systems (ship and fixed sites)	A priority pressure on marine ecosystems Link between nutrient inputs and coastal acidification opens options for ocean acidification mitigation via improved nutrient management to reduce inputs	EH02, EB02

		In a predictive capacity can inform strategic planning (e.g. resilience-based zoning)	
Extreme events (cyclones)	Spatial description of cyclone impacts to coral reefs — based on cyclone damage model (Marji Puotinen).	Informs the Authority's response to cyclone damage. Can trigger deployment of and guide field teams to assess the on ground damage post-cyclones (RHIS). Identify spatial patterns in historic tropical cyclone exposure to explain habitat condition trajectories.	EB02
	BoM cyclone tracking, including air pressure maps cyclone tracking, wind.	Informs the Authority's response to cyclone damage. Can trigger deployment of and guide field teams to assess the on ground damage post-cyclones (RHIS).	
	Waves' heights — observed (Queensland network, Modelled BoM models)	Informs the Authority's response to cyclone damage and is a factor in identifying resilient reefs.	
Sea level Rise	Spatial description and rate of sea level rise along the Queensland coast. Altimetry derived sea surface height	Strategic	EB02
Primary production	Phytoplankton community composition	Basis of the pelagic food web, important for fisheries. Inferred from indicators that inform other elements (e.g. chlorophyll, temperature). Trophic implications e.g. suspected shifts in size of plankton may have influenced recent crown-of-thorns starfish larval survival rates. An indicator of overall pelagic condition.	EH02
	Zooplankton community composition		
Noise	Ocean noise, 2Hz to 6kHz As an archive physical, man-made and biological sources	Assess anthropogenic noise in Australian marine soundscapes and its impact on marine fauna [to be completed].	EB02
Pesticides	PSII herbicides		WQ02, WQ01, EH02

	Non-PSII Herbicides including emerging ‘alternative’ herbicides.	Pesticides pose a risk to some coastal and inshore locations. Observed concentrations provide a measure of potential impact to inform prioritisation of catchment management action	
	Pesticides		

Existing monitoring efforts and information sources include contributions from national monitoring programs and operational environmental information services, such as the Integrated Marine Observing System (IMOS) and the Bureau of Meteorology (BoM), state-wide estuarine and coastal monitoring programs, such as Queensland coastal wave and tide monitoring and Reef water quality monitoring, and regionally specific Reef monitoring activities, including components of the Marine Monitoring Program (MMP). These existing data sources provide high quality and, in some cases, multi-decadal time series that have underpinned our current understanding of the system and have enabled the development of alternative environmental information sources, such as the development and validation of physical process and biogeochemical models such as those developed through the eReefs project.

For the priority indicators listed above, we propose a hierarchical approach of broad-scale indicators derived primarily from data-assimilating models and remote-sensing products, validated by routine *in situ* sampling at specific, fixed observing locations, and supported by process studies to answer specific knowledge gaps. Routine sampling at fixed locations is proposed to follow nationally recognised protocols, as employed for the IMOS national reference stations, augmented, where necessary, to be consistent with the approach followed by the MMP for inshore water quality monitoring.

The following table outlines the indicators to be monitored/derived at broad-scale, those observed at specific sites and those targeting specific processes.

Executive Summary Table 2. Proposed scale of monitoring and/or modelling effort for each priority indicator.

Indicator Group	***Priority Indicator***	***Broad-Scale***	***Site***	***Process***
Nutrients	Nutrients (N and P species)		X	X
	Nutrients (Carbon species)		X	X
	Chlorophyll *a*	X,X_m	X	X
	Nitrogen loading maps	X_m		
Sediment	Suspended sediments (solids)		X	X
	Turbidity	X,X_m	X	X
	Secchi depth	X,X_m	X	X
	Sediment loading maps	X,X_m		
Marine debris	Marine debris		X	
	Microplastics	X	X	
Light	Benthic PAR	X_m	X	
	K_d – vertical attenuation rate	X_m	`	
	Secchi depth	X,X_m	X	
Temperature	Sea surface temperature	X	X	X
	In situ water column temp		X	
	Water column temperature	X_m	X	X

Salinity	Salinity	X_m	X	X
Altered ocean currents	Ocean currents	X_m	X	X
Ocean acidification	pH, total alkalinity, DIC, pCO_2	X	X	X
Extreme events (cyclones)	Spatial description	X	X	
	BoM cyclone tracking,	X	X	
	Waves, sea levels	X_m	X	
Primary production	Primary production estimate	X,X_m		X
	Rates of change of chlorophyll *a*	X,X_m		X
	Phytoplankton / zooplankton community composition	X	X	
Marine Noise	Ocean noise, 2Hz to 6kHz As an archive physical, man-made and biological sources		X	
Pesticides	*In situ* concentration		X	

Note: columns marked with X represents an observation, and X_m represents information derived from models.

The full spatial coverage and high temporal frequency of physical and biogeochemical information provided by the eReefs model archive has been applied to perform Observation System Simulation Experiments, the results of which have informed site selection for specific fixed observing locations. Observation System Simulation Experiments involve using a model simulation to quantify the effectiveness of observation techniques and observation locations to quantify the state or phenomena of interest. In the Observation System Simulation Experiments undertaken here, we use the spatial correlation of physical (temperature) and biogeochemical (chlorophyll *a*, total suspended solids, dissolved inorganic nitrogen) properties in the eReefs four-kilometre biogeochemical model six-year simulation forced by SOURCE Catchments river loads. The years 2011 to 2016 represent a one-in-a-100-year wet season (2011), as well as some average and dry years. From a pragmatic perspective, the analysis of observing system design and observational locations focuses on assessing the adequacy of IMOS and MMP sampling locations to represent regional environmental characteristics. The rationale for this approach is to build on the existing time series already accumulated at many of these sites. In areas where existing monitoring efforts have been identified as spatially inadequate, the Observation System Simulation Experiments approach has been used to identify potential new sites. The analysis has identified candidate fixed monitoring sites in Cape York (Lockhart River), Cairns Region (Double Island), Wet Tropics (Russell Island), Central (Yongala), Whitsundays (Pine Island/Daydream), Mackay (Mackay) and the Fitzroy (Barren Island).

2.0 Background and design considerations

2.1 Objectives of RIMReP

The *Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan) provides an overarching strategy for managing the Great Barrier Reef (the Reef). It contains actions, targets, objectives and outcomes to address threats and protect and improve the Reef's health and resilience, while allowing ecologically sustainable use. The Reef 2050 Plan has been developed in consultation with partners, including Traditional Owners and the resource, ports, fishing, agriculture, local government, research and conservation sectors.

A key component of the Reef 2050 Plan is the establishment of the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP). RIMReP will provide a comprehensive and up-to-date understanding of the Reef — the values and processes that support it and the threats that affect it. This knowledge is fundamental to informing actions required to protect and improve the Reef's condition and to drive resilience-based management.

There are currently over 90 monitoring programs operating in the Great Barrier Reef World Heritage Area (the World Heritage Area) and adjacent catchment. These programs have been designed for a variety of purposes and operate at a variety of spatial and temporal scales. The comprehensive strategic assessments of the World Heritage Area and adjacent coastal zone — both of which formed the basis for the Reef 2050 Plan — identified the need to ensure existing monitoring programs align with each other and with management objectives. The program will fulfil this need.

RIMReP will provide information across the seven themes that make up the Reef 2050 Plan Outcomes Framework. The themes are ecosystem health; biodiversity; water quality; heritage; community benefits; economic benefits and governance.

The intent of RIMReP is not to duplicate existing arrangements but to coordinate and integrate existing monitoring, modelling and reporting programs across disciplines. For example, the *Reef 2050 Water Quality Improvement Plan* underpins the Reef 2050 Plan's water quality theme and its Paddock to Reef 2050 Integrated Monitoring, Modelling and Reporting Program will form a key part of the new integrated program.

As the driver of resilience-based management under the Reef 2050 Plan, RIMReP's primary purpose is to enable timely and suitable responses by Reef managers and partners to current and emerging issues and risks, and enable the evaluation of whether the Reef 2050 Plan is on track to meet its outcomes, objectives and targets.

RIMReP's vision is to develop a knowledge system that enables resilience-based management of the

Reef and its catchment, and provides managers with a comprehensive understanding of how the Reef 2050 Plan is progressing.

Three goals for the knowledge system are that it is:

- ***Effective*** in enabling the early detection of trends and changes in the Reef's environment, inform the assessment of threats and risks, and drive resilience-based management.

- ***Efficient*** in enabling management priorities and decisions to be cost effective, transparent, and based on cost-benefit and risk analyses.
- ***Evolving*** based on the findings of Great Barrier Reef Outlook Reports, new technologies and priority management and stakeholder needs.

RIMReP will be central to ensuring decisions regarding the protection and management of the Reef are based on the best available science, consistent with the principles of transparency and accountability, and underpinned by a partnership approach.

Figure 1. RIMReP program logic. Each of the three goals has associated development and implementation objectives as well as foundational inputs.

2.2 Information needs for the Great Barrier Reef Outlook Report and other reporting requirements

The physical and chemical environment ultimately underpins all ecological processes and other cultural and human values on the Reef. The Reef's 'water quality' is also a value in itself, and a pressure on many ecological, cultural, social and economic values through a range of physical and chemical processes. As such, understanding the state and trajectory of key physical and chemical indicators is fundamental to many of the information needs and reporting requirements for management of the Reef.

The five-yearly Outlook Report is required to report on the state and trend of a range of physical and chemical parameters and processes including:

- ocean currents;
- cyclones and changes in wind regimes;
- freshwater inflow;
- total suspended sediment loads;
- sea level;
- sea temperature;
- sub-surface light;
- nutrient cycling, including inputs and productivity;
- ocean pH and associated parameters; and
- ocean salinity.

Other reporting activities such as the Reef and Regional report cards are typically produced more frequently (yearly) and use monitoring activities that deliver a much richer level of detail for some water quality parameters for their specific purposes (for example, the Gladstone Healthy Harbour Partnership Report Card reports on specific metal concentrations relevant to local guidelines).

Suggested core, long-term monitoring objectives relevant to the physical and chemical environment to underpin an integrated monitoring framework for the Reef (Hedge et al. 2013) include the following:

Table 3. Draft core long-term monitoring objectives *(from Hedge et al. 2013).*

Draft core long-term monitoring objectives (from Hedge et al. 2013)		***Comments***
1	Determine trends in oceanic, Reef, regional and local scale water circulations.	
2	Determine trends in concentrations of nutrients, pesticides and sediments in relation to guidelines where they exist.	Expand to include other contaminants including plastics and emerging pollutants such as new agrichemicals and pharmaceuticals.
3	Measure trends in frequency, intensity and spatial extent of sea and air temperature variability.	Improve current *in situ* and satellite sea surface temperature products to include marine heatwave analysis and also low temperature analysis.
4	Determine trends in rising sea level.	Only two stations, Cape Ferguson and Rosslyn Bay, are a part of BoM's Australian Baseline Sea Level Monitoring Project. Develop coastal altimeter capability.
5	Determine trend in ocean acidification at the Reef scale.	
6	Track paths, intensities, spatial extent and system speed of all tropical cyclones in or near the Reef.	This is a routine activity for the Australian Bureau of Meteorology. Monitoring the severity of storms and related impacts on marine ecosystems is a relevant activity here.
7	Determine rainfall patterns as a result of tropical cyclones and lows.	This is a routine activity for the Australian Bureau of Meteorology.
8	Determine flow rates and volume of fresh water entering the Reef from adjacent catchments.	Primarily a terrestrial activity.
9	Determine three-dimensional extent and duration of flood plumes during flood plumes.	Capacity in eReefs and other models.
10	Measure status in extent of proposed and actual dredging activities. Determine properties of dredged materials including physical properties, nutrients, chemicals and toxins. Determine movement of sediments from dredging and dumping of dredged spoil. Determine contribution of dredging activity to sediment resuspension. Determine impact on sedimentation, turbidity and light levels from sediment plumes derived from dredging activities.	Dredging activities are typically conditional on compliance monitoring activities. Understanding the physical properties, nutrients, chemicals and toxins present in material to be dredged is a specific monitoring activity required (through legislation) prior to dredging. More general monitoring is required to observe Total Suspended Sediment concentrations and impacts on sub-surface light broadly across the Reef under different environmental events, and in response to different activities. Impacts of specific dredging activities should be monitored as part of activity compliance monitoring, and these would vary on a case by case basis.

Reporting products to be delivered as part of RIMReP, in addition to the regular Outlook Report and Reef and Regional report cards, have yet to be comprehensively defined. However, the Outlook reporting requirements and suggested monitoring objectives listed above provided broad guidance for the identification of relevant indicators.

The physical and chemicals properties of the Reef's waters provide the environmental context which supports ecological processes and other cultural and human values. It is therefore relevant to many of the Reef 2050 Plan outcomes, objectives and targets. The monitoring activities recommended for the physical and chemical environment will address the Reef 2050 outcomes, objectives and targets listed in Table 4.

Table 4. Reef 2050 outcomes, objectives and target to be addressed by the monitoring activities recommended for the physical and chemical environment.

Reef 2050 outcome	Objective	Target
The status and ecological functions of ecosystems within the World Heritage Area are in at least good condition with a stable to improving trend.	EHO2 — The World Heritage Area retains its integrity and system functions by maintaining and restoring the connectivity, resilience and condition of marine and coastal ecosystems.	EHT4 — Key direct human related activities are managed to reduce cumulative impacts and achieve a net benefit for the Reef.
	EHO3 — Trends in the condition of key ecosystems including coral reefs, seagrass meadows, estuaries, islands, shoals and inter-reefal areas are improved over each successive decade.	EHT5 — Condition and resilience indicators for coral reefs, seagrass meadows, islands, estuaries, shoals and inter-reefal shelf habitats are on a trajectory towards at least good condition at local, regional and Reef-wide scales.
The Reef maintains its diversity of species and ecological habitats in at least a good condition with a stable to improving trend.	BO2 The survival and conservation status of listed species within the World Heritage Area is promoted and enhanced.	BT2 — Trends in the availability and condition of habitats for species of conservation concern are improving at Reef-wide and regionally relevant scales.
	BO5 — Reef habitats and ecosystems are managed to sustain healthy and diverse populations of indicator species across their natural range.	BT5 — Trends in populations of key indicator species and habitat condition are stable or improving at Reef-wide and regionally relevant scales.
Reef water quality sustains the outstanding universal value, builds resilience and improves ecosystem health over each successive decade.	WQO1 — Over successive decades the quality of water entering the Reef from broad scale land use has no detrimental impact on the health and resilience of the Reef.	WQT3 — By 2020, Reef-wide and locally relevant water quality targets are in place for urban, industrial, aquaculture and port activities and monitoring shows a stable or improving trend.

		WQT4 — Water quality in the Reef has a stable or positive trend.
	WQO2 — Over successive decades the quality of water in or entering the Reef from all sources including industrial, aquaculture, port (including dredging), urban waste and stormwater sources has no detrimental impact on the health and resilience of the Reef.	WQT3 — By 2020, Reef-wide and locally relevant water quality targets are in place for urban, industrial, aquaculture and port activities, and monitoring shows a stable or improving trend. WQT4 — Water quality in the Reef has a stable or positive trend.
Economic activities within the World Heritage Area and its catchments sustain the Reef's outstanding universal value.	EBO2 — Protecting the Reef's outstanding universal value is embedded within decision making with impacts first avoided, then mitigated and then, as a final consideration, any residual impacts offset to achieve a net environmental benefit.	EBT3 — Cumulative impacts on the Reef from human activities are understood and measures are taken to ensure a net environmental benefit approach for the Reef are in place.

2.3 Information needs for Great Barrier Reef management

The combination of *in situ* observations via sampling or logging sensor-based systems at discrete sites, together with broader spatial coverage delivered through remote sensing and data-assimilating, deterministic, biogeochemical models provides a comprehensive and valuable data collection to support a range of tactical and strategic uses for managers of the Reef. Examples of management use range from situational awareness through to determining short and long-term trends in key indicators and predicting future states under altered management regimes. The following table outlines management uses for a potential list of priority indicators (to be described in more detail later).

Table 5. Proposed indicators and their potential use for management.

Indicator/ product	***Tactical***	***Operational***	***Strategic Planning***	***Quantifying effectiveness***	***Reporting***
Nutrients	Near real-time access to data Current status	Changes in water quality during previous year	Annual and inter-annual trends in water quality Resilience-based zoning	Link with change in adjacent catchments; pollution loads	Improvements towards water quality guidelines
Sediment	Near real-time access to data Current status	Changes in water quality during previous year	Annual and inter-annual trends in water quality (Pressure) Resilience based zoning	Link with change in adjacent catchments; other activities (maintenance dredging/ disposal)	Improvements towards water quality guidelines
Marine debris	Identify hotspots of pollution	Guide response/ cleanup		Link with potential change in plastic use laws	
Light		Support/guide impact assessments following events	Resilience based zoning		
Temperature	Near real-time access to data Current status	Bleaching response activities RHIS survey	Resilience based zoning		Articulation of climate related threats

Salinity	Near real-time access to data Current status	River plumes and intrusions	Resilience based zoning		Articulation of climate related threats
Ocean Currents		Incident response			Articulation of climate related threats
Ocean Acidification	Near real-time access to data Current status		Resilience based zoning		Articulation of climate related threats
Extreme events (cyclones)		Response activities Temporary zoning changes	Resilience based zoning		Articulation of climate related threats
Sea Level Rise		Island management	Resilience based zoning; Island management		Articulation of climate related threats
Primary production	Near real-time access to data Current status		Annual and inter-annual trends in water quality		
Noise		Identify acoustic background and anomalies	Quantification of acoustic pollution issue		
Pesticides	Identify hotspots of pollution Near real-time access to data Current status		Resilience based zoning	Link with change in adjacent catchments; pollution loads	Improvements towards water quality guidelines

The Great Barrier Reef Marine Park Authority (the Authority) publishes a *Science Strategy and Information Needs* on a five-yearly cycle, linked to the findings of the Outlook Report. The *Science Strategy and Information Needs 2014–2019* sets out the current scientific information needs of the Authority. It aims to ensure that science activities are relevant, targeted to address critical management issues, and that their outcomes are easily accessible. Science providers can use this strategy to design proposals for research and the Authority uses it to assess proposals.

3.0 Physical and chemical environment expert group

The objectives of the marine physico-chemical environment expert group include:

- Review of existing indicators of water quality and an assessment of their adequacy and ability to:
    - clearly resolve anticipated changes in reef water quality,
    - provide sufficient context to aid in the interpretation of ecological responses associated with changes in water quality.

  Identify alternative indicators where review suggests existing indicators are inadequate.

- Review and evaluate existing water quality monitoring programs and other sources of water quality information (e.g. marine modelling, satellite remote sensing) and existing and emerging technologies, as candidates for inclusion in future Reef monitoring to inform identified selected priority indicators.
- A gap analysis of information requirements for physico-chemical parameters as part of various reporting obligations.
- Recommendations for an observational strategy and sampling approach for Marine physico-chemical variables to inform selected priority indicators under RIMReP. This will include defining data needs of marine modelling activities if those activities are to underpin parts of RIMReP.
- Recommendations for the development of data aggregation techniques and reporting products as informed by the RIMReP process and through existing complementary projects[1].

[1] This will draw on work to be undertaken in NESP TWQ Project 3.2.5 testing and implementation of the water quality metric for the 2017 and 2018 reef report cards.

4.0 Current understanding of physical and chemical processes and status on the Great Barrier Reef

Synopsis of conceptual system understanding of the physical and chemical environment and processes on the Reef's water quality, and physical and chemical parameters and processes are pressures to many of the Reef's ecological systems, but are also values in their own right. The following conceptual diagram (Figure 2) outlines the understanding of the condition of the water column as a value, and identifies the pressures acting upon it.

Many of the processes (for example, ocean temperatures, nutrient and sediment inputs from catchments and impacts on light) are also primary pressures for other ecological and cultural values, and the impacts of these pressures on particular ecological systems will be captured in conceptual diagrams from other expert groups.

Within the conceptual understanding of 'open water' as a value, there are subcomponents of the system that are recognised knowledge gaps and require further investigation. Primary knowledge gaps include:

- Linkages between physical processes (waves, tides, freshwater discharge events) and benthic-pelagic coupling. This will provide a physical basis for interpreting water quality monitoring data and will improve numerical modelling exercises in the region. Process-based studies will help predict nutrient cycling, suspended particle composition, and benthic light availability.
- Cycling of terrestrially-derived nutrients, understanding the bioavailability of terrestrially sourced particulate nitrogen in the marine environment and its role in driving phytoplankton production and composition. Rates of transformation between refractory and labile nitrogen and phosphorus pools are critical knowledge gaps that will improve estimates of 'lag time' in changes to water quality. This is important for coastal water clarity and food webs, including promoting and sustaining crown-of-thorns starfish outbreaks.
- Calibration of remotely sensed estimates of pelagic primary productivity.
- Nutrient cycling, the role of organic matter and the significance of dissolved nitrogen (N) and phosphorus (P) fluxes as nutrient source that ultimately fuels coastal phytoplankton production and affects water quality is not presently clear and may vary with composition and source of particulate organic matter, physical processes (wave and tidal forcing), and seasonal or inter-annual variability in particulate organic matter inputs.
- The degree to which catchment runoff contributes directly to coastal particulate organic matter pools and thus acts as an additional nutrient source to the Reef lagoon is not presently well-established. The lability of particulate organic matter derived from different sources (for example, terrestrial or coastal) has been identified as a major knowledge gap for Reef catchment nutrient management.
- Ocean acidification processes and impacts have strong cross-shelf gradients. In offshore areas, ambient oceanic conditions and atmospheric carbon dioxide largely determine the seawater chemistry. In inshore areas a process known as 'coastal acidification' adds carbon dioxide to the coastal waters due to elevated nutrient concentrations from terrestrial runoff of soil and fertilisers, leading to higher

respiration rates from increased benthic and pelagic biomass and organic enrichment of sediments.

- Distinction of land-based influences versus other factors. For example, floods vs wind-driven resuspension, floods vs dredging (relevant to total suspended solids and potentially particulate nutrients — inner and mid-shelf)

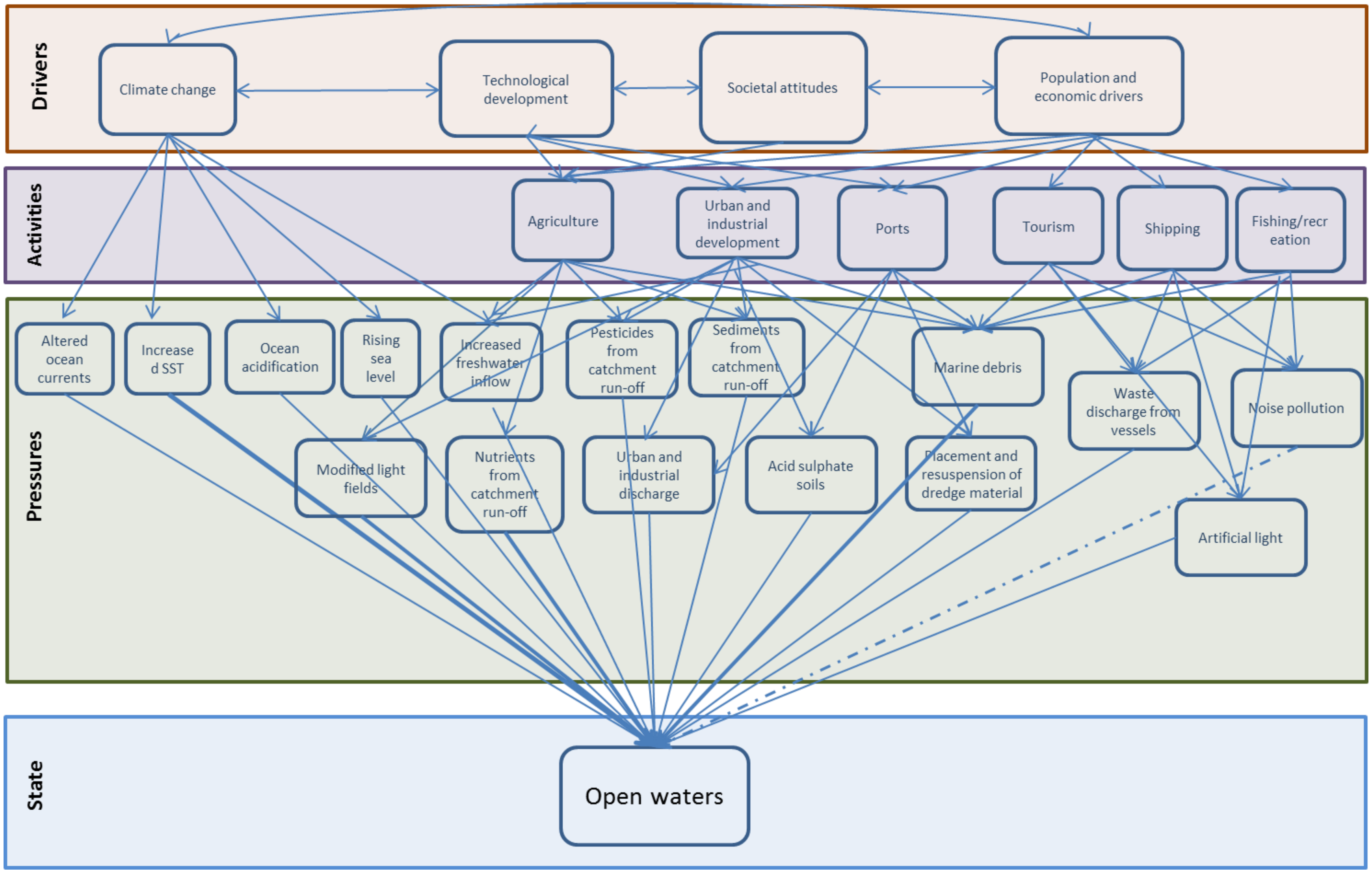


Figure 2. **Conceptual diagram of the drivers, activities and impacts that influence the state of the 'Water Column' value.**

4.1 Synopsis of current status of marine water quality and associated physical chemical variables and processes on the Great Barrier Reef

The *2017 Scientific Consensus Statement* and relevant chapter on the condition of coastal and marine ecosystems of the Reef (Schaffelke et al 2017), provides a good synopsis of the current status of marine water quality and associated variables and processes. Key points are as follows:

- Water temperatures on the Reef have warmed by approximately 0.80°C since the late 19th century. The warming trend will continue, but the rate of warming, both regionally and locally is unknown.
- Observations of turbidity and suspended sediment concentrations in coastal waters of the Reef demonstrate strong spatial and temporal variability across the Reef and at individual reefs. Analysis has shown that turbidity in the Reef lagoon is significantly affected by terrestrial loads delivered through river flow and rainfall, irrespective of wave height, wave period and tidal range.
- Poor water quality, especially elevated concentrations of and different ratios of, nutrients and high turbidity, has been shown to increase the likelihood of bleaching in corals. Experimental evidence suggests that increased temperatures, high dissolved inorganic nitrogen concentrations and unbalanced nitrogen: phosphorus ratios can increase the susceptibility of corals to bleaching. In addition to nutrients and temperature, light/turbidity also contribute to determining coral thermal tolerance.
- Evidence of the link between poor water quality (specifically nutrients) and crown-of-thorns starfish outbreaks has been strengthened. Knowledge gaps remain around the understanding of the detailed mechanisms and processes by which nutrient run-off promotes crown-of-thorns starfish outbreaks. A specific research need is to quantify phytoplankton responses in terms of suitability as crown-of-thorns starfish larval food (as energy or organic carbon content rather than chlorophyll) in response to various nutrient concentrations, forms and ratios.
- Ocean acidification is increasingly recognised as an important water quality pressure on the Reef and on coral reefs globally. The levels of partial pressure of carbon dioxide on inshore reefs have disproportionately increased compared to atmospheric levels, and inshore waters now have an environment that may adversely affect coral calcification and is more beneficial for benthic algae, seagrasses and phytoplankton. An analysis of a multi-year dataset of carbonate chemistry parameters (aragonite saturation, partial pressure of carbon dioxide) collected at the water quality monitoring sites of the Great Barrier Reef Marine Monitoring Program and some offshore reefs showed marked differences across the shelf. On inshore reefs, nocturnal metabolism of abundant organic matter releases additional carbon dioxide during the night, which reduces pH.
- Pesticides pose a risk in inshore waters at some locations, and a greater risk to adjacent freshwaters. The consequences of long-term exposure at concentrations below those known to affect most organisms is not well understood. PSII-inhibiting herbicides are regularly detected in the inshore Reef lagoon and, during flood events, may exceed guidelines and reach concentrations known to affect marine organisms. The risks associated with the use of new alternative pesticides in Reef catchments have not been fully quantified.

- Reducing end-of-catchment loads of nutrients, sediments and pesticides will help enhance reef resilience in the face of continuing climate change pressures. For example, if the impacts of crown-of-thorns starfish were reduced following nitrogen load reduction from the Wet Tropics, coral cover is predicted to either recover or at least stabilise.
- Acute disturbances such as severe tropical cyclones can result in localised sediment movement and nutrient release that is highly site-specific.

The Consensus Statement update also identifies knowledge gaps and research recommendations relevant to the physical and chemical environment components of RIMReP.

> *"To improve assessments of coastal and marine water quality and the attribution of changes to catchment activities and river water quality, it is important to:*
>
> - *improve validation and calibration of the eReefs biogeochemical model, through in situ observations of water quality from areas other than coastal Marine Monitoring Program locations (for example, Cape York, mid- and offshore areas).*
> - *clarify our understanding of the spatial and temporal patterns of water quality parameters in the Reef, for the purpose of refining existing water quality guideline values.*
> - *determine the bioavailability of terrestrially sourced particulate nutrients in the marine environment; the nitrogen forms dominate the terrestrially derived nitrogen and may play a critical role in driving phytoplankton production and composition, which in turn is important for coastal water clarity and food webs, including promoting and sustaining crown-of-thorns starfish outbreaks.*
> - *determine the transport, fate and impacts of the finest sediment factions and the formation and ecological significance of organic flocs in the receiving marine environment.*
> - *inform future risk assessments by conducting targeted monitoring campaigns for contaminants that may pose a relatively high risk to coastal and marine ecosystems, including marine debris / microplastics (Reef-wide), antifouling paint components (shipping lanes and anchoring areas) and personal care products (coastal and tourism sites).*
> - *ensure that all water quality data are available in the public domain for improving determinations of marine baselines and environmental risk assessments."*

5.0 Priority indicators to monitor on the Great Barrier Reef

The indicators presented in Table 6 are recommended as priority monitoring candidates as part of the physical and chemical environmental monitoring component of RIMReP.

Table 6. Indicators recommended as priority monitoring candidates as part of the physical and chemical environmental monitoring.

Indicator Group	Priority Indicator	Justification for selection*	Related Reef 2050 Objective/Target
Nutrients	Nutrients (N and P species; silica as well as chlorophyll *a* as a proxy of nutrient enrichment) (dissolved and particulate)	Nutrient delivery and enrichment is an underpinning process for many components of benthic and pelagic ecosystems. Considered a key pressure on marine ecosystems – primarily inshore and some areas of mid-shelf. Measure/evaluate marine ecosystem response to changes in catchment loadings.	WQO1, WQO2: species, speciation changes, trace nutrients, organic carbon; important for understanding management options and effectiveness (e.g. DIN versus OM); EH02 EB02
	Nutrients (Carbon species)	As above	
	Chlorophyll *a*	As a proxy for pelagic production and for dissolved inorganic nitrogen; major controls on benthic light availability.	
	Nitrogen river-derived loading maps (use DIN and PN as proxies)	Maps of DIN exposure from Rivers – useful spatial overlay.	
Primary production	Phytoplankton community composition	Basis of the pelagic food web, important for fisheries.	EH02
	Zooplankton community composition	Inferred from indicators that inform other elements (e.g. chlorophyll, temp). Trophic implications e.g. suspected shifts in size of plankton may have influenced recent crown-of-thorns larval survival rates.	

		An indicator of overall pelagic condition	
Sediment	Suspended sediment concentration (solids)	A key pressure on marine ecosystems – primarily inshore. It is a measure of marine effects of actual catchment load reductions.	WQO1, WQO2 EH02, EB02 As Above As Above
	Turbidity	Lack of water clarity and resultant light attenuation is a key indicator of poor water quality and is an essential environmental factor for phototrophic organisms that dominate coral reefs, seagrass meadows and the seafloor microphytobenthos. Light availability (integrated through time) is a key pressure for phototrophic organisms.	
	Secchi depth		
	Sediment river-derived loading maps	Model and remote sensing based – useful spatial overlay.	
Marine debris	Marine debris — density of plastics recovered (per unit effort) through beach cleanups.	Emerging contaminant of concern – broadscale ecosystem impacts unquantified at present. - measure of effectiveness of (terrestrial) waste management activities.	EH02, WQ02
	Microplastics — standardised density of microplastic particles	Emerging contaminant of concern — broadscale ecosystem impacts unquantified at present.	
Light	Vertical attenuation (spectrally resolved across frequencies)	Light is an essential environmental factor for phototrophic organisms that dominate coral reefs, seagrass meadows and the seafloor microphytobenthos.	WQ02, EH02, EB02
	Secchi depth		
	Benthic PAR		
	Surface PAR		

		Light availability (integrated through time) is a key pressure for phototrophic organisms. Measure of marine effects of actual catchment load reductions.	
Temperature	Sea Surface Temperature *In situ* water column temp — fixed sites Water column temperature (3D maps - modelled)	Priority Pressure on marine ecosystems. Coral bleaching indicator and predictor of thermal stress. Significant contributor to cumulative impacts. Informs tactical monitoring and deployment of field teams to assess bleaching damage. In a predictive capacity can inform strategic planning (e.g. zoning, resilience mapping).	EH02, EB02
Salinity	*In situ* water column salinity Water column Salinity (3D maps - modelled)	Pressure on marine ecosystems Useful, but local indicator of river plume extent Indicator of circulation	EH02, EB02
Ocean currents	*In situ* water column current observations - fixed sites	Underpins understanding of connectivity. Can inform strategic planning for management response (for example, zoning, approvals, resilience mapping). Tactical information required for operational activities (maritime operations) and response (maritime incident) operations.	EH02, EB02
Ocean acidification	Operational pCO_2 systems (ship and fixed sites)	A priority pressure on marine ecosystems Link between nutrient inputs and coastal acidification opens options for ocean acidification	EH02, EB02

	Discrete water samples for chemical analysis (e.g. dissolved inorganic carbon;total alkalinity).	mitigation via improved nutrient management to reduce inputs. In a predictive capacity can inform strategic planning through identification of areas of high/low ocean acidification exposure (e.g. resilience-based zoning).	
Extreme events (cyclones)	Spatial description of cyclone impacts to coral reefs – based on cyclone damage model (Marji Puotinen).	Informs the Authority's response to cyclone damage. Can trigger deployment of and guide field teams to assess the on-ground damage post cyclones (RHIS). Identify spatial patterns in historic tropical cyclone exposure to explain habitat condition trajectories. Extreme wave exposure is a factor in identifying resilient reefs.	EB02
	BoM cyclone tracking, including air pressure maps cyclone tracking, wind.		
	Waves heights – observed (Queensland network, BoM models)		
Sea Level Rise	Spatial description and rate of sea level rise along the Reef coast. Altimetry derived Sea Surface Height	Strategic	EB02
Noise	Ocean noise, 2 Hz to 6 kHz As an archive physical, man-made and biological sources.	Anthropogenic noise in Australian marine soundscapes and assess the impact on marine fauna [to be completed].	EB02
Pesticides in high flow events at priority locations	PSII herbicides	Pesticides pose a risk to some coastal and inshore locations. Observed concentrations provide a measure of potential impact to inform prioritisation of catchment management action.	WQ02, WQ01,EH02
	Non-PSII herbicides including emerging 'alternative' herbicides.		
	Pesticides		

6.0 Evaluation of the adequacy of current monitoring of the physical and chemical environment area on the Great Barrier Reef

6.1 Synopsis of existing monitoring programs

A synopsis of existing monitoring programs, their methods, coverage, adequacy and gaps in monitoring effort were assessed for each of the priority indicators identified for the physical and chemical environment (Appendix A). The information in Appendix A is intended to only cover monitoring programs relevant to priority indicators and sub indicators.

6.2 Adequacy of existing monitoring programs

The combination of *in situ* observations — via sampling or logging sensor based systems at discrete sites — together with broader spatial coverage delivered through remote sensing and data assimilating deterministic biogeochemical models, provides a comprehensive and valuable data collection to support a range of tactical and strategic uses for managers of the Reef. These uses include, for example, incident response, situational awareness through to determining trends in key indicators over short- to long-term horizons, and predicting future states under altered management regimes. There is, however, a need for an integrated representation of many of the priority indicators across the entire Reef and water column that combines models and observations from various platforms. The NESP-funded *Project 3.2.5: Improvements to the marine water quality metric for Reef Report Card* has made significant progress in determining and evaluating approaches for data integration and aggregation collected/produced by remote sensing, models, *in situ* sampling and logger data for a range of parameters including chlorophyll *a*, total suspended solids, secchi depth and nitrogen oxides.

The recommendations from this report rely heavily on the application of marine models to fill data deficiencies related to geographic coverage, temporal frequency, derivation and delivery of some priority indicators. When considering the adequacy of existing monitoring, we must also consider the adequacy of the monitoring required to provide the models with sufficient required information to ensure relevant, useful outputs of known or ascertainable accuracy.

The adequacy of broad-scale monitoring to support marine modelling should consider the following factors:

- Remotely sensed Earth observing systems play a fundamental role in generating regional-scale data beyond the limits of the Reef, and this must maintain currency with international capability and standards.
- The majority of offshore data (i.e. oceanic inputs to the Reef) is obtained through remote sensing with little calibration/validation due to a limited number of *in situ* moorings, limited coverage by ARGO profilers and infrequent ship-of-opportunity transits.
- Data about the physical state of the Reef and regions adjacent obtained by remote sensing is relatively comprehensive, however, *in situ* observations are sparse and sporadic. IMOS has provided a few long-term sustained observations/measurements

since 2007. Of the basic physical parameters, there is less confidence in salinity observations than for temperature, pressure and currents.

- There remains several notable gaps in related parameters such as sound and light (including its spectral composition) through the full water column and sea surface height within the Reef itself, although near-shore measurements are relatively robust.
- Due to the Reef's large expanse, data coverage is sparse, with access to many locations hindered by a dependence on ship-based methodologies. Existing physical monitoring would benefit from an increased spatial coverage and resolution. This has already been recognised by the Queensland Node of the Integrated Marine Observing System (Q-IMOS) Science and Implementation Plan 2015-25 which notes that the array has reduced since 2014 due to cessation of co-investment by Queensland Government and other time-limited co-investors.
- Monitoring of the chemical parameters of the Reef's seawater and the oceanic waters that enter it has commenced, but it needs to be sustained and developed to capture parameters currently measured in an *ad-hoc* or unsustained manner (for example, partial pressure of carbon dioxide, dissolved oxygen, and nutrient concentrations).
- There remains a number of one-off datasets that require generation and which will not require ongoing funding after they have been obtained, except in those cases where less intensive checks need to be undertaken to determine if change has occurred since the baseline dataset was generated (for example, high resolution bathymetry of major estuaries and rivers).
- Similarly, some fundamental process parameters need to be determined but this requires a singular effort and is not part of a sustained observing program, although the parameters may be derived from observation time series. Example processes that are critical to inform biogeochemical models include descriptions/parameterisations of plankton dynamics such as growth and grazing rates, and definition of size classes.
- Observations that can be used for calibration/validation are sparse and geographically restricted. This contributes to a wide variety of uncertainty across models that cover the whole Reef domain, with highest uncertainty in some critical locations (for example, northern Reef).
- Pelagic biological observing is very weak with the most substantial data streams being fluorescence time series, with some water sampling to link fluorescence to chlorophyll *a*, which is a proxy for phytoplankton biomass, and to a lesser degree plankton productivity.
- Most programs are the result of organisational imperatives and, as such, can be subject to the priorities of the investing organisation (for example, Earth observing systems).

6.3 Gaps in current monitoring effort

Gaps in monitoring effort were assessed for each of the priority indicators identified for the physical and chemical environment. This information is contained in Appendix A.

Notable gaps are as follows:

- *Geographic:*
    - Very sparse *in situ* observation on northern Reef, inshore, mid-shelf, offshore.
    - Limited *in situ* monitoring on mid-shelf and offshore parts of the Reef across all regions.
    - No ongoing monitoring of inshore areas in the Fitzroy and Burnett Mary regions.
    - Within regions — offshore from: Herbert (Hinchinbrook area); Haughton (Bowling Green Bay); Plane; Mary.

- *Parameters:*
    - Need for an integrated representation of nutrients/primary production across the entire Reef and water column that combines models and observations to allow for improved risk assessment when combined with habitat mapping. Most direct sampling (point in time for nutrients and instrument loggers for chlorophyll) covers the inner shelf region of the Reef — the mid and outer-shelfs are represented poorly in most sampling programs, or not represented at all. Determining whether required nutrients vary among different phytoplankton species would also be important.
    - Need to resolve estimates of chlorophyll derived from in-situ bio-optical and remotely sensed spectral observations, in optically complex waters such as those of the Reef. The correct application and interpretation of bio-optical instrumentation is a key component of understanding of physical-chemical-biological linkages in coastal and oceanic Australian waters. Unlike standard physical measurements such as temperature and salinity, the calibration, validation and interpretation of data generated by these bio-optical instruments and remote sensing techniques is not necessarily straight forward.
    - Need for an integrated representation of suspended sediment across the entire Reef and water column that combines models and observations to allow for improved risk assessment when combined with habitat mapping. Need to also consider differences in sediment particle size (and composition such as organic material) as finer particles can travel further and stay in suspension longer and have different effects on corals and fish. Most direct sampling (point in time for total suspended solids and instrument loggers for turbidity) covers the inner shelf region of the Reef — the mid and outer shelfs are poorly represented in most sampling programs, or not represented at all. Modelling needs *in situ* data to validate results.
    - No co-ordinated noise monitoring on the Reef.
    - Limited ocean acidification observations.

- Primary productivity has not been implemented operationally in Australia. Primary productivity is a derived product based on remotely sensed inputs (chlorophyll *a* and sea surface temperature).
- Need standardised protocols for sampling, processing and analyses of marine debris (including microplastics) in marine waters, sediment and biota.

7.0 New technologies for monitoring the marine physical and chemical environment of the Great Barrier Reef

The pipeline of experimental monitoring tools applicable to observing the physical and chemical environment on the Reef contains a number of emerging technologies and products (for example, ocean surface current radars, *in situ* chemical samplers and logger) as well as platforms to carry them, such as autonomous vehicles (gliders, autonomous underwater vehicles) and reef-based wireless sensor networks.

However, their application to the Reef is currently limited by operational maturity of technology, and the large spatial extent and required frequency of observations. We propose that only mature technology or monitoring protocols be applied following a framework of readiness levels recommended by the Global Ocean Observing System[2].

The identification and evaluation of new technology should consider technological advances at every stage along the entire data collection and delivery spectrum, from sensor, platform, processing, telemetry, analysis/modelling to reporting and delivery.

We propose a structure of regular review and revisiting of new and emerging technology as it arises. Through existing partnerships with broader monitoring activities and the scientific communities, the adoption of new technologies should follow the lead of initiatives such as IMOS and the Global Ocean Observing System.

Autonomous ocean gliders represent a mature technology that has proved suitable for regional observing in remote parts of the Reef. Through recent partnerships with IMOS and the Great Barrier Reef Foundation, Slocum glider missions on the Reef have demonstrated the utility of the gliders to operate effectively in bathymetrically and oceanographically complex environments. Reef glider missions have covered regions from the northern (Princess Charlotte Bay), central (Wet Tropics region) and southern (Heron Island) Reef and have captured oceanographically and ecologically relevant processes that have previously been poorly observed. Subsurface data collected by gliders have been used as an assessment data set for the eReefs marine models. Data assimilation activities within eReefs are now focused on integration of satellite remote sensing information. This approach has proven to increase the accuracy in prediction of subsurface biogeochemical parameters, and glider data will remain a valuable source for model assessment.

[2] A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing, UNESCO 2012, IOC/INF-1284 rev., doi: 10.5270/OceanObs09-FOO

8.0 Recommendations for integrated monitoring of the marine physical and chemical environment of the Great Barrier Reef

For the priority indicators, we propose a hierarchical approach of some broad scale indicators derived primarily from data assimilating models and remote sensing products, validated by regular *in situ* sampling at specific fixed observing locations, and supported by process studies to answer specific knowledge gaps.

The following table outlines the indicators to be monitored/derived at broad-scale, those observed at specific sites and those targeting specific processes.

Table 7. Hierarchical approach to monitoring priority indicators.

Indicator Group	***Priority Indicator***	***Broad-Scale***	***Site***	***Process***
Nutrients	Nutrients (N and P species)		X	X
	Nutrients (Carbon species)		X	X
	Chlorophyll *a*	X,X_m	X	X
	Nitrogen: river derived loading maps	X_m		X
Sediment	Suspended sediments (solids)		X	X
	Turbidity	X,X_m	X	X
	Secchi depth	X,X_m	X	X
	Sediment: river derived loading maps	X,X_m		
Light	Benthic PAR	X_m	X	
	K_d – vertical attenuation rate (spectrally resolved)	X_m		
	Secchi depth	X,X_m	X	
Marine debris	Marine Debris		X	
	Microplastics	X	X	
Temperature	Sea Surface Temperature	X	X	X
	In situ water column temp		X	
	Water column temperature	X_m	X	X
Salinity	Salinity	X_m	X	X
Altered Ocean Currents	Ocean Currents	X_m	X	X

Ocean Acidification	pH, Total Alkalinity, DIC, pCO_2	X	X	X
	pH, Total Alkalinity, Aragonite Saturation	X_m	X	
Extreme events (cyclones)	Spatial description	X	X	
	BoM cyclone tracking	X	X	
	Waves	X_m	X	
	Sea Levels	X_m	X	
Primary production	Primary production estimate	X,X_m		X
	Rates of change of chlorophyll *a*	X,X_m		X
	Phytoplankton / zooplankton community composition	X	X	
Marine Noise	Ocean noise, 2 Hz to 6 kHz		X	
Pesticides	*In situ* concentration		X	

Note: columns marked with X represents an observation, and X_m represent information derived from models.

8.1 Broadscale

Broadscale indicators, by their very nature, need to cover the full extent of the Reef using cost-effective technology and approaches. Primary information generation and observing technologies include broad-scale marine models, remote sensing and shipborne observations on repeat transects.

Marine models:

Marine models simulate and predict the physical hydrodynamic state, sediment transport, water quality and basal ecology of the Reef lagoon and reef matrix. Together, these models represent a capability to simulate the transport and fate of waterborne material on Reef water quality.

The eReefs project has delivered a suite of hydrodynamic, sediment transport and biogeochemical models, applied at a range of spatial scales for the Reef (see Herzfeld et al, 2016).

The eReefs biogeochemical model is coupled to a near-real time, fully baroclinic hydrodynamic model, forced by historical data from the atmosphere and oceanic boundary that produces skilful assessments of circulation (at four kilometre and one kilometre resolution) for a very large marine domain, inclusive of the entire continental shelf and proximate Coral Sea, from Papua New Guinea to the New South Wales border (Herzfeld

2015, Baird et al. 2016). The presently archived model simulations received freshwater flows with associated sediment and nutrient loads from 17 of the 35 major basins in the Reef catchment: Normanby, Daintree, Barron, Mulgrave-Russell, Johnstone, Tully, Herbert, Haughton, Burdekin, Don, O'Connell, Pioneer, Fitzroy, Boyne, Calliope, Burnett and Mary. The loads and flows of the remaining basins are being introduced in the next phase of eReefs.

The Bureau of Meteorology has also developed an operational ocean forecasting system that produces real-time daily analyses and forecasts out to three days of currents, temperature, salinity, sea-level and river tracer concentrations from major rivers for the Reef region.

Other marine models are used to simulate and predict ocean temperatures and sea levels anomalies. The Bureau of Meteorology's seasonal prediction ACCESS-S forecasts sea surface temperature anomaly for the subsequent six months in the Reef.

Under the current eReefs Agreement (2018-2019) the following will be undertaken:

- **Biogeochemical modelling improvements**

  The eReefs biogeochemical model will be further refined in the areas of suspended solids modelling, integration of models of different resolutions, time coverage, ongoing skill assessment and inclusion of new variables (such as herbicides or other contaminants of interest).

- **Marine water quality modelling and reporting for regional and whole-of-Reef report card delivery**

  The application of the eReefs System to marine water quality reporting (as demonstrated in Phases 2 and 3) will be further refined to improve outputs in coastal areas and extended to contribute to regional report cards.

- **River flow and water quality modelling framework**

  The eReefs System will expand the river flow and water quality modelling capability developed in Phases 2 and 3 to cover more catchments including ungauged areas. Catchment flow forecasting models will continue to provide temporally relevant hydrological and water quality outputs feeding into other modelling components of the eReefs System and specifically the eReefs biogeochemical model.

- **Water quality management scenarios**

  The eReefs System will expand on the scenario modelling capability demonstrated in Phase 3 in the development of basin specific water quality targets and will model a range of additional whole-of-Reef and regional scenarios contributing to policy development and decision making by Reef water quality managers.

- **Reef-wide mapping**

  The eReefs System will deliver a range of mapping outputs to further the understanding of pressures and impact on the Reef system, such as coral bleaching, resilience areas and other focus areas.

- **Data access and visualisation**

  Improvements in the access to and visualisation of eReefs model outputs and data will be implemented to further the eReefs System capability, scalability and routine delivery in a range of areas, including user access to time series, libraries of scenarios, high resolution model outputs visualisation and access portals.

- **Critical observations**

  The eReefs System will integrate observations from new satellite systems and identify areas for further investment in observations to maintain and or improve the ongoing delivery of services.

Remote Sensing: Ocean Colour

Satellite-based remote sensing collects estimates of ocean surface reflectance from which can be estimated daily concentrations of optically active marine constituents (chlorophyll, colour dissolved organic matter and non-algal particulate matter) over the Reef region. Current algorithms are based on using MODIS data which are custom-processed through a local atmospheric correction that accounts for the spectral light field leaving the bright waters of the Reef (Schroeder et al. 2007), and the application of an adaptive in-water algorithm that selects the most appropriate in-water properties, based on a range of possible combinations determined to be representative from *in situ* measurement (Brando *et al.* 2012). Near-shore coastal waters of the Reef are optically complex and standard global Ocean Colour algorithms are inaccurate because of the large variability in Inherent Optical Properties (IOP) spectral shapes (Brando et al. 2006).

Satellite-based remote sensing of ocean surface reflectance can also be used to derive estimates of ocean clarity and light attenuation to estimate photic depth from various satellite platforms. For example, MODIS-Aqua (2002-2010) and SeaWiFS (1997-2010) satellite data (Weeks et al. 2012).

As satellite sensor technology evolves, it is important to appreciate issues surrounding algorithm development, calibration of algorithms and validation of derived products. There is a need to demonstrate consistency of derived products between platforms (and/or sensors and algorithms) to enable long-term trend analysis of the state of marine systems from data that was collected over multiple platforms.

Remote Sensing: Sea Surface Temperature and Sea Surface Temperature Anomaly

The Bureau of Meteorology generates IMOS L3S AVHRR sea surface temperature products daily. The sea surface temperature product used in ReefTemp Next Generation is comprised of one-day, night-only sea surface temperature from multiple NOAA satellites (NOAA-11, 12, 14, 15, 16, 17, 18, 19) at a grid resolution of 0.02° x 0.02° (approximately two by two kilometres).

Sea surface temperature anomaly is calculated as the difference between sea surface temperature values and climatology, the monthly long-term mean sea surface temperature. Two climatologies are used to produce products. The first is an IMOS climatology for 2002 to 2011, constructed for each month using IMOS L3S one-day, night-only sea surface temperature products in that period. The second climatology used is the CSIRO 1993 to

2003 climatology that the legacy ReefTemp (V1) system utilised. The use of both climatologies allows for comparisons of products based on different reference periods. All sea surface temperature anomaly values appear in the range minus four to plus four degrees Celsius.

Ship-bourne underway systems

The IMOS Sensors on Tropical Research Vessels' sub-facility maintains the set of automated sensors designed for taking observations from research vessels that operate in Australia's tropical waters. The instruments obtain underway observations of temperature, salinity, chlorophyll fluorescence, and turbidity. The *R.V. Cape Ferguson* collect observations along the Reef. The IMOS Continuous Plankton Recorder Sub-Facility uses a number of Continuous Plankton Recorders and is the only platform that can assess plankton species and be towed behind ships of opportunity. Ships of opportunity also provide ideal platforms to support repeat tows for microplastic sampling.

The Rio Tinto vessel, the *RTM Wakmatha*, travels the length of the Reef, from Weipa to Gladstone, on a regular basis and continuously collects ocean chemistry data along the length of the Reef during its regular voyages. The sensors sample surface waters every one to two minutes, taking measurements of carbon dioxide, ocean acidity, temperature, salinity and dissolved oxygen.

The list of indicators recommended to be monitored or derived at a broad scale are presented in Table 8.

Table 8. Summary of indicators to be observed at a broad scale, and suggested approach.

Indicator Group	***Priority Indicator***	***Broadscale***	***Approach***
Nutrients	Chlorophyll *a*	X,X_m	Remote sensing — mid-shelf and offshore, eReefs biogeochemical (BGC) model, Ships of Opportunity (fluorescence proxy)
	Nitrogen loading maps	X_m	Remote sensing
Sediment	Turbidity	X,X_m	Remote sensing, eReefs BGC model, Ships of Opportunity
	Sediment loading maps	X_m	Remote sensing
Marine debris	Microplastics	X	Ships of opportunity
Light	Benthic PAR (photosynthetic active radiation)	X_m	eReefs BGC model
	K_d - attenuation	X_m	eReefs BGC model

	Secchi depth	X,X_m	Remote sensing, eReefs BGC model
Temperature	Sea surface temperature	X	Remote sensing, Ships of Opportunity
	Water column temperature	X_m	eReefs BGC model
Salinity	Salinity	X_m	Ships of Opportunity, eReefs BGC model
Altered ocean currents	Ocean currents	X_m	eReefs BGC model
Ocean Acidification	pH, Total Alkalinity, DIC, pCO_2	X	Ships of opportunity, eReefs BGC model
Extreme events (cyclones)	Spatial description	X	BoM observations, remote sensing, and atmospheric models
	BoM cyclone tracking	X	BoM observations, remote sensing, and atmospheric models
	Waves,	X_m	BoM oceanic and wave models
	Sea Levels	X_m	BoM oceanic and wave models
Primary production	Primary production estimate	X,X_m	Remote sensing, eReefs BGC model
	Rates of change of chlorophyll *a*	X,X_m	Remote sensing, eReefs BGC model
	Phytoplankton / zooplankton community composition	X	Continuous plankton recorder on Ships of Opportunity

8.2 Site specific indicators

The suite of site-specific indicators build upon and extend existing, well established Reef monitoring programs. We propose a series of fixed sites at which comprehensive sampling of priority indicators is undertaken at regular intervals. Primary observing and monitoring technologies include fixed autonomous logging systems (for example, IMOS moorings, MMP loggers, temperature loggers) and regular, structured *in situ* sampling and collection activities (for example, MMP sampling, IMOS National Reference Stations).

IMOS National Reference Stations include surface observations (wind velocity, temp, pressure, light, ocean surface temperature), sub-surface observations (water temperature, current velocity, turbidity, fluorescence, benthic photosynthetically active radiation, light transmission) recorded by logging based sensors, and augmented by monthly water sampling for biogeochemical parameters CTD (Conductivity, Temperature, Density) and secchi disk sampling, to ground truth sensor data and other measurements, Hydrochemistry and plankton sampling of variables required to monitor nutrients, microbes, phytoplankton and zooplankton, water sampling of variables required for carbon monitoring (i.e., total dissolved inorganic carbon, total alkalinity, and salinity). We would propose to also add regular microplastic sampling and ocean acidification sampling.

Only one site is currently active under this program in the Reef — at the Yongala Wreck — and this is currently unable to provide Reef-wide representative information. Expansion of National Reference Station-style moorings (regional) would extend a well-established observing network that operates to (inter)national protocols to observe a suite of marine parameters.

The Inshore Water Quality portion of the Marine Monitoring Program (MMP) collects water samples for analysis of nutrient and suspended sediment concentrations. Vertical profiles of light, salinity, and temperature are collected at all sites. Sampling occurs at up to 31 sites in in Cape York NRM region sampled five times per year; six sites in the Cairns region sampled three times per year; 11 sites in the Wet Tropics NRM Region, sampled 11 times per year; six sites in the Burdekin NRM region, sampled 11 times per year; five sites in the Mackay Whitsunday NRM region, sampled five times per year. Roughly half the sites above are sampled during flood events (up to 6 events per year). Prior to 2015, MMP monitoring was also conducted at 3 sites in the Fitzroy NRM region. The MMP has been in operation since 2005, and in 2015 a comprehensive independent review of the program was undertaken (Kuhnert et al. 2015). Based on these recommendations, the number and frequency of sampling was substantially increased in each NRM region to increase statistical power.

The list of indicators recommended to be monitored or derived at specific sites are presented in Table 8.

Table 9. Summary of indicators to be observed at a specific sites and suggested approach.

Indicator Group	***Priority Indicator***	***Site***	***Approach***
Nutrients	Nutrients (N and P species)	X	MMP-based approach, IMOS protocol monthly sampling
	Nutrients (Carbon species)	X	MMP-based approach, IMOS protocol monthly sampling
	Chlorophyll *a*	X	MMP-based approach, IMOS protocol monthly sampling IMOS moorings (fluorescence)
Sediment	Suspended sediments (solids)	X	MMP-based approach, IMOS protocol monthly sampling

	Turbidity	X	MMP-based approach, IMOS protocol monthly sampling
	Secchi depth	X	MMP-based approach, IMOS protocol monthly sampling
Marine debris	Marine Debris	X	Beach surveys - structured
	Microplastics	X	Monthly sampling at reference sites
Light	Benthic PAR	X	IMOS moorings (benthic PAR)
	Secchi depth	X	MMP-based approach, IMOS protocol monthly sampling
Temperature	Sea surface temperature	X	IMOS protocol monthly sampling IMOS moorings/logger
	In situ water column temp	X	IMOS protocol monthly sampling IMOS moorings/logger
	Water column temperature	X	IMOS monthly protocol sampling IMOS moorings/logger
Salinity	Salinity	X	IMOS protocol monthly sampling IMOS moorings/logger
Altered Ocean Currents	Ocean Currents	X	IMOS moorings/logger
Ocean Acidification	pH, Total Alkalinity, DIC, pCO_2	X	MMP-based approach, IMOS protocol monthly sampling
Extreme events (cyclones)	Spatial description	X	Observation and Modelling of cyclone track
	BoM cyclone tracking,	X	Modelling of cyclone track
	Waves, Sea Levels	X	Queensland Government wave and tide network
Primary production	Rates of change of chlorophyll *a*	x	MMP-based approach, IMOS protocol monthly sampling

	Phytoplankton / zooplankton community composition	X	MMP-based approach IMOS protocol monthly sampling
Marine Noise	*In situ* concentration	X	Passive acoustic loggers on existing (expanded) infrastructure

8.2.1 Analysis of the spatial coverage of existing programs

International observational programs have been assessed using Observation System Simulation Experiments in order to optimise temporal and spatial coverage (Jones et al., 2015). Observation System Simulation Experiments involve using a model simulation to quantify the effectiveness of observation techniques and observation locations to quantify the state or phenomena of interest.

In the simple Observation System Simulation Experiments undertaken here, we use the spatial correlation of physical (temperature and salinity) and biogeochemical (chlorophyll *a*, total suspended solids, dissolved inorganic nitrogen) properties in the eReefs four-kilometre, coupled, hydrodynamic – biogeochemical model six-year simulation, forced by SOURCE Catchments river loads (GBR4_H2p0_B2p0_Cbas_Dhnd). The years 2011 to 2016 represent a one-in-a-100-year wet season (2011), as well as some average and dry years.

Spatial correlation is tightly linked to temporal scales. One component of the analysis is to choose a timescale over which we are looking for the spatial correlation. The timescale is identified by calculating spatial correlations over a defined time period, say one year, repeating this calculation for each year in the analysis period, and then generating a mean of all years. In general, the longer the timescale, the greater the spatial correlation. For example, coastal chlorophyll concentrations are typically higher in the wet season than the dry season along the entire Queensland coast. Therefore, an observation of chlorophyll off the Whitsundays anytime in February is likely to be greater than in October, and this change is likely to be true in the coastal Wet Tropics also. Ideally, the observation system will sample all spatial and temporal scales adequately. Since the longer timescales, dominated by seasonal changes, are well correlated over the entire Reef, the greater challenge is to observe shorter timescales.

Analysis has been undertaken for weekly (7 day), monthly (30 day) seasonal (90 day) and yearly timescales. Once the analysis is undertaken, it is possible to consider the footprint of the entire observation system, and the role each observation site makes to this system footprint. In the following section we discuss only the weekly timescale analysis. This most stringent of tests was undertaken as for much of the Reef, the sampling programs appear to be achieving spatially-representative data at the longer timescales, so it is primarily at the weekly timescale that we can improve on the present observations.

When considering this analysis, keep in mind that it is based on spatial correlations in the eReefs biogeochemical model. Conclusions drawn from the Observation System Simulation Experiments rely on accurate representations of spatial distributions more than absolute values. For example, if the model underestimates the spatial extent of a river plume, then Observation System Simulation Experiment analysis will underestimate the spatial footprint of an observation taken within that plume. It is also worth remembering that the model variables may not be identical to the observed quantities. For example, the model output is chlorophyll *a*, and would be more closely aligned to a high-performance liquid chromatography (HPLC) determination of chlorophyll *a* than a fluorometric technique. It is possible that the footprints of HPLC-determined chlorophyll and fluorescence-based chlorophyll vary, especially as the sources of difference, such as community composition, are likely to have their own coherent spatial structure. Even given these limitations, the Observation System Simulation Experiment provides new information for observation design.

The analysis below considers the IMOS and MMP programs separately. Finally, we also look at potential new sites with the Mackay-Whitsundays and Cape York regions where experts have identified a spatial gap in observations.

Description of the graphical representation of spatial footprints

The spatial footprints of observation sites are determined using the correlation coefficient for each variable between the observation site and all other grid cells in the model (Figure 3). For brevity we will show only one instance of this calculation. Figure 3 shows the spatial correlation of chlorophyll *a* of the Double Cone MMP site, extending primarily southward at the interface between the Reef lagoon and the inshore reefs. It shows waters on the inshore edge of the lagoon off Rockhampton behave more like Double Cone than the closer inner-most sections of Repulse Bay. Thus, a closer vicinity does not necessary ensure better correlation. For the analysis below we will consider only correlation coefficients greater than 0.5 as being useful.

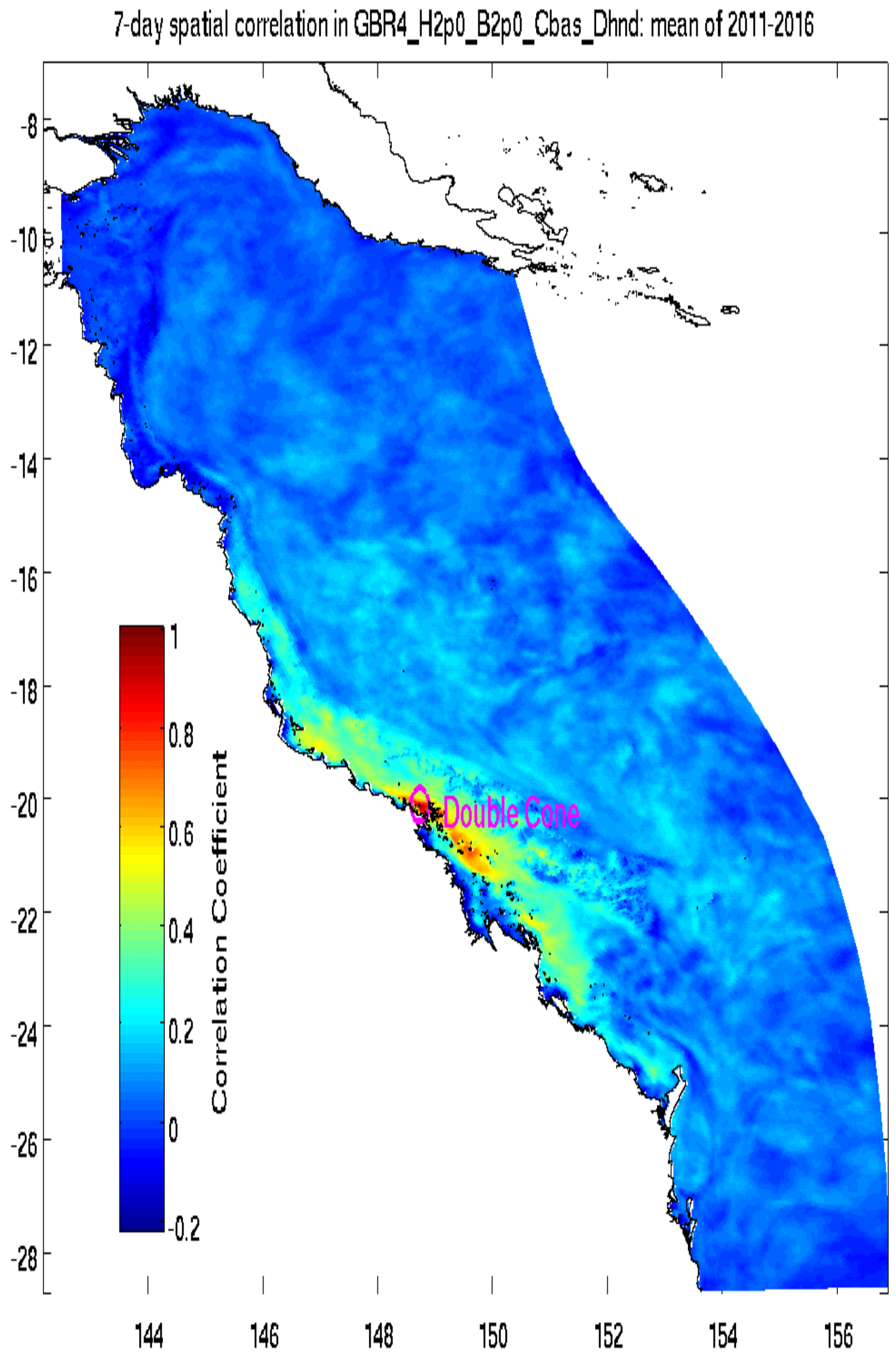


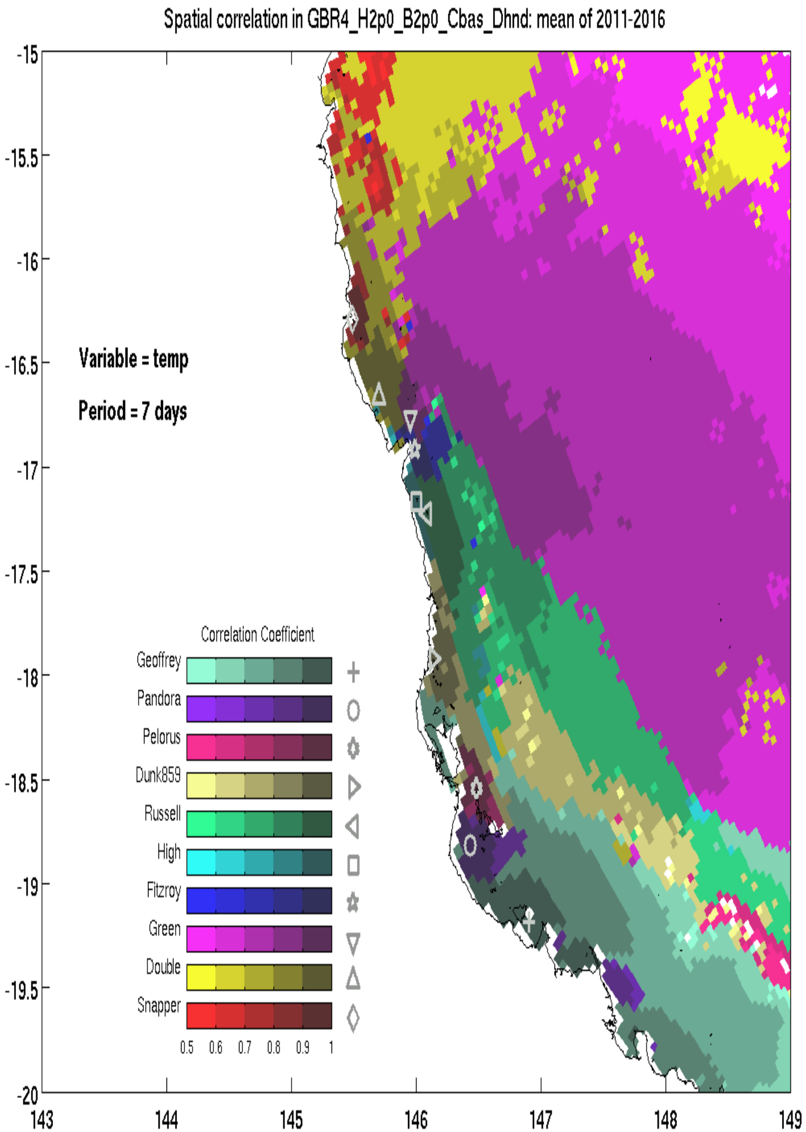
Figure 3. Mean spatial correlation of total chlorophyll *a* at each surface model pixel with the total chlorophyll *a* at the Double Cone observation site. The mean correlation is generated from (52 x 6 years) estimates of correlation over each successive 7-day period. Mean correlation is 1 at the observation site.

If analysis like Figure 3 is undertaken for one variable at multiple sites, it is possible to determine within a program which sites have the greatest footprints. In Figure 4, the colours show the maximum correlation coefficient at each model pixel of all the observations sites. Looking at Double Cone, its footprint is similar to that seen in Figure 3 for the correlation coefficient greater than 0.5. But Figure 4 shows some regions where although the correlation with Double Cone is above the threshold (Figure 3), it is higher still with Pine Island (yellow shading). Figure 4 provides a means to consider the value of observation sites within a program, and to condense the number of figures to one for each program and variable.

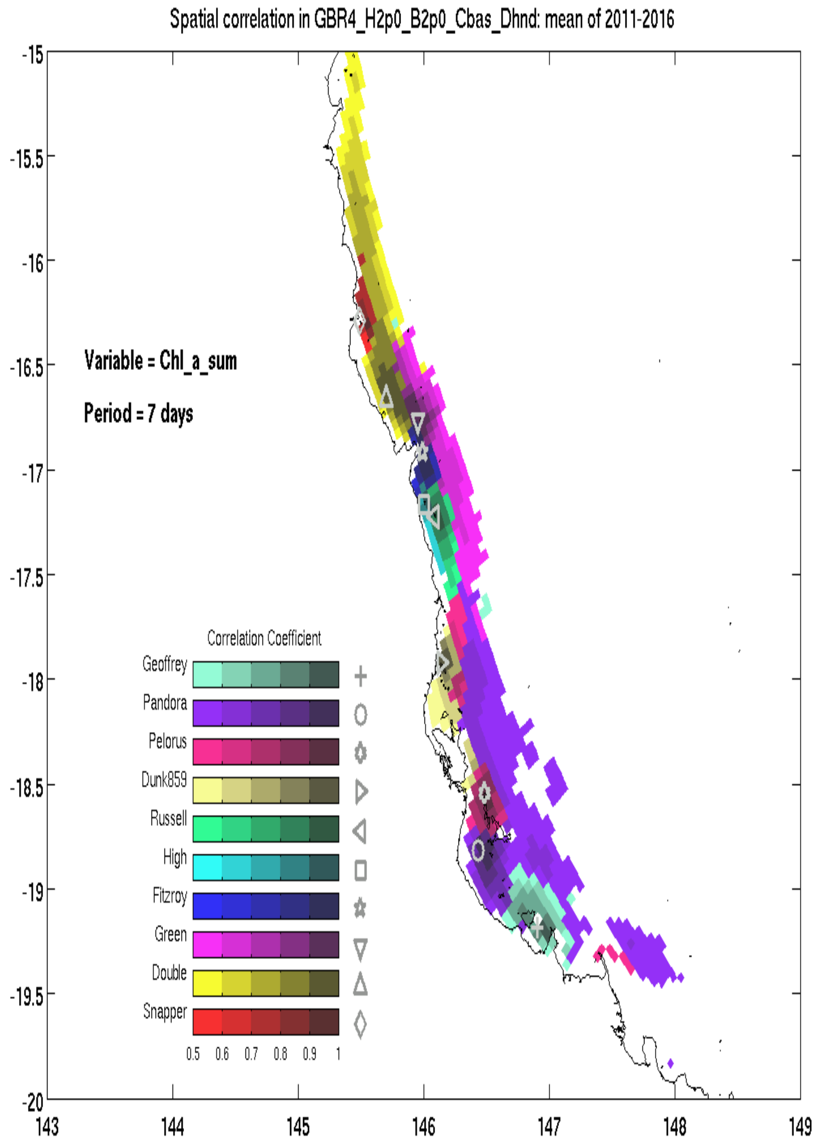
Results of the Observation System Simulation Experiments for the MMP sampling program

For simplicity, the MMP sites have been split into northern (southern-most site being Geoffrey Bay), and southern (northern most site being Double Cone) regions. This split works for chlorophyll because all of the southern sites, including Double Cone, have footprints that do not reach to Upstart Bay, and vice versa (Figure 4). Immediately this demonstrates an important gap in our observing capacity. The eReefs catchment scenarios showed that the largest change in chlorophyll concentration due to anthropogenic loads of anywhere along the Queensland coast was in Upstart Bay. This is because it represented the location where anthropogenic nutrients in the Burdekin River plume had reached, but suspended sediment had sunk out, allowing phytoplankton biomass to increase. This increased chlorophyll could only be observed by a site in, or upstream, of Upstart Bay, but there is no such site. While the gap in Upstart Bay is of a relatively small spatial extent, it is arguably the most important location due to the anthropogenic influence. It is also convenient for a sampling program run by the Australian Institute of Marine Science (AIMS).

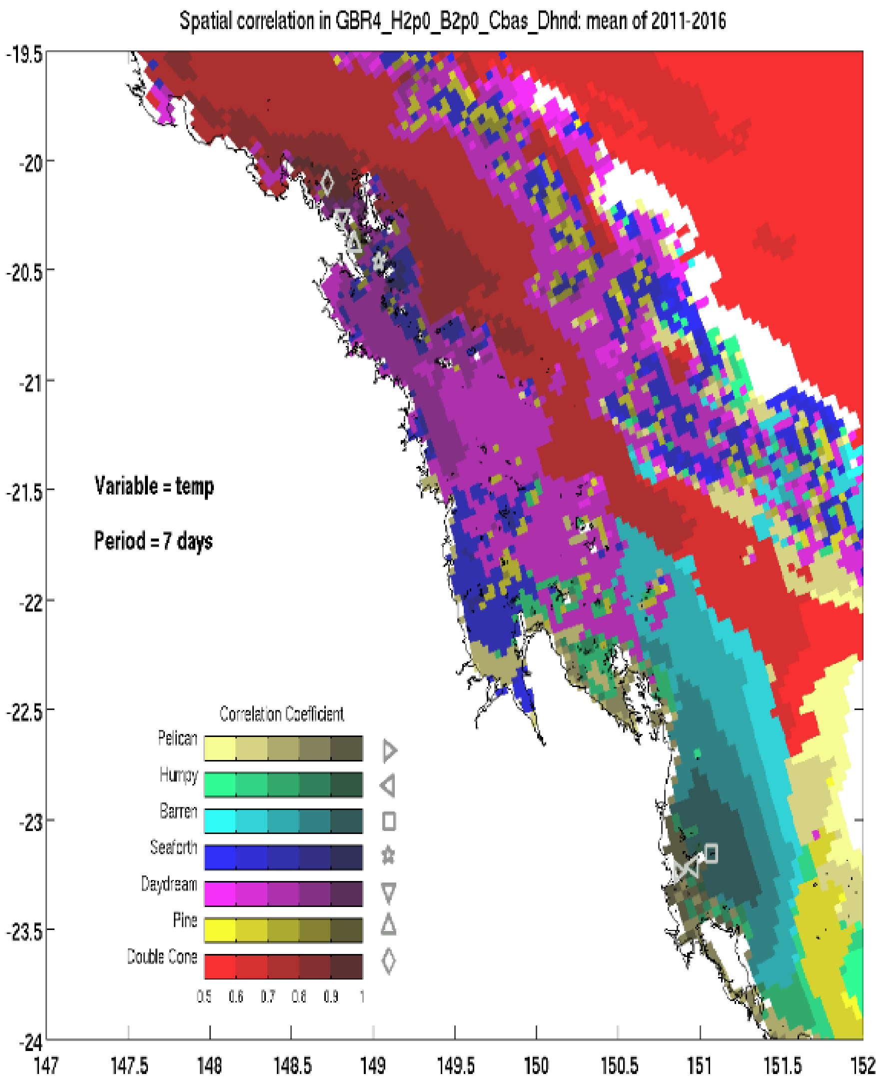
The other major gaps in the MMP program are between Repulse Bay and the Keppel Islands, and north of Cape Tribulation. These are discussed below.



Spatial correlation in GBR4_H2p0_B2p0_Cbas_Dhnd: mean of 2011-2016
Variable = temp
Period = 7 days
Correlation Coefficient
Geoffrey
Pandora
Pelorus
Dunk859
Russell
High
Fitzroy
Green
Double
Snapper
0.5 0.6 0.7 0.8 0.9 1
-15 -15.5 -16 -16.5 -17 -17.5 -18 -18.5 -19 -19.5 -20
143 144 145 146 147 148 149



Spatial correlation in GBR4_H2p0_B2p0_Cbas_Dhnd: mean of 2011-2016
Variable = Chl_a_sum
Period = 7 days
Correlation Coefficient
Geoffrey
Pandora
Pelorus
Dunk859
Russell
High
Fitzroy
Green
Double
Snapper
0.5 0.6 0.7 0.8 0.9 1
-15 -15.5 -16 -16.5 -17 -17.5 -18 -18.5 -19 -19.5 -20
143 144 145 146 147 148 149



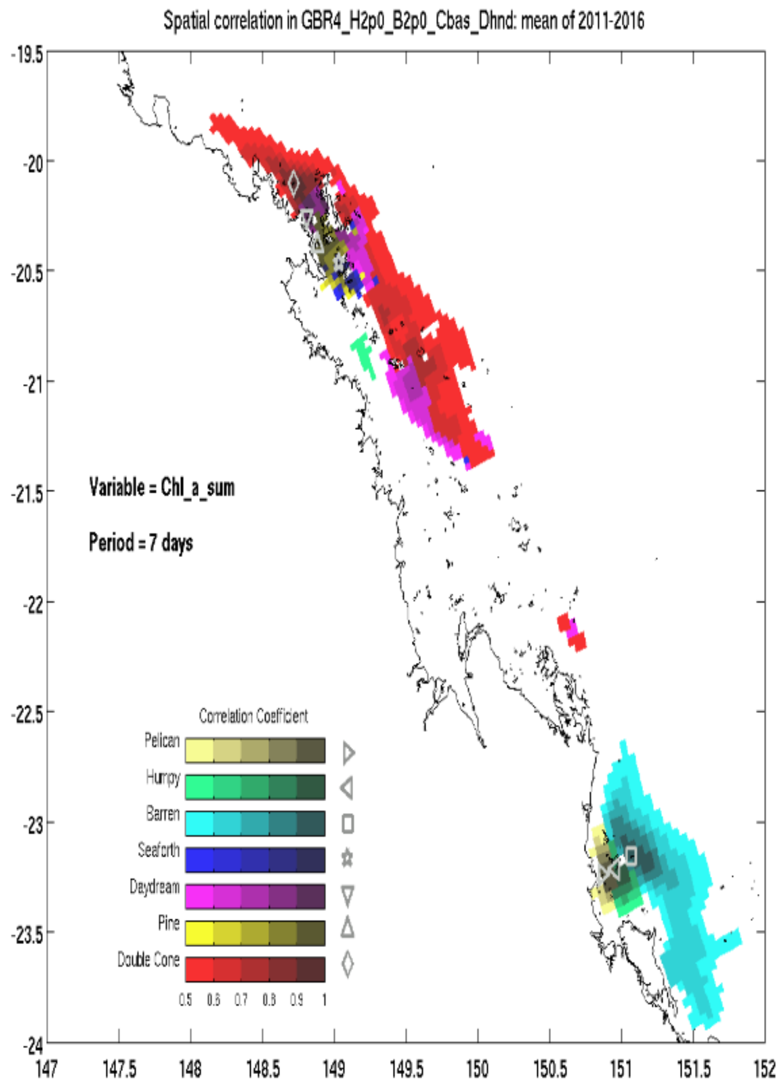
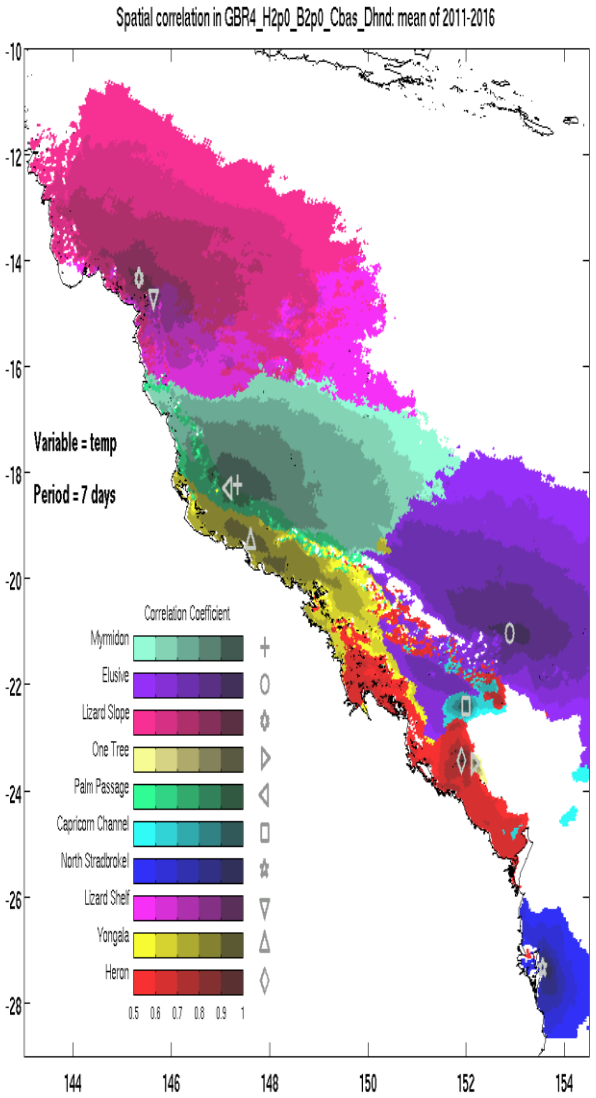


Figure 4. **Mean spatial correlation of temperature (left panels) and total chlorophyll *a* (right panels) at each surface model pixel with the respective parameter at the observational site, at the existing MMP sampling sites for central (top) and southern (bottom) Great Barrier Reef.**

8.2.1.1 *Results of the Observation System Simulation Experiments for the IMOS sampling program*

The analysis for the combined IMOS mooring array and NRS station show that even at the weekly timescale, temperature is well covered at the 0.5 level, and along the shelf even the 0.7 correlation coefficient (Figure 5). One notable exception is the waters offshore of Fraser Island. Here local upwelling processes at weekly timescale are unobserved by sites at North Stradbroke and Heron Island.

The spatial footprints for chlorophyll *a* are much smaller. In particular, the placement of the moorings at mid-shelf and outer-shelf locations determine that the footprints are quite extensive in the alongshore direction, but do not observe processes occurring adjacent to the coast line.



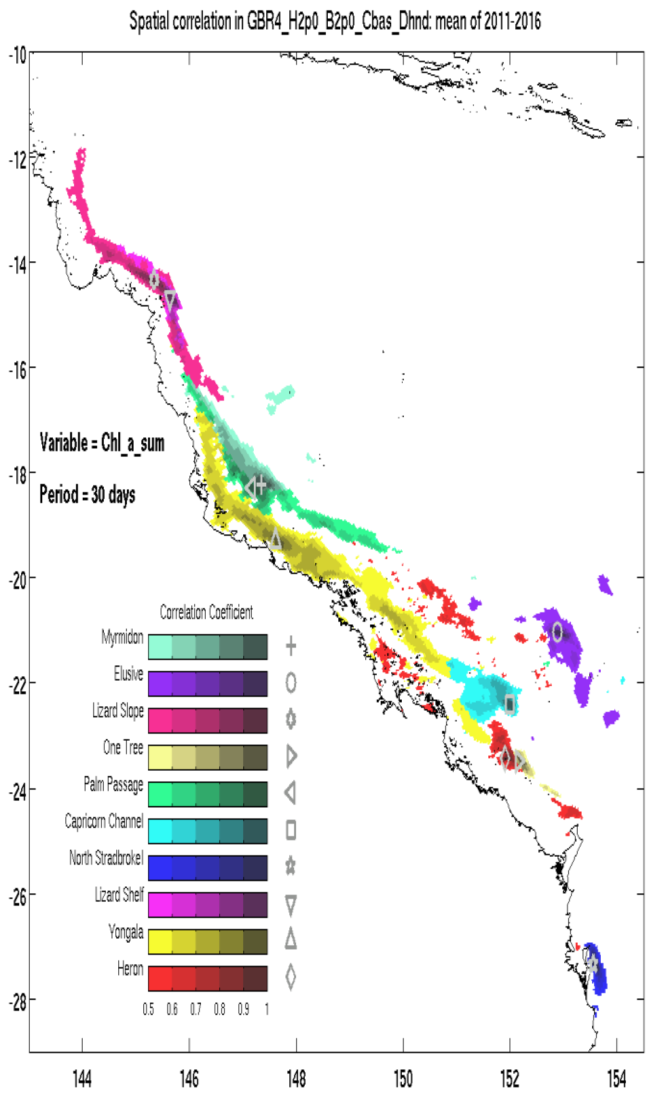


Figure 5. **Mean spatial correlation of temperature (left panel) and total chlorophyll *a* (right panel) at each surface model pixel with the respective parameter at the observational site, at the existing IMOS sampling sites.**

8.2.1.2 *Results of proposed sites in Cape York region.*

The coastline from Cape Tribulation to Torres Strait has been identified as a region with poor spatial coverage. This is backed up by the analysis above showing the furthest-north IMOS (Lizard Island mooring) and MMP sites (Double Island) do not have footprints extending into the Cape York region (Figure 6). To assess the best site for an addition observation, we placed sites at Warraber Island in eastern Torres Strait, offshore of Somerset and Lockhart River, and in Princess Charlotte Bay and on Lizard Island. As measured by spatial extent, Lockhart River is the most informative site for chlorophyll *a*, although the answer is less clear for dissolved inorganic nitrogen concentration, which is probably functionally zero anyway. The temperature footprint (not shown) shows all sites well correlated, while suspended sediments are quite localised. Nonetheless the Lockhart River still has a larger footprint for temperature than the other sites.

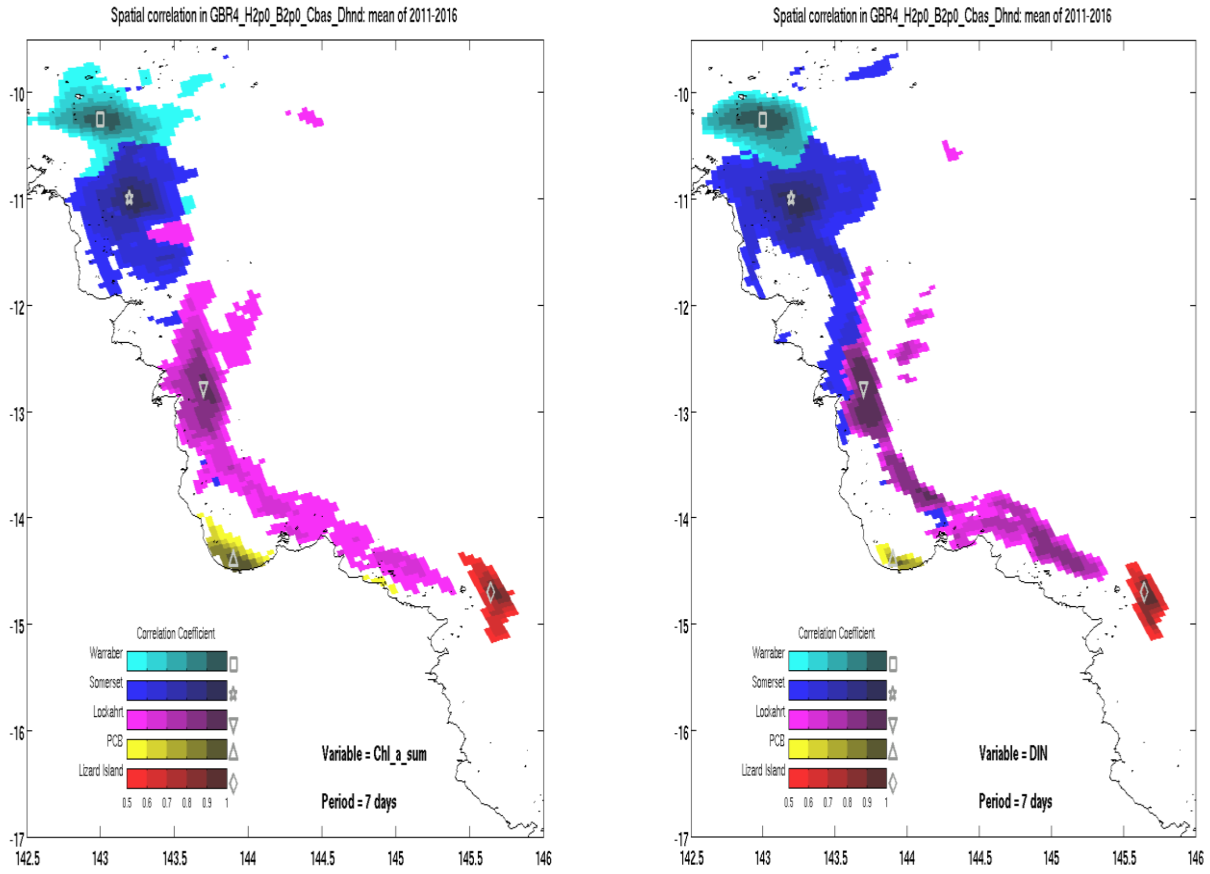


Figure 6*.* **Mean spatial correlation of total chlorophyll *a* (Left panel) and dissolved inorganic nitrogen (right panel) at each surface model pixel with the total chlorophyll *a* and dissolved inorganic nitrogen at the investigated sites.**

8.2.1.3. *Results of a proposed site near Mackay.*

The region between the Keppel Islands and Repulse Bay has been recognised as being under sampled. To investigate the impact on the existing MMP program (including some no longer active sites), we placed a site offshore of Mackay. The analysis for chlorophyll *a* shows that the Mackay site has a large footprint, and is well worth considering (Figure 7). In particular, the area with a correlation greater than 0.7 is larger than the present MMP sites within the Mackay-Whitsundays region. A more in-depth analysis of this region has been submitted to the Mackay-Whitsundays partnership.

While the addition of a Mackay site would represent much of the waters from Broad Sound to Repulse Bay, it would not well represent the waters offshore of Townshend Island.

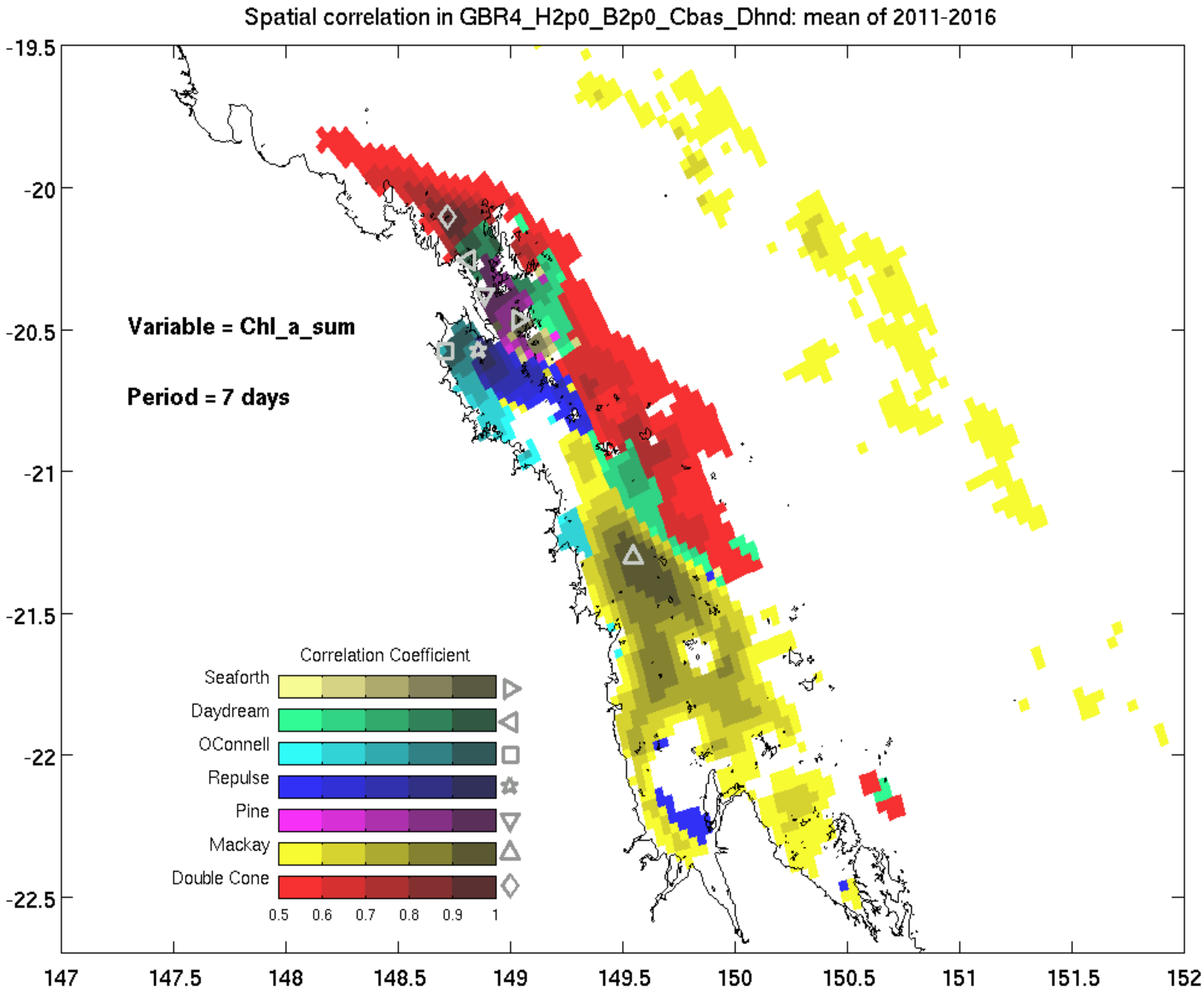


Figure 7. Mean spatial correlation of total chlorophyll *a* at each surface model pixel with the total chlorophyll *a* with the observational site at the sampling sites in the Mackay Region. Note: locations shown represent existing MMP and proposed (Mackay) sites.

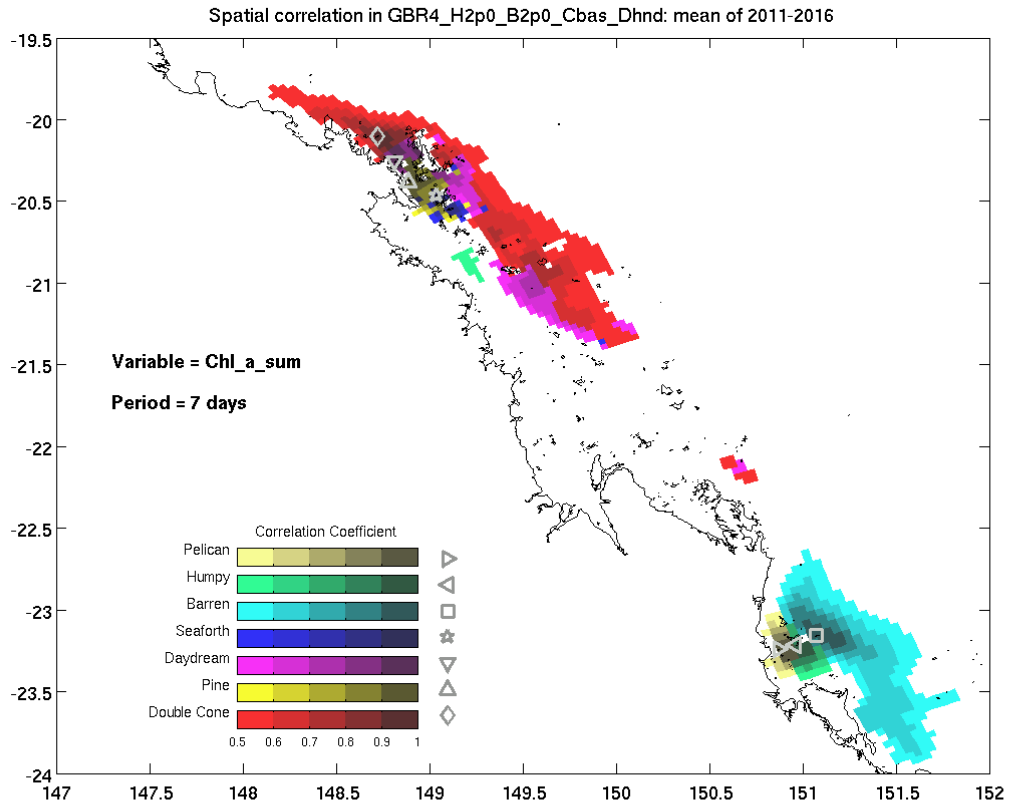


Figure 8. Mean spatial correlation of total chlorophyll *a* at each surface model pixel with the total chlorophyll *a* with the observational site at the sampling sites at seven MMP sites within the MMP program in the Mackay and Fitzroy Regions. Note: locations shown represent existing MMP sites.

The full spatial coverage and high temporal frequency of physical and biogeochemical information provided by the eReefs model archive has been applied to perform Observation System Simulation Experiments, the results of which have informed site selection for specific fixed observing locations. Observation System Simulation Experiments involve using a model simulation to quantify the effectiveness of observation techniques and observation locations to quantify the state or phenomena of interest. In the analysis presented here, we use the spatial correlation of physical (temperature) and biogeochemical (chlorophyll *a*, total suspended solids, dissolved inorganic nitrogen) properties in the eReefs four-kilometre biogeochemical model, six-year simulation forced by SOURCE Catchments river loads. The years 2011 to 2016 represent a one-in-a-100-year wet season (2011), as well as some average and dry years. From a pragmatic perspective, the analysis of observing system design and observational locations focuses on assessing the adequacy of IMOS and MMP sampling locations to represent regional environmental characteristics. The rational for this approach is to build on the existing time series already accumulated at many of these sites. In areas where existing monitoring efforts have been identified as spatially inadequate, the Observation System Simulation Experiment approach has been used to identify potential new sites.

The analysis has identified candidate fixed monitoring sites as shown in Table 10.

Table 10. Summary of identified candidate fixed monitoring sites

Region	Location	Priority	Rationale
Cape York	Lockhart River	High	Geographic – coverage of northern Reef
Cairns Region	Double Island	Med	Part of existing long term monitoring program (MMP)
Wet Tropics	Russell Island	High	High impact of terrestrial activities – opportunity to observe marine impacts of catchment improvement. Part of existing Long-Term Monitoring Program (MMP)
Central	Yongala	High	Part of existing long term observational network (IMOS)
Whitsundays	Pine Island/Daydream	Med	Part of existing long term monitoring program (MMP)
Mackay	Mackay	High	Geographically representative site in high value (Tourism) region
Fitzroy	Barren Island	High	Geographical coverage of southern Reef

The sites listed above are a combination of existing sites, and proposed new sites. Exact locations of existing sites can be found in relevant reporting documents for these activities. At this design stage, proposed new sites are not defined to specific lat/lon, but should the design proceed to implementation, specific sites will be determined from analysis of model results and other constraints (shipping lanes, Marine Park zoning, etc.).

8.2.2 Augmenting fixed monitoring sites with regional deployments of autonomous vehicles:

The marine environment of the Reef is characterised by strong vertical and horizontal gradients in many bio-physical parameters. From large-scale latitudinal gradients in water temperature to cross-shelf gradients in salinity, turbidity and nutrients, the processes underpinning the spatial variability are controlled by both local and remote forcing with strong variability at seasonality and inter-annual timescales, punctuated by extreme weather events (see summary in Q-IMOS Science and Implementation Plan). While fixed assets such as moorings can provide insight into local temporal variability, their ability to elucidate spatial variability is limited. The accumulated experience of operating Slocum gliders on the Reef has demonstrated their suitability to operate over regional (hundreds of nautical miles) spatial scales in the complex reef environment.

Marine models are proposed to provide detailed broad scale information for assessment of marine water quality, and ongoing assessment of model performance will be required to quantify uncertainty in the derived water quality metrics. Subsurface observations of biogeochemical parameters collected by gliders will provide an independent data source for this assessment.

Combined with a regional array of fixed infrastructure (for example, moorings), gliders are able to provide fit for purpose data at temporal and spatial resolution and scale that is difficult to achieve with other platforms alone. Gliders represent a highly cost-effective approach compared to other observational platforms that have traditionally been utilised to collect subsurface observations in the Reef (for example, sampling from research vessels, delayed-mode diver deployed loggers, shelf moorings).

8.2.3 Activity scheduling of site specific monitoring activities:

Activity scheduling is based upon preserving the sampling frequency and intensity of established long-term monitoring activities (for example, Marine Monitoring Program inshore water quality monitoring and the IMOS National Reference Station) and replicating suitable sampling at new sites at a frequency that is consistent with integration into the longer term established programs (for example, monthly or seasonal water sampling, or wet season focused activities).

The following table is a conceptual representation of sampling regimes across the five high priority regions identified in Table 10. Specific details of sampling timing will be determined during the detailed design phase (post trade-off analysis).

Table 11. Conceptual representation of sampling regimes for candidate fixed monitoring sites

Region	**Activity**	**Q1**	**Q2**	**Q3**	**Q4**
		Trips per quarter			
Cape York					
	Mooring (sensor based time series) + water sampling	1		1	
	Vessel-based water sampling (quarterly - IMOS NRS protocol)		1		1
	Glider deployment	1		1	
Wet Tropics					
	Mooring (sensor based time series) + water sampling	1		1	
	Vessel-based water sampling (MMP Russell-Mulgrave sites - existing)	2	1		1
	Glider deployment (Wet Tropics/Central Reef)	1		1	
Central					
	Mooring (sensor based time series) + water sampling (existing)	1		1	
	Vessel-based water sampling (monthly IMOS NRS - existing)	2	3	2	3
	Vessel-based water sampling (MMP Burdekin sites - existing)	2	1	1	
Mackay - Whitsundays					
	Mooring (sensor based time series) + water sampling	1		1	
	Vessel-based water sampling (monthly IMOS NRS protocol)	2	3	2	3
	Vessel-based water sampling (MMP Whitsunday sites - existing)	2	1		1
	Glider deployment	1		1	
Fitzroy					
	Mooring (sensor based time series) + water sampling	1		1	
	Vessel-based water sampling (quarterly - IMOS NRS protocol)		1		1
	Vessel-based water sampling (MMP protocol)	2		1	

Note – activities listed as existing are at existing sites, and may include increased frequency at these sites. Other activities are new. The timing is a conceptual representation of sampling regimes across the five high priority regions. Specific details of sampling timing will be determined during the detailed design phase (post trade-off analysis).

8.3 Indicators for specific processes

Indicators for specific processes represent measures that **quantify key processes**, including environmental linkages, and the impact human activities have on the natural assets of the Reef. The intents of specific process-based observations are, in most cases, to quantify key processes and related variables, such that indicators used at broader scales can be improved e.g. the improvement in estimates of primary productivity, the improved calibration of bio-optical sensors, improvement of remote sensing algorithms etc. In the case of pesticides, the specific study is to provide a snapshot of contaminants at a lower frequency (every 5 years) than other components of the observational program.

The summary of indicators recommended to be monitored for specific processes are presented in Table 12.

Table 12. Summary of indicators to be determined through specific process studies.

Indicator Group	*Priority Indicator*	*Process*	*Approach*
Nutrients	Nutrients (N and P species)	X	MMP flood plume dynamics monitoring; 5 yearly nutrient, primary productivity, remote sensing validation cruises — wet season-based.
	Nutrients (Carbon species)	X	
	Chlorophyll *a*	X	
Sediment	Suspended sediments (solids)	X	MMP flood plume dynamics monitoring; Five-yearly nutrient, primary productivity, remote sensing validation cruises — wet season-based.
	Turbidity	X	
	Secchi depth	X	
Ocean Acidification	pH, Total Alkalinity, DIC, pCO_2	X	Reef-based and inshore-based regular observations of ocean acidification parameters.
Pesticides	Suite of known and emerging pesticides	X	Refocus to wet season events as ambient concentrations are so low that the continuation of the program is of limited value. It may be appropriate that five-yearly or so the ambient concentrations are checked.
Primary production	Primary production estimate	X	Five-yearly nutrient, primary productivity, remote sensing validation cruises — wet season-based.
	Rates of change of chlorophyll *a*	X	

9.0 Assessment of the resources required to implement the recommended design

The following table provides a guide to estimate the effort and associated costs of monitoring activities recommended by the RIMReP Program Design Expert Groups. The template captures effort from the planning to the reporting of a project in order to capture the complete costs of a project and to identify potential areas for efficiency gains (e.g. improved technology to reduce image analysis time). This information will also inform the trade-off analysis.

Table 13. Estimate of the resources required to implement the recommended design

Explanation	***Name of the discrete monitoring activity or program proposed. For example, Seagrass process sites; aerial/drone surveys of dugongs; medium scale coral reef monitoring etc.***	***How many person days do you estimate that it will take to plan the monitoring/ modelling effort per annum (e.g. 2 people x 5 days = 10 person days).***	***Number of people in the team required to deploy this monitoring trip/survey.***	***Should include all field work days (boat-based, shore-based land-based etc). Should also include travel days before and after field work, where required.***	***Number of days per annum required to conduct the survey/monitoring. Specify which platform is required. For boat-based, include size, where 'small' boat = trailorable and/or <9m long; large boat = not-trailorable; and/or >9m long.*** ***Includes conducting surveys and interviews (e.g. phone surveys, boat ramp surveys etc.).***	***Number of person days per annum required to analyse the sample collected (e.g. water samples, image and video processing etc.).*** ***List for individual indicators or collection methods, where applicable.***	***Number of person days per annum required to analyse the data collected. Include analysis of satellite data, big data analytics, desktop studies.*** ***List for individual indicators or collection methods, where applicable.***	***Number of person days required to complete reporting components associated with this monitoring.***	***Annual dollar value for any significant (>$2,000) costs that are not included in the previous columns. Include significant costs for laboratory time, hire of equipment, satellite time, consumables, analytical costs, maintenance of equipment, software charges). Does not include institute-owned assets.***	***Note here whether the proposed monitoring activity, or components thereof, have existing funding commitments. If so, please stipulate the amount and length of time of the commitment (Y/N, $/year).***
Heading	**Discrete monitoring activity**	**Planning: person days**	**Field work: team size**	**Field work: person days**	**Field work: platform days**	**Sample analysis: person days**	**Data analysis: person days**	**Reporting: person days**	**Additional costs**	**Current funding arrangements (Y/N, $/year)**
Broad scale indicators										
	Marine Models: Under the current eReefs Agreement (2018-2019), marine models and their associated systems developed and deployed through the eReefs collaboration will be improved as follows: Biogeochemical modelling improvements The eReefs biogeochemical model will be further refined in the areas of suspended solids modelling, integration of models of different resolutions, time coverage, ongoing skill assessment and inclusion of new variables (such as herbicides or other contaminants of interest). Marine water quality modelling and reporting for regional and whole-of-Reef report card delivery The application of the eReefs System to marine water quality reporting (as demonstrated in Phases 2 and 3) will be further refined to improve outputs in coastal areas and extended to contribute to regional report cards. River flow and water quality modelling framework The eReefs System will expand the river flow and water quality modelling capability developed in Phases 2 and 3 to cover more catchments including ungauged areas. Catchment flow forecasting models will continue to provide temporally relevant hydrological and water quality outputs feeding into other modelling components of the eReefs System and specifically the eReefs biogeochemical model. Water quality management scenarios						Captured in existing modelling projects and operational activities (e.g. eReefs, BoM)	Captured in existing modelling projects and operational activities (e.g. eReefs, BoM)	Captured in existing modelling projects and operational activities (e.g. eReefs, BoM)	Under the current eReefs Agreement (2018-2019) activities will be undertaken to refine model capabilities, refine their operational implementation, improve the integration of observations from new satellite systems, and improve access to and visualisation of eReefs model outputs. The total funding and in-kind support from research and operational agencies to support development and modelling activities is ~$3.8M over 2 years.

	The eReefs System will expand on the scenario modelling capability demonstrated in Phase 3 in the development of basin specific water quality targets and will model a range of additional whole-of-Reef and regional scenarios contributing to policy development and decision making by Reef water quality managers. Reef-wide mapping The eReefs System will deliver a range of mapping outputs to further the understanding of pressures and impact on the Reef system, such as coral bleaching, resilience areas and other focus areas. Data access and visualisation Improvements in the access to and visualisation of eReefs model outputs and data will be implemented to further the eReefs System capability, scalability and routine delivery in a range of areas, including user access to time series, libraries of scenarios, high resolution model outputs, visualisation and access portals. Critical observations The eReefs System will integrate observations from new satellite systems to improve the performance of the eReefs models and identify areas for further investment in observations to maintain and or improve the ongoing delivery of services including the improvement of satellite derived products.					
	Marine models – ambient and extreme events: BoM marine models provide information on sea levels, surges and waves as operational products.		Captured in existing operational activities (BoM).	Captured in existing operational activities (BoM).	Captured in existing operational activities (BoM).	Modelling and observational products routinely delivered by the BoM as operational products.
	Atmospheric Models: Data on atmospheric temp, winds, and extreme events are delivered as operational products.		Captured in existing operational activities (BoM).	Captured in existing operational activities (BoM).	Captured in existing operational activities (BoM).	Modelling and observational products routinely delivered by the BoM as operational products.
	Remote sensing: Operational agencies (BoM) continue to provide remote sensing products including: • The marine water quality dashboard portal (http://www.bom.gov.au/marinewaterquality/) to access Reef specific satellite derived estimates of: ○ Chlorophyll *a* concentration (Chl) ○ Coloured dissolved organic matter (CDOM) ○ Non-algal particulates (NAP) or sediments • ReefTemp Next Generation (SST and anomaly products) http://www.bom.gov.au/environment/activities/reeftemp/reeftemp.shtml eReefs project (2018-2019) includes activities to integrate observations from new satellite systems and identify areas for further investment in observations to maintain and or improve the ongoing delivery of services.					Remote sensing products routinely delivered by the BoM as operational products. eReefs activities to improve remote sensing observations covered in eReefs funding description (see above).

	Ships of Opportunity: ***Temperature, Salinity, Fluorescence,*** ***Turbidity*** IMOS Ships of Opportunity (SOOP)- Sensors on Tropical Research Vessels (TRV)	10 x 1	Vessel of opportunity	20 x 1 person	Vessel of opportunity	17 x 1	16 x 1	10 x 1	$15,000 p.a. calibrations/transport $45,000 capital /5 years	IMOS Ships of Opportunity (SOOP)- Sensors on Tropical Research Vessels currently funds the SOOP on RV Cape Ferguson @ ~$61k p.a. with in-kind from AIMS of ~$85k (2018 figures)
	Ships of Opportunity: ***Ocean Acidification*** – augment SOOP TRV	10 x 1	Vessel of opportunity	10 x 1 person	Vessel of opportunity	17 x 1	16 x 1	10 x 1	$30,000 p.a. calibrations/transport $180,000 capital / 5 years	No current funding
	Ships of Opportunity: ***Ocean Acidification*** *–RTM Wakmatha -* The Future Reef 2.0	20	1	120 20 days x 6 trips x 1	Vessel of opportunity	>100	>100	>100	Total project costs ~$1M p.a.	Future Reef map project : Funded through GBRF + RioTinto + CSIRO
	Ships of Opportunity: ***Atmospheric conditions and SST*** *(real time Bureau of Met system) to augment TRV and Ocean Acidification*	10	Vessel of opportunity	5 x 1 person	Vessel of opportunity		5	5	$20,000 capital $10,000 operational	No current funding
	Ships of Opportunity: ***Continuous Plankton Recorder***	8 (2 days x 4 trips)	Vessel of opportunity Ship Crew	Vessel of opportunity Ship Crew	Vessel of opportunity	20 (5 days x 4 trips)	40 (10 d x 4 trips)	5	$8000 p.a.	Partial - IMOS currently funds CPR observations along selected routes.

Site Specific Indicators:

Resource estimates in this section are based on collecting a suite of measurements at each site, on the valid assumption that the primary cost is access (i.e. the incremental cost of additional sampling for parameters at each site is insignificant compared to access (vessel) costs).

Resource estimate is based on establishing 5 (five) fixed monitoring sites within specified regions (as described in Table 10)

Cape York -	**Cape York - Lockhart River monitoring site:** ***In-water, sensor-based time series***: temperature, salinity, currents, waves, fluorescence, oxygen, turbidity, Photosynthetically Active Radiation (PAR)	24 (3 pp x 8 days)	4	48 (2 x 6 days x 4 pp)	12 (2x6) days Large vessel oceanographic (A- frame, winches)	12 (total across 2 pp)	12 (total across 2 pp) Data analysis, QA/QC	6 (1pp x 6) Data submission/ real-time monitoring	$200,000 capital (initial) $40,000 operating p.a. (operating includes field allowance, travel, consumables)	No current funding
	Cape York - Lockhart River monitoring site: ***Quarterly monthly vessel-based sampling*** Salinity, temperature, depth, oxygen, fluorometry (CTD) and turbidity (CTD and Secchi disk), Phytoplankton and pigments Zooplankton samples	8 (2 days x 2pp x 2 trips) – note 2 months covered in sensor mooring trips	3	18 (3 pp x 2 x 3 day trips (including travel)	2 days – medium (7-8m vessel) davit, winch, deck space for sample prep – locally based (Lockhart River)	24 (2pp x 12 days) Sample prep/analysis		Data submission/ oversight of real-time data systems	$25,000 operating p.a. ($15,000 operating consumables; $10,000 travel) ~$10,000 Sample analysis by CSIRO hydrochem lab (consistent with IMOS NRS protocols)	
	Cape York **Glider deployment** Deployed from large research vessel during mooring cruise – recovered 2-3 weeks later on charter	4 (1p x 2 d x 2 trips)	1	Deployment - Shared team accounted for in other components; Recovery 4d (1p x 2d x 2 trips)	Deployment - Shared team accounted for in other components; Recovery 2d small vessel (7-9m)	Currently covered through IMOS Glider facility	Currently covered through IMOS Glider facility	Currently covered through IMOS Glider facility	~$20,000 operational per 3 week mission	Partially funded through IMOS – provides access to assets, and support for data processing, QA/QC
	Marine Noise	4 (1pp x 4 days)	Shared team (accounted for in other components	Shared team (accounted for in other components	Shared platform (accounted for in other components	10 (1pp x 10 days)	10 (1pp x 10 days)	2 (1 x 2 days)	$50,000 initial Capital $5,000 p.a. Operational	No current funding

	Microplastics	2 (1 pp x 2 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	2 day (assume 2 hrs/sample. 8 samples/years)	1 day (assume 2 hrs/sample. 8 samples/years)	1 (1p x 1 day)	equipment maintenance and replacement $500/year (e.g. freight, nets, cod ends, chemicals, sieves, instrumentation)	No current funding
Wet Tropics	**Wet Tropics Russell Island monitoring site:** ***In water sensor-based time series***: temperature, salinity, currents, waves, fluorescence, oxygen, turbidity, Photosynthetically Active Radiation (PAR)	24 (3 pp x 8 days)	4	24 (2 x 3 days x 4 pp)	6 (2x3) days Large vessel oceanographic (A- frame, winches)	12 (total across 2 pp)	12 (total across 2 pp) Data analysis, QA/QC	6 (1pp x 6) Data submission/ oversight of real-time data systems	$200,000 capital (initial) $40,000 operating p.a. (operating includes field allowance, travel, consumables – based Yongala NRS IMOS budget)	No current funding
	Wet Tropics Russell Island monitoring site: MMP Style - Quasi-monthly vessel based sampling: Salinity, temperature, depth, oxygen, fluorometry (CTD) and turbidity (CTD and Secchi disk),	48 (4 trips each requiring (2ppX 3days/trip) + 1pp x 6days) See Note	3 See Note	36 (3 pp x 4 trips @ 3 days) See Note	8 days (4trips x 2 days) – medium (7-8m vessel) davit, winch, deck space for sample prep See Note	36 (2pp x 3days/field days) Sample prep/analysis See Note	18 (1pp x 18 days) See Note	20 (2pp x 10) Data submission, reporting See Note	$11,000 instrument repairs/calibration p.a. $10,000 consumables See Note	Y - Part of the existing MMP inshore WQ monitoring Total cost of MMP inshore WQ program (across 4 regions) is ~$1.58M p.a. (2018). The Authority's contribution is ~$715k; AIMS contribution ~$870k. Funded until 2020
		NOTE: the above figures are based on disaggregating the MMP inshore WQ monitoring to estimate costs per regional monitoring								
	Wet Tropics – Central **Glider deployment** Deployed from large research vessel during mooring cruise – recovered 2-3 weeks later on charter	4 (1p x 2 d x 2 trips)	1	Deployment - Shared team accounted for in other components; Recovery 4d (1p x 2d x 2 trips)	Deployment - Shared team accounted for in other components; Recovery 2d small vessel (7-9m)	Currently covered through IMOS Glider facility	Currently covered through IMOS Glider facility	Currently covered through IMOS Glider facility	~$20,000 operational per 3 week mission	Partially funded through IMOS – provides access to assets, and support for data processing, QA/QC

	Marine Noise	4 (1pp x 4 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	10 (1pp x 10 days)	10 (1pp x 10 days)	2 (1 x 2 days)	$50,000 initial Capital $5,000 p.a. Operational	No current funding
	Microplastics	2 (1 pp x 2 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	2 day (assume 2 hrs/sample. 8 samples/years)	1 day (assume 2 hrs/sample. 8 samples/years)	1 (1p x 1 day)	Equipment maintenance and replacement $500 / year (e.g. freight, nets, cod ends, chemicals, sieves, instrumentation)	No current funding
Central Reef	**Yongala Fixed monitoring site:** In water sensor-based time series: temperature, salinity, currents, fluorescence, oxygen, turbidity, Photosynthetically Active Radiation (PAR)	24 (3 pp x 8 days)	4	24 (2 x 3 days x 4 pp)	6 (2x3) days Large vessel oceanographic (A- frame, winches)	12 (total across 2 pp)	12 (total across 2 pp) Data analysis, QA/QC	6 (1pp x 6) Data submission/ real-time monitoring	$30,000 capital p.a. $40,000 operating p.a. (operating includes field allowance, travel, consumables – based on highly scrutinised and efficient IMOS budget)	IMOS currently co-invests into the IMOS Yongala National Reference Station ~$140,000 p.a. with matching co-investment from AIMS
	Yongala Fixed monitoring site: Monthly/quasi-monthly vessel-based sampling Salinity, temperature, depth, oxygen, fluorometry (CTD) and turbidity (CTD and Secchi disk), Phytoplankton and pigments Zooplankton samples	12 (0.75 days x 2pp x 12 trips)	3	36 (3 pp x 12 1 day trips)	12 days – medium (7-8m vessel) davit, winch, deck space for sample prep	24 (2pp x 12 days) Sample prep/analysis		10 (1pp x 10) Data submission/ oversight of real-time data systems	$30,000 operating p.a. (operating includes field allowance – based on highly scrutinised and efficient IMOS budget)	Sample analysis by CSIRO hydrochem lab of monthly samples is funded through IMOS/CSIRO. Annual costs is ~$74,000 for Yongala NRS
	Central Reef (Burdekin) inshore monitoring site: MMP Style - Quasi-monthly vessel based sampling: Salinity, temperature, depth, oxygen,	48 (4 trips each requiring (2ppX 3days/trip) + 1pp x 6days) See Note	3	36 (3 pp x 4trips @ 3day)	8 days (4trips x 2 days) – medium (7-8m vessel) davit, winch, deck space for sample prep See Note	36 (2pp x 3days/field days) Sample prep/analysis	18 (1pp x 18 days)	20 (2pp x 10) Data submission, reporting See Note	$11,000 instrument repairs/calib p.a. $10,000 consumables	Y - Part of the existing MMP inshore WQ monitoring Total cost of MMP inshore WQ program (across 4 regions) is ~$1.58M p.a. (2018).

	fluorometry (CTD) and turbidity (CTD and Secchi disk),		See Note	See Note		See Note	See Note		See Note	The Authority's contribution is ~$715k; AIMS contribution ~$870k. Funded until 2020
		NOTE: the above figures are based on disaggregating the MMP inshore WQ monitoring to estimate costs per regional monitoring.								
	Marine Noise	4 (1pp x 4 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	10 (1pp x 10 days)	10 (1pp x 10 days)	2 (1 x 2 days)	$50,000 initial Capital $5,000 p.a. Operational	No current funding
	Microplastics	2 (1 pp x 2 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	6 day (assume 2 hrs/sample. 24 samples/years)	3 day (assume 2 hrs/sample. 24 samples/years)	1 (1p x 1 day)	equipment maintenance and replacement $500 / yr (freight, nets, cod ends, chemicals, sieves, instrumentation, etc)	Y - Current funding through AIMS appropriation. Assessed on year to year basis.
Mackay /Whitsunday	**Mackay monitoring site:** In water sensor-based time series: temperature, salinity, currents, fluorescence, oxygen, turbidity, Photosynthetically Active Radiation (PAR)	24 (3 pp x 8 days)	4	24 (2 x 3 days x 4 pp)	6 (2x3) days Large vessel oceanographic (A- frame, winches)	12 (total across 2 pp)	12 (total across 2 pp) Data analysis, QA/QC	6 (1pp x 6) Data submission/ real-time monitoring	$200,000 capital (initial) $40,000 operating p.a. (operating includes field allowance, travel, consumables – based Yongala NRS IMOS budget)	No current funding
	Mackay monitoring site: Monthly/quasi-monthly vessel based sampling Salinity, temperature, depth, oxygen, fluorometry (CTD) and turbidity (CTD and Secchi disk), Phytoplankton and pigments Zooplankton samples	12 (0.75 days x 2pp x 12 trips)	3	36 (3 pp x 12 1 day trips)	12 days – medium (7-8m vessel) davit, winch, deck space for sample prep	24 (2pp x 12 days) Sample prep/analysis		10 (1pp x 10) Data submission/ real-time monitoring	$30,000 operating p.a. ~$70,000 Sample analysis by CSIRO hydrochem lab (consistent with IMOS NRS protocols)	No current funding

	Whitsunday inshore monitoring site: MMP Style - Quasi-monthly vessel-based sampling: Salinity, temperature, depth, oxygen, fluorometry (CTD) and turbidity (CTD and Secchi disk),	48 (4 trips each requiring (2ppX 3days/trip) + 1pp x 6days) See Note	3 See Note	36 (3 pp x 4trips @ 4day) See Note	8 days (4trips x 2 days) – medium (7-8m vessel) davit, winch, deck space for sample prep See Note	36 (2pp x 3days/field days) Sample prep/analysis See Note	18 (1pp x 18 days) See Note	20 (2pp x 10) Data submission, reporting See Note	$11,000 instrument repairs/calib p.a. $10,000 consumables See Note	Y - Part of the existing MMP inshore WQ monitoring Total cost of MMP inshore WQ program (across 4 regions) is ~$1.58M p.a. (2018). The Authority's contribution is ~$715k; AIMS contribution ~$870k. Funded until 2020
		NOTE: the above figures are based on disaggregating the MMP inshore WQ monitoring to estimate costs per regional monitoring								
	Mackay - Whitsunday **Glider deployment** Deployed from large research vessel during mooring cruise – recovered 2-3 weeks later on charter	4 (1p x 2 d x 2 trips)	1	Deployment - Shared team accounted for in other components; Recovery 4d (1p x 2d x 2 trips)	Deployment - Shared team accounted for in other components; Recovery 2d small vessel (7-9m)	Currently covered through IMOS Glider facility	Currently covered through IMOS Glider facility	Currently covered through IMOS Glider facility	~$20,000 operational per 3 week mission	Partially funded through IMOS – provides access to assets, and support for data processing, QA/QC
	Marine Noise	4 (1pp x 4 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components_	10 (1pp x 10 days)	10 (1pp x 10 days)	2 (1 x 2 days)	$50,000 initial Capital $5,000 p.a. Operational	No current funding
	Microplastics	2 (1 pp x 2 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	2 day (assume 2 hrs/sample. 8 samples/years)	1 day (assume 2 hrs/sample. 8 samples/years)	1 (1p x 1 day)	equipment maintenance and replacement $500 / yr (freight, nets, cod ends, chemicals, sieves, instrumentation, etc)	No current funding
Fitzroy	**Fitzroy – Barren Island monitoring site:** In water sensor-based time series: temperature, salinity, currents, fluorescence, oxygen, turbidity, Photosynthetically	24 (3 pp x 8 days)	4	24 (2 x 3 days x 4 pp)	6 (2x3) days Large vessel oceanographic (A- frame, winches)	12 (total across 2 pp)	12 (total across 2 pp) Data analysis, QA/QC	6 (1pp x 6) Data submission/ real-time monitoring	$200,000 capital (initial) $40,000 operating p.a. (operating includes field allowance, travel, consumables – based Yongala NRS IMOS budget)	No current funding

	Active Radiation (PAR)									
	Fitzroy – Barren Island monitoring site: Quarterly vessel based sampling Salinity, temperature, depth, oxygen, fluorometry (CTD) and turbidity (CTD and Secchi disk), Phytoplankton and pigments Zooplankton samples	8 (1 days x 2pp x 4 trips)	3	12 (3 pp x 4 1 day trips)	4 days – medium (7-8m vessel) davit, winch, deck space for sample prep	8 (1pp x 8 days) Sample prep/analysis		10 (1pp x 10) Data submission	$10,000 operating p.a. ~$10,000 Sample analysis by CSIRO hydrochem lab (consistent with IMOS NRS protocols)	No current funding
	Fitzroy inshore: MMP Style - Quasi-monthly vessel based sampling: Salinity, temperature, depth, oxygen, fluorometry (CTD) and turbidity (CTD and Secchi disk),	48 (4 trips each requiring (2ppX 3days/trip) + 1pp x 6days) See Note	3 See Note	36 (3 pp x 4trips @ 4day) See Note	8 days (4trips x 2 days) – medium (7-8m vessel) davit, winch, deck space for sample prep See Note	36 (2pp x 3days/field days) Sample prep/analysis See Note	18 (1pp x 18 days) See Note	20 (2pp x 10) Data submission, reporting See Note	$11,000 instrument repairs/calib p.a. $10,000 consumables See Note	No current funding
		NOTE: the above figures are based on disaggregating the MMP inshore WQ monitoring to estimate costs per regional monitoring								
	Marine Noise	4 (1pp x 4 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	10 (1pp x 10 days)	10 (1pp x 10 days)	2 (1 x 2 days)	$50,000 initial Capital $5,000 p.a. Operational	No current funding
	Microplastics	2 (1 pp x 2 days)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	2 day (assume 2 hrs/sample. 8 samples/years)	1 day (assume 2 hrs/sample. 8 samples/years)	1 (1p x 1 day)	Equipment maintenance and replacement $500 / yr (freight, nets, cod ends, chemicals, sieves, instrumentation, etc.)	No current funding

Process studies:										
	Nutrient Dynamics Cairns water quality transect – process based experimental work. Include Ocean Acidification	15 (2pp x 5 days x 3 trips)	4	48 (4pp x 3 trips @ 4d)	12 – large vessel – liveaboard, lab space, winch, davit	24 (2p x 12 days)	12 (1p x 12d)	5 (1p x 5d)	$15,000 p.a. (consumables, field allowances)	Y - Part of the existing MMP inshore WQ monitoring Total cost of MMP inshore WQ program (across 4 regions) is ~$1.58M p.a. (2018). The Authority's contribution is ~$715k; AIMS contribution ~$870k. Funded until 2020
	Ocean Acidification – captured in activities described above (Nutrient Dynamics)									
	Nutrient and Sediment inputs from Rivers –Flood plume monitoring (MMP flood response monitoring) • Up to 31 sites in Cape York NRM region sampled 5 times per year; • 6 sites in Cairns region sampled 3 times per year; • 11 sites in Wet Tropics NRM Region sampled 11 times per year; • 6 sites in Burdekin NRM region sampled 11 times per year;	48 (2p x 24d – depends on intensity of wet season and flooding)	2	132 2p x 20d (5x4d) Cape York 2p x 9d (3x3d) Cairns 2p x 11d (11 x 1d) Wet Tropics 2p x 11d (11 x 1d) Burdekin 2p x 15d (5 x 3d) Mackay	40 days – trailerable boat	220 (>1200 samples, 4p x 55d)	200 (4p x 50d)	40 (4p x 10d)	$248,000 sample analysis (1200 samples @$200 + 1200 samples @$15); $26,000 car hire, accommodation $15,000 consumables	Y – Funded through MMP flood plume response.

	• 5 sites in Mackay Whitsunday NRM region sampled 5 times per year • (Note most sampling focused on wet season).									
	Pesticides monitoring wet season events – grab sampling; 11 sites across 4 NRM regions • 5 in Wet Tropics; • 1 in Burdekin; • 4 in Mackay Whitsundays; • 1 in Fitzroy).	10 (1p x 10d)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	40 (1p x 40d)	20 (1p x 20d)	10 (1p x 10d)	$8000 sample analysis Collection costs accounted for in other components	Not currently funded
	Pesticides monitoring Five-yearly ambient concentrations	20 (2p x 10d)	Shared team (accounted for in other components)	Shared team (accounted for in other components)	Shared platform (accounted for in other components)	40 (1p x 40d)	20 (1p x 20d)	10 (1p x 10d)	$35,000 (11 sites x $3000 per site per deployment period. This includes sample preparation, extraction, analysis, data processing and reporting, consumables and freight)	Not currently funded
	Primary production Five-yearly nutrient, primary productivity, remote sensing validation cruises – wet season-based	20 (2p x 10d)	4	28 (4p x 7d)	5 – Medium vessel (winches for profiling, net towing davit etc.)	40 (2p x 20d)	20 (2p x 10d)	20 (2p x 10d)	$125,000 ($50,000 sample analysis; $50,000 instrument hire; $25,000 consumables	

10.0 References

Baird, M. E., N. Cherukuru, E. Jones, N. Margvelashvili, M. Mongin, K. Oubelkheir, P. J. Ralph, F. Rizwi, B. J. Robson, T. Schroeder, J. Skerratt, A. D. L. Steven and K. A. Wild-Allen (2016) Remote-sensing reflectance and true colour produced by a coupled hydrodynamic, optical, sediment, biogeochemical model of the Great Barrier Reef, Australia: comparison with satellite data. *Env. Model. Software* 78: 79-96.

Brando, Vittorio E & Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (Australia) (2006). Chlorophyll and suspended sediment assessment in a macrotidal tropical estuary adjacent to the Great Barrier Reef: spatial and temporal assessment using remote sensing. CRC Coastal Zone Estuary and Waterway Management, Indooroopilly, Qld.

Brando, V. E., A. G. Dekker,Y. J. Park, and T. Schroeder (2012), An adaptive semi-analytical inversion of ocean colour radiometry in optically complex waters, Applied Optics, 51(15), 2808-2833.

Hedge P, Molloy F, Sweatman H, Hayes K, Dambacher J, Chandler J, Gooch M, Chinn A, Bax N, Walshe T, 2013 An integrated monitoring framework for the Great Barrier Reef World Heritage Area, Department of the Environment, Canberra.

Herzfeld, Mike; Andrewartha, John; Baird, Mark; Brinkman, Richard; Furnas, Miles; Gillibrand, Philip; Hemer, Mark; Joehnk, Klaus; Jones, Emlyn; McKinnon, David; Margvelashvili, Nugzar; Mongin, Mathieu; Oke, Peter; Rizwi, Farhan; Robson, Barbara; Seaton, Shane; Skerratt, Jenny; Tonin, Hemerson; Wild-Allen, Karen. (2016) eReefs Marine Modelling: Final Report. CSIRO Hobart: CSIRO; csiro:EP172488.

Kuhnert, P.M., Liu, Y., Henderson, B., Dambacher, J., Lawrence, E. and Kroon, F. (2015) Review of the Marine Monitoring Program (MMP), Final Report for the Great Barrier Reef Marine Park Authority, CSIRO, Australia.

Schaffelke, B., Collier, C., Kroon, F., Lough, J., McKenzie, L., Ronan, M., Uthicke, S., Brodie, J., 2017. Scientific Consensus Statement 2017. Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 1: The condition of coastal and marine ecosystems of the Great Barrier Reef and their responses to water quality and disturbances. State of Queensland, 2017.

Schroeder, T., Behnert, I., Schaale, M., Fischer, J., and Doerffer, R. (2007), Atmospheric correction algorithm for MERIS above case-2 water, International Journal of Remote Sensing 28, 7, 1469-1486.

Weeks, S.; Werdell, P.J.; Schaffelke, B.; Canto, M.; Lee, Z.; Wilding, J.G.; Feldman, G.C. Satellite-Derived Photic Depth on the Great Barrier Reef: Spatio-Temporal Patterns of Water Clarity. Remote Sens. 2012, 4, 3781-3795.

Appendix A: Synopsis of existing monitoring programs — including their adequacy and gaps in monitoring effort for each of the priority indicators identified for the physical and chemical environment.

10.1 Nutrients

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Nutrients (N and P species; silica as well as chlorophyll *a* as a proxy of nutrient enrichment)	*In situ* (surface and ~ 1 m from bottom) point-in-time measurements at MMP routine sites	Up to 31 sites in Cape York NRM region sampled 5 times per year; 6 sites in Cairns region sampled 3 times per year; 11 sites in Wet Tropics NRM Region sampled 11 times per year; 6 sites in Burdekin NRM region sampled 11 times per year; 5 sites in Mackay Whitsunday NRM region sampled 5 times per year (Note most sampling focused on wet season).	*In situ*	Grab sample with either bucket (surface) or niskin bottle (surface and depth)	Direct measure should be most accurate and precise but only covers small area	Analysis cost (~$200 for full suite of N and P species) as well as sample collection (i.e. boat cost and labour)	Directly linked to primary productively in marine environment Measure of water condition Indirect influence on a number of ecosystem impacts including macro-algal proliferation, coral disease and	Need for an integrated representation of nutrients/primary production across the entire Reef and water column that combines models and observations to allow for improved risk assessment when combined with habitat mapping. Most direct sampling (point in time for nutrients and instrument loggers for chlorophyll) covers the inner shelf region of the Reef – the mid- and outer-Reef shelfs are poorly (or not) represented in most sampling programs. Also
Nutrients (N and P species; silica as well as	*In situ* (surface) point-in-time measurements at MMP ‘flood plume’ sites	Up to 31 sites in Cape York NRM region; 22 sites in Wet Tropics NRM Region; 14 sites in Burdekin NRM region;	*In situ*	Grab sample with either bucket (surface) or niskin bottle	Direct measure should be most accurate and precise	Analysis cost (~$200 for full suite of N		

chlorophyll *a* as a proxy of nutrient enrichment)	(response monitoring when flooding)	11 sites in Mackay Whitsunday NRM region.		(surface and depth)	but only covers small area	and P species) as well as sample collection (i.e. boat cost and labour)	bioerosion, crown of thorns starfish outbreaks, coral bleaching susceptibility, eutrophication. Link to most other RIMReP ecological working groups.	question whether other nutrient species needed (e.g. iron) to account for different phytoplankton species…
Nutrients (C species)	*In situ* (surface and ~ 1 m from bottom) point-in-time measurements at MMP routine sites	6 sites in Cairns region sampled 3 times per year; 11 sites in Wet Tropics NRM Region sampled 5 times per year; 6 sites in Burdekin NRM region sampled 4 times per year; 5 sites in Mackay Whitsunday NRM region sampled 5 times per year (Note most sampling focused on wet season).	*In situ*	Grab sample with either bucket (surface) or niskin bottle (surface and depth)	Direct measure should be most accurate and precise but only covers small area	Analysis cost as well as sample collection (i.e. boat cost and labour)		
Chlorophyll *a*	*In situ* (from near seafloor) continuous measurements using chlorophyll a loggers (AIMS MMP logger program)	15 stations across the Wet Tropics (6 stations), Burdekin (5 stations) and Mackay Whitsunday (4 stations) regions	*In situ*	WET Labs ECO FLNTUSB Combination Fluorometer and Turbidity Sensors	Calibration issues with chlorophyll sensor (accuracy/bias issues?) but logging continuously from one site.	Sensor and mooring maintenance		

Chlorophyll *a*	Satellite colour Remote sensing	Whole of Reef coverage (dashboard)	Remote sensing/model algorithm (CSIRO)	Various satellites: MODIS up to 2018, VIIRS from 2018	For performance see Brodie and Waterhouse (2016), King et al. (2016).	Labour		
Chlorophyll *a*	Satellite true colour remote sensing (Colour Class maps)	Whole of Reef coverage	Remote sensing	MODIS calibrated against *in situ* data (Alvarez-Romero et al. 2013 + others Devlin/Petus)	Devlin et al. (2015) review of performance	Labour		
Nutrients	Nutrient in plumes (models)	Whole of Reef coverage	Modelled	eReefs	Accuracy poor	Model parameterisation and run time		
Nitrogen loading maps (use DIN and PN as proxies)	Use either hydrodynamic model or JCU MMP model	Whole of Reef coverage	Modelled	JCU model (but can apply eReef hydrodynamic model)	Fair for general exposure assessment – will improve if using eReefs hydrodynamic model	Model parameterisation and run time		

Chlorophyll *a*	eReefs	Whole of Reef coverage	Modelled	eReefs	Fair but calibration issues?	Model parameterisation and run time		
Nutrients (upwelling)	*In situ* temperature and salinity loggers	Sections of central Reef outer shelf	*In situ* temperature and salinity loggers	Use temperature and salinity measures as a proxy for nutrient in the upwelled water	Indication of intensity of upwelling (Benthuysen et al. 2016). Importance in nutrient budgets (e.g. Furnas et al. 2011).			
Nutrients at IMOS NRT								
Estuary monitoring from Queensland Government								

10.2 Sediments

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Suspended sediments	*In situ* (surface and ~ 1 m from bottom) point-in-time measurements at MMP routine sites.	Up to 31 sites in Cape York NRM region sampled 5 times per year; 6 sites in Cairns region sampled 3 times per year; 11 sites in Wet Tropics NRM Region sampled 11 times per year; 6 sites in Burdekin NRM region sampled 11 times per year; 5 sites in Mackay Whitsunday NRM region sampled 5 times per year (Note most sampling focused on wet season).	*In situ*	Grab sample with either bucket (surface) or niskin bottle (surface and depth).	Direct measure should be most accurate (although there can be issues with analytical precision with samples < 5 mg.L^{-1}. Also note filter papers used across programs can vary in pore size (0.4 to 1.2 µm) – can be issue for fine particles < 1 µm but unlikely to be considerable influence in	Analysis cost relatively cheap ($10-20 per sample range) but expense is in sample collection (i.e. boat cost and labour).	Measure of particles in water column Turbidity measurement related to light Effect on fish Measure of water condition Influence on (but not measure of) sedimentation Link to most other RIMReP	Need for an integrated representation of suspended sediment across the entire Reef and water column that combines models and observations to allow for improved risk assessment when combined with habitat mapping. Also need to consider differences in sediment particle size (and composition such as organic material) as finer particles can travel further and stay in suspension longer and have different effects on corals and fish.

					most conditions).		ecological working groups.	Most direct sampling (point in time for TSS and instrument loggers for turbidity) covers the inner shelf region of the Reef – the mid- and outer-Reef shelfs are poorly (or not) represented in most sampling programs. Modelling needs *in situ* data to validate results.
Suspended sediments	*In situ* (surface) point-in-time measurements at MMP 'flood plume' sites (response monitoring when flooding).	Up to 31 sites in Cape York NRM region; 22 sites in Wet Tropics NRM Region; 14 sites in Burdekin NRM region; 11 sites in Mackay Whitsunday NRM region.	*In situ*	Grab sample with either bucket (surface) or niskin bottle (surface and depth).	Direct measure should be most accurate (although there can be issues with analytical precision with samples < 5 $mg.L^{-1}$. Also note filter papers used across programs can vary in pore size – can be issue for fine particles < 1 µm but unlikely to be considerable influence in most conditions).	Analysis cost relatively cheap ($10-20 per sample range) but expense is in sample collection (i.e. boat cost and labour).		
Turbidity	*In situ* water column point-in-time	Routine sampling: 11 sites in Wet Tropics NRM Region sampled 5	*In situ*	SeaBird 19	Provides a whole water column	Sensor maintenance but part of an		

	measurements using Acoustic Backscatter Senor (JCU MMP routine and flood plume sites).	times per year; 6 sites in Burdekin NRM region sampled 5 times per year (Note most sampling focused on wet season). During flood events: 22 sites in Wet Tropics NRM Region; 14 sites in Burdekin NRM region; 11 sites in Mackay Whitsunday NRM region.			measure of TSS at sampling sites. Instrument needs calibration for local sediment composition to calculate TSS.	existing logger so cost is in the field collection (i.e. boat cost and labour).		
Turbidity	*In situ* (from near seafloor) continuous measurements using turbidity loggers (AIMS MMP logger program).	15 stations across the Wet Tropics (6 stations), Burdekin (5 stations) and Mackay Whitsunday (4 stations) regions.	*In situ*	WET Labs ECO FLNTUSB Combination Fluorometer and Turbidity Sensors.	Good measure of turbidity but sensor needs calibration to local sediment to calculate TSS (or variable inputs of sediment).	Sensor and mooring maintenance.		
Turbidity	*In situ* (from near seafloor) continuous measurements using turbidity	7 stations across Burdekin (6) and Wet Tropics (1) regions.	*In situ*	Campbell turbidity logger	Good measure of turbidity but sensor needs calibration to local	Logger changeover every 2-3 months.		

	loggers (Lewis NESP program).				sediment to calculate TSS (or variable inputs of sediment).			
Turbidity	*In situ* (from near seafloor) continuous measurements using turbidity loggers (port monitoring programs).	Unknown number of sites around different ports including Townsville, Abbot Point, Hay Point, Gladstone.	*In situ*	Campbell turbidity logger	Good measure of turbidity but sensor needs calibration to local sediment to calculate TSS (or variable inputs of sediment).	Logger changeover every 6 weeks to 2 months.		
Sediment	*In situ* (from near seafloor) continuous measurements using turbidity loggers (Lewis NESP and port monitoring programs).	As above	*In situ*	Campbell turbidity logger	Deposition senor provides some indication of sedimentatio n.	Logger changeover every 6 weeks to 3 months.		
Sediment	*In situ* (from near seafloor) using SediSampler.	7 stations across Burdekin (6) and Wet Tropics (1) regions.	*In situ*	SediSampler	Provide measure of sediment accumulation	Changeover at specific time intervals		

					at locations (not sedimentation but tells presence/exposure of suspended sediment at site).	relating to question.		
Suspended sediments	Satellite colour Remote sensing	Whole Reef coverage	Remote sensing/model algorithm (CSIRO).	Various satellites: MODIS up to 2018, VIRS from 2018.	For performance see Brodie and Waterhouse (2016), King et al. (2016). Generally fair for TSS except in shallow waters < 5 m depth (poor).	Labour cost to run		
Suspended sediments	Satellite true colour remote sensing (Colour Class maps)	Whole Reef coverage	Remote sensing	MODIS calibrated against *in situ* data (Alvarez-Romero et al. 2013 + others Devlin/Petus).	Devlin et al. (2015) review of performance.	Labour		

Suspended sediments	Suspended sediment in plume (models)	Whole Reef coverage	Modelled	eReefs	Fair/good but calibration issues.	Model parameterisation and run time.		
Suspended sediments	Suspended sediment resuspension (models)	Whole Reef coverage	Modelled	eReefs	Fair/good but calibration issues.	Model parameterisation and run time.		
Photic depth	Satellite remote sensing	Whole Reef and daily?	Remote sensing	Various satellites: MODIS up to 2018, VIRS from 2018.	Okay calibrated against Secchi depth data (Weeks et al. 2012).	Model parameterisation and run time.		
Secchi depth	*In situ* as MMP monitoring locations both ambient and plume	See previous MMP sites	*In situ*	Secchi disk	Good – note can be related to photic depth and light.	Cost is in field collection		
Sediment loading maps	Use either hydrodynamic model or JCU MMP model	Whole Reef coverage	Modelled	JCU model (but can apply eReef hydrodynamic model).	Fair for general exposure assessment – will improve if using eReefs hydrodynamic model.	Model parameterization and run time.		

Light (see other report by Baird et al.)	Loggers	Select sites	*In situ* loggers					

10.3 Marine debris

Existing measure and monitoring programs	Coverage	*In situ*, RS or modelled	Method	Performance	Cost	Links to other RIMReP groups	Gaps
Marine debris – beaches Australian Marine Debris Initiative of the Tangaroa Blue Foundation (1997-current). This includes Eco Barge Marine Debris Cleanup and Monitoring (Eco Barge) (2009 – current)	Whole Reef, focused on beach clean-ups along the coast and on islands.	*In situ*	Beach clean-ups	Clean-ups not randomised in time or space. QA/QC issues with data.	Reef Trust funding ($800K), included Reef Clean-up in 2015 (600 volunteers cleaned up > 5.5 tons).	Ecosystem health (e.g. coral disease, rafting of invasive species, food web effects). Biodiversity (e.g. entanglement, ingestion; including threatened species such as turtles, dolphins, dugongs and whales). Heritage (e.g. reduced heritage values for indigenous and non-indigenous peoples). Water quality (e.g. adsorption of	Need scientifically sound protocols (including experiment design) for sampling and processing (including QA/QC) for marine debris data, collected during beach clean-ups. Need standardized protocols for sampling, processing and analyses of marine debris (incl. microplastics) in marine waters, sediment and biota AIMS is developing these for microplastics for the Reef, and more broadly. Need hydrodynamic modelling to identify hot-spots to (i) better target clean-up efforts, and
Marine debris – beaches CSIRO's survey of marine debris (2011-2013)	Whole of Reef, focused on beach clean-ups along the coast.	*In situ*	Beach surveys	One-off systematic survey	Sample, processing and analysis cost (i.e. transport, equipment, and labour costs).		
Marine debris – water	Whole of Reef, focused on mid-shelf waters	*In situ*	Surface tows (manta and neuston nets).	One-off systematic survey	Sample, processing and analysis cost (i.e. boat,		

Existing measure and monitoring programs	Coverage	*In situ*, RS or modelled	Method	Performance	Cost	Links to other RIMReP groups	Gaps
CSIRO's survey of marine plastic pollution					equipment, and labour costs).	POPs, metals, etc.).	importantly, (ii) identify and mitigate sources.
Microplastics – water AIMS: monthly microplastic monitoring (2016 – current)	IMOS National Reference Station, Yongala	*In situ*	Surface tows (neuston net) to sample the air-sea interface.	Repeated systematic survey	Sample, processing and analysis cost (i.e. boat, equipment, instrument, and labour costs). Currently piggy-backing onto the IMOS trips, removing boating costs.	Community benefits (e.g. reduced nature appreciation, reduced opportunities for enjoyment).	Need better understanding of the relative risk of marine debris pollution versus other pollutants and contaminants (e.g. sediment, nutrients, pesticides). Need improved coordination of management of marine pollution and debris. Arguably there is nothing coordinated and/or effective in place for the Reef, or Australia as a whole for that matter.
Microplastics – water AIMS: tri-annual monitoring (2017 – current)	Wet Tropics coast (Tully to Cape Tribulation)	*In situ*	Surface tows (neuston net) to sample the air-sea interface.	Repeated systematic survey	Sample, processing and analysis cost (i.e. boat, equipment, instrument, and labour costs). Currently piggy-backing onto the MMP		

Existing measure and monitoring programs	**Coverage**	***In situ*, RS or modelled**	**Method**	**Performance**	**Cost**	**Links to other RIMReP groups**	**Gaps**
					trips, removing boating costs.		
Microplastics – water, organisms AIMS: opportunistic microplastic monitoring, e.g. student projects (2016 – current)	Whole Reef	*In situ*	Surface tows (neuston net) to sample the air-sea interface. Biological organisms to examine ingestion.	Repeated systematic or opportunistic survey.	Sample, processing and analysis cost (i.e. boat, equipment, instrument, and labour costs). Currently piggy-backing onto various AIMS trips, removing boating costs.		

10.4 Light

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Secchi depth	AIMS in situ monitoring	Temporal average available at eAtlas (1992-2006)	*In situ*	Maximum depth at which a black and white disk can be seen from the surface.	Good. Errors introduced through solar angle (determining path through water column), solar radiation intensity, and perhaps eyesight.	Low	Link to most other RIMReP ecological working groups.	
Secchi depth	AIMS in situ monitoring	Tri-annual samples	*In situ*	Maximum depth at which a black and white disk can be seen from the surface.	Good. Errors introduced through solar angle (determining path through water column), solar radiation intensity, and perhaps eyesight.	Low		
Secchi depth	IMOS NRS moorings	Monthly since April 2009 (NS)	*In situ*	Maximum depth at which a	Good. Errors introduced through solar	Low		

		and Sept 2009 (YON)		black and white disk can be seen from the surface.	angle (determining path through water column), solar radiation intensity, and perhaps eyesight.			
Secchi depth	MODIS via $K_{d,490}$ And potential other platforms (VIIRS)	Since 2002.	RS	Weeks et al.	Local algorithm for Reef to reconcile *in situ* and remote observations.	Low, after RS algorithms developed.		
Secchi depth	eReefs model	Jan 2011 – present day at 4 km, Dec 2015 – present at 1 km.	Model	Depth at which light intensity at 488 nm becomes less than 0.37 of the surface value (Lee et al.).	Annual spatial averaged assessed (Robson et al., 2017), but no model / observation point by point comparison.	Low cost assessment required.		
$K_{d,490}$ – vertical attenuation	IMOS Moorings	Since 2017	*In situ*	.loggers	.TBD			

$K_{d,490}$ – vertical attenuation	MODIS via $K_{d,490}$	Since 2002.	RS	Ratio of remote-sensing reflectance at 488 and 547 nm Weeks et al.	Global calibration Local correction for Reef to reconcile *in situ* and remote observations.	Low, after RS algorithms developed Low.			
$K_{d,490}$ – vertical attenuation	eReefs model	Jan 2011 – present day at 4 km, Dec 2015 – present at 1 km.	modelled	Sum of modelled IOPs absorption + scattering, solar angle .	Error at North Stradbroke: (-0.04 +/ 0.1) m^{-1}, Yongala: (-0.07 +/- 0.1) m^{-1}.				
Simulated turbidity	eReefs model	Jan 2011 – present day at 4 km, Dec 2015 – present at 1 km.	modelled	Modelled total scattering at 590 nm correlated with WQM at LJCO.					
Turbidity	AIMS and IMOS	14 Marine Monitoring Program (MMP) (2009 to present) and IMOS	*In situ*	Tudbidimeter (NTU) on sensor network moorings.					

		NRS moorings.						
Benthic PAR	eReefs	Jan 2011 – present day at 4 km, Dec 2015 – present at 1 km.	modelled	Downwelling irradiance quantum-weighted 400 – 700 nm.	Not assessed.			
Benthic PAR	AIMS		*In situ*	Downwelling PAR at seabed.				
Benthic PAR	AIMS	At 4 IMOS Moorings, 26 m depth, at 15 min resolution, since June 2016: Yongala Myrmidon Palm Passage Heron Island South	*In situ*	Downwelling PAR at 26 m depth on mooring lines.	Overall good. First PAR measurements away from optically shallow waters. Two to three instrument exchanges per year. Gaps in data due to instrument failures are less than 30%.	NESP2 and IMOS		
Surface PAR	AIMS Weather Stations: **Station** **Lon** **Lat**	Some stations go back as far	*In situ*	PAR loggers deployed on	Loggers exchanged every other	AIMS, NESP		

	Agincourt Reef_PAR 145.8225 -15.9828 Cape Bowling Green_PAR 147.3928 -19.305 Davies Reef_PAR 147.6345 -18.8316 Hardy Reef_PAR 149.1826 -19.7459 Heron Island_PAR 151.9798 -23.44 Lizard Island_PAR 145.4664 -14.6915 Masig Island_PAR 143.4 -9.76 Bramble Cay_PAR 143.876 -9.1424 OneTree Island_PAR 152.0917 -23.5075 Square Rocks_PAR 150.8855 -23.0986	as the year 1990		reef surface structures.	year. Data holdings are presently cleaned up by Scott Bainbridge.			
Benthic PAR	JCU		*In situ*	Downwelling PAR at seabed.				
Remote-sensing reflectance	Lucinda Jetty Coastal Observatory	Single point (2014 onwards)	*In situ*, calculated from measured	Radiometer	Good			

			irradiance and radiance .						
Remote-sensing reflectance	IMOS Dynamic above water radiance and irradiance collector (DALEC) on *RV Solander*	On boat track, tropical waters.	*In situ*, calculated from measured radiance and irradiance.	Radiometer - DALEC					
Remote-sensing reflectance	MODIS, VIIRS, Sentinel, Himawari	0.3-1 km pixels, up to daily.	Remote sensing	Satellite radiometer					
Remote-sensing reflectance	CORAL	High resolution, one campaign.	Remote sensing	Airborne radiometer		NASA program			
Remote-sensing reflectance	eReefs	Jan 2011 – present day at 4 km, Dec 2015 – present at 1 km; MODIS, VIIRS, Sentinel, Himawari wavebands	Modelled	Semi-empirical optical model.	Quantified in Baird et al., 2016				

Remote sensing reflectance	eReefs	MODIS-Aqua, VIIRS.	Remote sensing inversion.	Inverse modeling using artificial neural networks (ANN).	Schroeder et al. 2007, Goyens et al. 2012.			
In water inherent optical properties	CSIRO LJCO	Single point (continuous, 2014 onwards).	*In situ*	BB9, WQM, ACS, EcoTriplet, WetStar.	Good.	~5k per year when embedded in larger observational program.		
In water inherent optical properties	eReefs	Jan 2011 – present day at 4 km, Dec 2015 – present at 1 km.	modelled	Total absorption at 440 nm, Total scattering at 550 nm, Kd, PAR.	Good.	~5k per year when embedded in larger observational program.		
In water inherent optical properties	IMOS Bio-optics database	1996 – Present, around Australia HPLC pigments and absorption properties.	*In situ* HPLC, absorption (CDOM, NAP, Algae), TSS.		Good.	~5k per year when embedded in larger observational program.		

True colour	MODIS, VIIRS, Sentinel, Himawari		Remote sensing	Combination of remotely-sensed RGB wavelengths.				
True colour	eReefs	Jan 2011 – present day at 4 km, Dec 2015 – present at 1 km.	Modelled	Combination of modelled RGB wavelengths.				
UV radiation/index	Provided by BoM	Continental scale	Modelled	Produced by the European Commission Copernicus Atmosphere Monitoring Service.				

10.5 Temperature

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Temperature	SST (ReefTemp, NOAA etc)	Whole Reef on 1-3 day cycle.	Remote sensing	instruments on multiple polar- and geostationary-orbiting platforms with accepted state of art algorithm etc.	Accuracy can be defined in terms of degrees but limited by cloud cover.	Minimal data processing cost.	Critical pressure for bleaching risk. A primary driver force for biological productivity. State of water condition. Link to most other RIMReP ecological working groups.	Need for an integrated representation of temperature across the entire Reef and water column that combines models and observations to allow for improved risk assessment when combined with habitat mapping.
	In situ water column temp (MMP loggers)	12 sites, one depth (5m) on continuous basis.	*In situ*	SeaBird SBE37	± 0.002 °C (-5 to +35 °C);	Sensor CAPEX and mooring maintenance.		
	In situ water column temp (AIMS Temperature logger program)	80 sites, one depth (12m) on continuous basis.	*In situ*	Various, SeaBird 39, SBE56, Vemco.	± 0.002 °C (-5 to +35 °C) at best; +/- 0.1°C from -5°C to 35°C at worst.	Sensor CAPEX and mooring maintenance.		

	In situ water column temp — IMOS moorings	6(+) sites, various depth in water column at each site, continuous basis.	*In situ*	SeaBird SBE37, SBE56, SBE16	± 0.002 °C (-5 to +35 °C);	Sensor CAPEX and mooring maintenance.		
	SST – near surface. Underway Thermosalinograph IMOS tropical Research Vessels	Ship track – local coverage over entire Reef.	*In situ*	SeaBird SBE21	± 0.001 °C (-5 to +35 °C);	Sensor CAPEX and mooring maintenance.		
	Water column temp (Argos)	Coral Sea coverage, critical for offshore boundary conditions for models, single locations with vertical profiles every X hours.	*In situ*	Sensor type	± 0.002°C	Argo floats cost		
	Water column (Gliders)	Presently 8 mission p.a. in the Reef tracks and vertical profiling with X data points per mission.	*In situ*	Various sensor type - Seabird	± 0.002°C	Slocum and other costs IMOS co-investment		
	Water column temp (models)	Whole of Reef, 47 depths and hourly.	Modelled	eReefs SHOC	Accuracy is quantifiable	Minimal cost (currently		

					See see Herzfeld et al, 2016.	operated by hosts)		
	Water column temp (models)	Whole of Reef, vertically resolved and hourly.	Modelled	eReefs BoM ROMS	Accuracy is quantifiable see Herzfeld et al, 2016.	Minimal cost (currently operated by hosts).		
ReefTemp Next Generation – Degree Heating Day (DHD)	http://www.BoM.gov.au/environment/activities/reeftemp/reeftemp.shtml	Reef and Coral Sea	Remote sensing	IMOS L3S processing of AVHRR ReefTemp DHD Model				
ACCESS – S1 http://www.BoM.gov.au/oceanography/oceantemp/GBR_SST.shtml	Sea surface temperature anomaly (SSTA) forecasts	Reef	Modelled	The forecast presented is based on the ensemble mean of the latest 33-member multi-model forecasts. Sea surface				

				temperature (SST) anomalies are calculated as the difference between SST values and the 1982-2010 climatology, the monthly long-term mean SST.				
Coral Reef Watch Satellite Monitoring • Near-Real-Time Data (5-km Resolution) • Bleaching Alert Area • Degree Heating Week • HotSpot • Sea Surface	https://coralreefwatch.noaa.gov/satellite/index.php	Reef	Remote sensing Modelled					

Temperature • SST Anomaly • Virtual Stations/Gauges								

10.6 Salinity

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Salinity	*In situ* water column salinity (MMP loggers)	12 sites, one depth (5m) on continuous basis.	*In situ*	SeaBird SBE37	Conductivity: 0 to 7 S/m (0 to 70 mS/cm)	Sensor CAPEX and mooring maintenance.	Pressure for ecosystem health, bleaching risk A driver of biological productivity State of water condition	Need for an integrated representation of salinity across the entire Reef and water column that combines models and observations to allow for improved risk assessment when combined with habitat mapping.
	In situ water column salinity – IMOS moorings	6(+) sites, various depth in water column at each site, continuous basis.	*In situ*	SeaBird SBE37SBE 16	Conductivity: 0 to 7 S/m (0 to 70 mS/cm)	Sensor CAPEX and mooring maintenance.		

	SSS – near surface. Underway Thermosalinograph IMOS tropical Research Vessels	Ship track – local coverage over entire Reef	*In situ*	SeaBird SBE21	Conductivity: 0 to 7 S/m (0 to 70 mS/cm)	Sensor CAPEX and mooring maintena nce.	Link to most other RIMReP ecological working groups. Links to estuaries	
	Water column (Gliders)	Presently 8 mission p.a. in the Reef. tracks and vertical profiling with X data points per mission	*In situ*	Various sensor type - Seabird	Conductivity: 0 to 7 S/m (0 to 70 mS/cm)	Slocum and other costs IMOS co-investmen t		
	Water column Salinity (models)	Whole Reef, 47 depths and hourly.	Modelled	eReefs SHOC	Accuracy – unquantified, but validated against MMP and IMOS data.	Minimal cost (currently operated by hosts)		
	In situ water samples point-in-time measurements at MMP + IMOS routine sites	MMP Sites/frequency; IMOS NRS Yongala - quarterly	*In situ*	Grab sample with niskin bottle (surface and depth)	Direct measure should be most accurate (although there can be issues with analytical precision with samples.			

10.7 Ocean currents

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Ocean Currents	*In situ* water column salinity – IMOS moorings	6(+) sites, various depth in water column at each site, continuous basis	*In situ*	ADCP	High temporal frequency (5 min) Vertically resolved (full water column)	Sensor CAPEX and mooring maintenanc e	Pressure for ecosystem health, bleaching risk	Need for an integrated representation of currents across the entire Reef and water column that combines models and observations to allow for improved risk assessment.
	Water column Ocean Current (models)	Whole Reef, 47 depths and hourly	Modelled	eReefs SHOC	Accuracy – unquantified, but validated against MMP and IMOS data.	Minimal cost (currently operated by hosts)	Link to most other RIMReP ecological working groups.	
	Satellite Altimetry (IMOS ocean current)	Reef + regional	Remote sensing	Altimetry	Adequate performance for low frequency offshore circulation; Poor/unvalidated performance for shelf and coastal regions.	Minimal cost (currently operated by hosts)	Links to estuaries	

10.8 Ocean acidification

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Carbon Chemistry	Ship of Opportunity Reef Future Reef Map • underway measurements of the fugacity of CO_2, atmospheric pressure, and sea surface temperature and salinity	Reef transect — Weipa to Gladstone. Monthly	*In situ*	Underway observations Various sensors	High precision (climate record quality)	TBA	Critical pressure for coral growth/health Link to most other RIMReP ecological working groups.	Need for an integrated representation of carbonate chemistry across the entire Reef and water column that combines models and observations to allow for improved risk assessment when combined with habitat mapping.
	Ship of Opportunity RV Cape Ferguson • underway measurements of the fugacity of CO_2, atmospheric pressure, and sea surface temperature and salinity	Ship track — local coverage over entire the Reef	*In situ*	Underway observations Various sensors	High precision (climate record quality)	TBA		
	Davies Reef Tower Fixed site measurements of the fugacity of CO_2, atmospheric pressure, and sea surface	Fixed location — Davies Reef	*In situ*	Various sensors Bottle sampling for DIC, TA and standard				

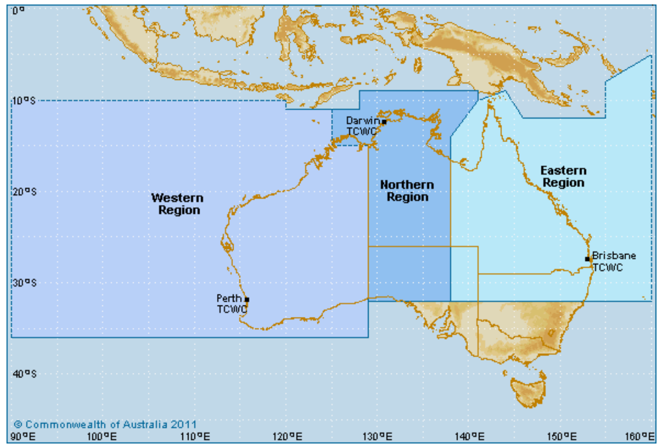
	temperature and salinity			chemical indices (temp., salinity, etc.)				
	In situ water column temp (MMP sites) Bottle sampling for DIC, TA and standard chemical indices (temp., salinity, etc.)	Subset of sites, one depth – water samples:	*In situ*	Bottle sampling for DIC, TA and standard chemical indices (temp., salinity, etc.)	TBA	TBA		
	In situ water column temp – IMOS NRS moorings Bottle sampling for DIC, TA and standard chemical indices (temp., salinity, etc.)	Subset of sites, one depth – water samples:	*In situ*	Bottle sampling for DIC, TA and standard chemical indices (temp., salinity, etc.)	TBA	TBA		
	Water column (models) pH, Total Alkalinity, Aragonite Saturation	Whole Reef, 47 depths and hourly	Modelled	eReefs SHOC	TBA	Minimal cost (currently operated by hosts)		

10.9 Extreme events (cyclones)

<table>
<tr><th>Indicator</th><th>Existing measure and monitoring programs</th><th>Coverage</th><th>In situ, RS or modelled</th><th>Method</th><th>Performance</th><th>Cost</th><th>Links to other RIMReP groups</th><th>Gaps</th></tr>
<tr>
<td>TROPICAL CYCLONE TECHNICAL BULLETIN: AUSTRALIA - NORTHERN REGION
Issued by DARWIN TROPICAL CYCLONE WARNING CENTRE
at: 0730 UTC 24/03/2013
Name: Frankie
Identifier: 04U
Data At: 0600 UTC
Latitude: 11.4S
Longitude: 136.6E
Location Accuracy: within 45 nm (80 km)
Movement Towards: west southwest (210 deg)
Speed of Movement: 8 knots (15 km/h)
Maximum 10-Minute Wind: 35 knots (65 km/h)
Maximum 3-Second Wind Gust: 50 knots (95 km/h)
Central Pressure: 997 hPa
Radius of 34-knot winds NE quadrant: 100 nm (185 km)</td>
<td>Tropical Cyclone Technical Bulletin from Bureau of Meteorology

http://www.BoM.gov.au/cyclone/index.shtml

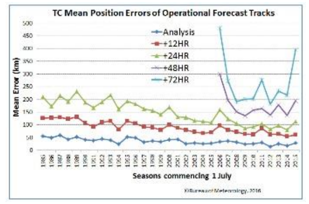
Current Tropical Cyclones

http://www.BoM.gov.au/cyclone/index.shtml</td>
<td>The Bureau of Meteorology responsibility for cyclone services is divided between three Tropical Cyclone Warning Centres (TCWCs): Perth, Darwin and Brisbane.

</td>
<td>In situ, RS and modelled</td>
<td>All standard observational data are used: surface stations, ships, drifting buoys, aircraft, radiosondes in addition to pilot and profiler winds, as well as data from the Advanced Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (ATOVS), the High Resolution Infrared Radiation Sounder (HIRS), the Advanced Microwave Sounding Unit (AMSU-A and AMSU-B), the Atmospheric Infrared Sounder (AIRS), atmospheric motion vector winds derived from geostationary satellite data,</td>
<td>Tropical cyclones (TC) have historically had a reputation for being unpredictable. Much effort has been dedicated to improving the forecasting skill in both location and intensity. The Bureau of Meteorology routinely issues forecasts of cyclone location and intensity to 5 days (120 h). All official forecasts are verified by comparison with the best track, the official estimate of the location and intensity of a tropical cyclone. A best track is prepared for every tropical cyclone, after the event using all available data.

Tropical cyclones vary considerably in their predictability. Some exhibit rapid changes in intensity or change course, speed up or slow down, primarily in response to changes in the surrounding environment.

Figure 2. shows the yearly accuracy of position, year for the Australian region since 1985–86. The five-year average (2011–12 to 2015–16) accuracy is 20 km for the initial position, 69 km at 12 hours, 89 km at 24 hours, 154 km at 48 hours and 221 km at 72 hours. Today a 24 hour forecast is as accurate as those issued for a 12-hour</td>
<td>Tropical Cyclone Technical Bulletins available to General Public</td>
<td>Links to RIMREP Data management and systems working group could enhance the delivery of TC data.</td>
<td>AIMS is running cyclone impacts models for the Authority in near real time, and use data from the BoM technical bulletins which get emailed to AIMS automatically via a scraper bot the Authority created.

There are opportunities to improve the near real time delivery of TC data from BoM to AIMS and the Authority and it is recommended to establish a short-term project be considered within RIMReP and managed by the data management and systems working group.</td>
</tr>
</table>

Radius of 34-knot winds SE quadrant: 100 nm (185 km) Radius of 34-knot winds SW quadrant: 80 nm (145 km) Radius of 34-knot winds NW quadrant: 40 nm (75 km) Radius of 48-knot winds NE quadrant: Radius of 48-knot winds SE quadrant: Radius of 48-knot winds SW quadrant: Radius of 48-knot winds NW quadrant: Radius of 64-Knot Winds: Radius of Maximum Winds: 30 nm (55 km) Dvorak Intensity Code: T3.0/3.0/D1.0/24HRS Pressure of outermost isobar: 1008 hPa Radius of outermost closed isobar: 140 nm (260 km) FORECAST DATA Date/Time : Location :Loc. Accuracy: Max Wind : Central Pressure (UTC) : degrees : nm (km) :knots(km/h): hPa +06: 24/1200: 11.4S 135.7E: 075 (140): 040 (075): 995				scatterometer winds (Advanced Scatterometer, ASCAT), and synthetic MSLP observations from the vortex specification (no upper-air synthetic observations)	prediction in the 1990s. Note that the errors were higher in 2015–16 partly because of the fewer number of forecasts issued as there were only three tropical cyclones in that season. Figure 2: Yearly tropical cyclone position accuracy for the Australian region, 1985–86 to 2015–16  Click for full sized image Improvements in forecast position accuracy are due to a combination of more accurate computer model guidance, improved monitoring technology, and improved methods to combine computer model information. The use of multiple models has increased the forecast skill. Understanding the historical skill and model variations, allows forecasters to present the official forecast track with the accompanying area of uncertainty Although the skill in track forecast has improved greatly, there has been much slower progress in intensity forecasting. This remains the focus of intensive study around the world. Forecasters can determine the general intensity changes but TCs can change their intensity very quickly.			

+12: 24/1800: 11.5S 135.5E: 075 (140): 040 (075): 995 +18: 25/0000: 11.5S 135.2E: 080 (150): 045 (080): 993 +24: 25/0600: 11.5S 134.3E: 095 (175): 045 (080): 990 +36: 25/1800: 11.7S 132.9E: 100 (185): 050 (110): 980 +48: 26/0600: 12.3S 132.2E: 120 (220): 060 (090): 970 +72: 27/0600: 12.9S 131.8E: 170 (320): 040 (065): 990 +96: 28/0600: 13.4S 131.9E: 190 (350): 035 (065): 995 +120: 29/0600: 14.2S 131.3E: 200 (370): 030 (065): 997 REMARKS: Frankie continues to develop steadily, with excellent outflow in the upper levels. Dvorak based on 0.6-wrap curved band evident in VIS for last 4 hours. Further intensification is expected due to favourable environmental conditions, including high SSTs and very low vertical wind shear. The cyclone is expected to move steadily towards the southwest, being steered around the northwest flank of a mid-level ridge and								

cross the coast in 24 to 36 hours.								

10.10 Sea level - storm tides

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Sea level: storm-tide	Storm tide monitoring program	Four sites in the Gulf of Carpentaria; six sites in Torres Strait; 19 sites in the Reef (coastal)	*In situ*	A microwave guided wire sensor is mounted inside a stilling well and/or an open to air microwave radar is mounted above the highest expected storm surge height.	One minute data with accuracy within 3mm with high data recovery rates; >99%.	Sensor maintenance, CAPEX and field servicing (labour & travel costs)	Links to other groups that rely on hydrodynamic information such as sediments and nutrients.	Sites are scattered along the Queensland coastline. No sites between Rosslyn Bay and Mackay (where tides are the largest). No sites on the outer reefs or further offshore. No sites north of Cooktown.

Waves and sea surface temperature	Wave monitoring program	1 site in the Gulf of Carpentaria and 8 sites in the Reef	*In situ*	Datawell WaveRider buoys	30 minute records with high data recovery rates; >98%.	Sensor maintenance, CAPEX and field servicing (labour, boat & travel costs)	Links to other groups that rely on hydrodynamic information such as sediments and nutrients.	Buoys are located in the nearshore and are considerable distances apart. No sites north of Cairns. No sites offshore of the Reef.

10.11 Sea level rise

Indicator	*Existing measure and monitoring programs*	*Coverage*	*In situ, RS or modelled*	*Method*	*Performance*	*Cost*	*Links to other RIMReP groups*	*Gaps*
Australian Baseline Sea Level Monitoring Project Hourly Sea Level and Meteorological Data			*In situ*	http://www.BoM.gov.au/ntc/IDO71002/IDO71002_2017.csv				
Internal IDZ00154: ~2km coastal grid: national barotropic 3-day			Modelled	http://www.BoM.gov.au/oceanography/forecasts/idyoc13.shtml?region=13&forecast=4				

10.12 Primary production

Indicator	*Existing measure and monitoring programs*	*Coverage*	*In situ, RS or modelled*	*Method*	*Performance*	*Cost*	*Links to other RIMReP groups*	*Gaps*
Primary Production	No current sustained direct (*in situ*) monitoring programs		*In situ*	Various definitions and methods, such as incubations.	Measurement limits can be of the order of the changes being measured. E.g. 0.1 - 5 umol L^{-1} limits/changes for background concentrations 100 – 1000 units.	There are various approaches to defining and measuring PP, but in general there are significant costs per sample/measurement. Boats plus significant effort required to process samples.	Fisheries	
Primary Production	Historical data?	Extensive point samples	*In situ*	Mainly incubations			Fisheries	
Primary Production	No current program	Whole of Reef Potentially archived data from	Remote sensing	Various satellites	Absolute uncertainty is typically chlorophyll *a* concentration dependent. For chlorophyll *a* < 0.3 mg/m^3, the derived primary productivity is less certain than for chlorophyll *a* > 0.3 mg m-3.	Access to raw satellite data is free. Processing is easily automated so cost is minimal. Largest cost associated with		Primary productivity processing has not been implemented operationally in Australia. Primary productivity

		1980's onwards			Comparisons of modelled/RS PP relative to *in situ* have shown factors ranging from half to two. Relative PP values do provide useful spatial/temporal context with good confidence. Skill level of RS and modelled PP is highly dependent on accuracy of input data/parameters. To add another perspective, note comment in the literature "RS potential to obtain better estimates of marine primary production than are possible with ship-based methods"	effort to review and assess results.		is a derived product based on remotely sensed inputs (chlorophyll *a* and sea surface temperature). Chlorophyll *a* is often reported as a proxy or indicator for primary productivity. Uncertainties in chlorophyll *a* and total suspended solids (and various model assumptions) are passed on to the derived primary productivity. Note: Remotely sensed

								Flourescence Line Height may be worthy of further exploration.
Primary Production	eReefs	Whole of Reef	Modelled	eReefs	Unreported for eReefs model. Note: typical comparisons of modelled and remotely sensed primary productivity relative to *in situ* have shown factors ranging from half to two. Skill level of remote sensing and modelled primary productivity is highly dependent on accuracy of input data/parameters.	Model parameterisation and run-time. Model review and improvement. Cost associated with effort to review and assess results.		Primary production is not a specified output, but examples of products related to primary productivity have been produced.
Chlorophyll *a*	See the Chlorophyll *a* entries in the light and nutrient reports. Chlorophyll *a* is an input to primary production modelling, and often used as an indicator of production.							

Phytoplankton characteristics	Many PP models include parametrisations of phytoplankton photophysiological characteristics such as photosynthetic response/rate, absorption, quantum yield, temperature effects							

10.13 Noise

Indicator	***Existing measure and monitoring programs***	***Coverage***	***In situ, RS or modelled***	***Method***	***Performance***	***Cost***	***Links to other RIMReP groups***	***Gaps***
Marine Noise Ocean Noise, 2Hz to 6kHz As an archive of physical, man-made and biological sources							Marine fauna Marine mammals Megafauna Coral reefs	No coordinated noise monitoring on the Reef

10.14 Pesticides

Indicator	*Existing measure and monitoring programs*	*Coverage*	*In situ, RS or modelled*	*Method*	*Performance*	*Cost*	*Links to other RIMReP groups*	*Gaps*
PSII herbicides	*In situ*	11 ‘routine’ sites across 4 NRM regions (5 in Wet Tropics; 1 in Burdekin; 4 in Mackay Whitsundays; 1 in Fitzroy). During flood plume sampling, passive samplers have been deployed in previous years along transects extending from selected rivers in the Wet Tropics and Burdekin regions.	*In situ*	Passive samplers (Chemcatchers) are deployed in replicate monthly during the wet season (November to April) and bi-monthly in the dry season (May – October). Passive samplers deployed during flood plume sampling are typically deployed for less than 7 days.	Passive samplers provide a time-averaged estimate of concentration at the deployed location. The passive sampler acts to concentrate the water and delivers typically lower detection limits than is possible with traditional 1L grab samples. A time-averaged concentration provided by passives is arguably more ecologically relevant than grab sampling. It	Preparation, extraction and analysis of samplers (approximately an average of $3000 per site per deployment period. This includes salaries associated with the organisation of volunteers, sample preparation, extraction, analysis, data processing and reporting, consumables and freight). Passive samplers are	Measure of water quality Pesticide loads monitoring program Coral and seagrass health	The relationship between herbicide concentration and salinity (conservative mixing model) is not well understood. An understanding of how ‘impacted’ a passive sampler site has been by flood plumes during a given deployment period is not well understood (i.e. the frequency and duration of flood plumes and the source of the river water). Calibration data (i.e. the rate of uptake of a particular chemical into the passive sampler) is required for estimation of water concentration.

					captures the low-level chronic exposure of marine organisms. Passive samplers are particularly vulnerable to damage/ loss due to weather or interference by members of the public. In a given sampling year, 15% of samplers may be compromised	deployed by 'locals' at minimal cost (maximum cost of $1000 per site per year)		Calibration data for some chemicals (particularly emerging alternatives) is not available, and an assumed sampling rate is adopted that still allows for spatial and temporal trend analysis. Links to coral and seagrass sampling results from overlapping sampling sites have not yet been explored Partnership with eReefs and access to their hydrodynamic model would be enormously helpful in identifying true change in herbicide concentration, by understanding/ removing the annual variability caused by changing annual rainfall/ river discharge, plume extent etc. There is potential to parameterise the model using data from the
PSII herbicides	*In situ* (surface) point-in-time measurements at MMP 'flood plume' sites (response monitoring when flooding).	Plume sampling activities have centered around the Russell-Mulgrave/ Tully and Barratta Creek/ Burdekin Rivers. The Herbert River has also been targeted in previous years.	*In situ*	Grab (snap shot) samples taken at an approximate depth of 1 m. Samples are typically collected along a 'transect' extending from the River mouth. Samples are typically collected during the 'wet season'	Direct measure has the potential to capture the true 'peak' in concentration; however, it is only representative of a small area over a small time frame. Sampling frequency and ideal locations may be hindered	Analysis cost only (~$8,000 annually excluding salaries) as well as sample collection costs incurred by JCU who undertake sampling (i.e. boat cost and labour).		

				(November onwards).	due to poor weather.			pesticide loads monitoring program,
Non-PSII herbicides including emerging ‘alternative’ herbicides	*In situ*	11 ‘routine’ sites across 4 NRM regions (5 in Wet Tropics; 1 in Burdekin; 4 in Mackay Whitsundays; 1 in Fitzroy).	*In situ*	Passive samplers (Chemcatchers) deployed monthly during the wet season (November to April) and bi-monthly in the dry season (May – October).	As above for PSII herbicides	Included in the costs above		together with the physico-chemical properties of individual herbicides to ‘map’ their movements in the near shore area, predicting pesticide ‘hotspots’ and concentrations that could be validated in the field.
Non-PSII herbicides including emerging ‘alternative’ herbicides	*In situ* (surface) point-in-time measurements at MMP ‘flood plume’ sites (response monitoring when flooding)	Plume sampling activities have centered around the Russell-Mulgrave/ Tully and Barratta Creek/ Burdekin Rivers. The Herbert River has also been targeted in previous years.	*In situ*	Grab (snap shot) samples taken at an approximate depth of 1 m. Samples are typically collected along a ‘transect’ extending from the river mouth. Samples are typically collected during the ‘wet season’ (November onwards).	As above for PSII herbicides	Included in the costs above		A pesticide metric that incorporates differing modes of action as presumably the use and presence of alternative herbicides in the marine environment is increasing.

Pesticides	*In situ*	5 ‘routine’ sites across 3 NRM regions (1 in Wet Tropics; 1 in Burdekin; 3 in Mackay Whitsundays).	*In situ*	Passive samplers (PDMS cages) deployed monthly during the wet season (November to April) only.	Provides a time-averaged estimate of concentration at the deployed location.	Included in the costs above		