2017 Scientific Consensus Statement

CHAPTER FIVE

Overview of key findings, management implications and knowledge gaps

Jane Waterhouse
James Cook University

Britta Schaffelke
AIMS

Rebecca Bartley
CSIRO

Rachel Eberhard
Eberhard Consulting

Jon Brodie
James Cook University

Megan Star
CQU

Peter Thorburn
CSIRO

John Rolfe
CQU

Mike Ronan
Queensland Department of Environment and Heritage Protection

Bruce Taylor
CSIRO

Frederieke Kroon
AIMS

Citation:

Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J., Star, M., Thorburn, P., Rolfe, J., Ronan, M., Taylor, B., Kroon, F., 2017. 2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 5: Overview of key findings, management implications and knowledge gaps. State of Queensland, 2017.

This document was prepared by a panel of scientists with expertise in Great Barrier Reef water quality. This document does not represent government policy.

Contents

Acronyms, units and definitions

Acronyms

DIN = Dissolved Inorganic Nitrogen

ms-PAF = multisubstance-Potentially Affected Fraction

NRM = Natural Resource Management

PSII herbicides = photosystem II inhibiting herbicides

QLUMP = Queensland Land Use Mapping Program

TSS = Total suspended sediment[1]

Units

$/tonne = dollar per tonne

kg/yr = kilogram per year

kt/yr = kilotonne per year

m = metres

t/km^2/yr = tonne per square kilometre per year

µm = micrometres

Definitions

Basin: There are 35 basins that drain into the Great Barrier Reef. A basin can be made up of a single or multiple rivers (e.g. North and South Johnstone rivers belong to one basin, the Johnstone Basin). Basins are primarily used here when discussing the relative delivery of a pollutant to the marine system.

Catchment: The natural drainage area upstream of a point that is generally on the coast. It generally refers to the 'hydrological' boundary and is the term used when referring to modelling in this document. There may be multiple catchments in a basin.

Management unit: There are 47 management units in the Great Barrier Reef catchment, which incorporate the 35 basins that drain directly to the Great Barrier Reef including additional internal catchments or management units within the Burdekin and Fitzroy basins.

Other pollutants: Includes contaminants such as antifouling paints, coal particles, metals and metalloids, marine debris/microplastics, personal care products, petroleum hydrocarbons, and pharmaceuticals. In addition, contaminants such as nanomaterials, perfluorooctane sulfonate and perfluorooctanoic acid may be present, but no monitoring information is available for the Great Barrier Reef lagoon (Kroon et al., 2015).

Pollutants: Pollution means the introduction by humans, directly or indirectly, of substances or energy into the environment resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to aquatic activities including fishing, impairment of quality for use of water and reduction of amenities (GESAMP, 2001). This document refers to suspended (fine) sediments, nutrients (nitrogen, phosphorus) and pesticides as pollutants. Within this chapter we explicitly mean enhanced concentrations of or exposures to these pollutants, which are derived (directly or indirectly) from human activities in the Great Barrier Reef ecosystem or adjoining systems (e.g. river catchments). Suspended sediments and nutrients naturally occur in the environment; all living things in ecosystems of the Great Barrier Reef require nutrients, and many

[1] TSS is also often referred to as total suspended solids.

have evolved to live in or on sediment. The natural concentrations of these materials in Great Barrier Reef waters and inflowing rivers can vary, at least episodically, over considerable ranges. Most pesticides do not naturally occur in the environment.

Region: There are six natural resource management (NRM) regions covering the Great Barrier Reef catchments. Each region groups and represents catchments with similar climate and bioregional setting, with boundaries extending into the adjacent marine area. The regions are Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary.

Source Catchment pollutant loads: Unless otherwise specified, the modelling results presented in this document are based on the most recent Report Card 2015 (or Report Card 7) baseline modelling predictions, which represent pollutant delivery to the Great Barrier Reef for the 2012-2013 baseline period. This is used as a point of reference to assess progress towards load reduction targets. The model includes hydrology data from 1986-2014 (28-year record) and static land-use data over the model run period, which were based on the latest available Queensland Land Use Mapping Program (QLUMP) data in each natural resource management region (McCloskey et al., 2017a; McCloskey et al., 2017b).

Note: Inshore coral reefs are equivalent in terminology here as inner shelf coral reefs, as distinct from mid-shelf reefs and outer shelf reefs.

Acknowledgements

This chapter was led by TropWATER James Cook University with contributions from several representatives from the Australian Institute of Marine Science (AIMS), Central Queensland University, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Queensland Department of Environment and Heritage Protection (DEHP) and Eberhard Consulting.

This chapter is a synthesis of chapters 1 to 4 and therefore has drawn on contributions from the following additional co-authors (in alphabetical order): Fernanda Adame, Zoe Bainbridge, Mark Baird, Andrew Brooks, Jo Burton, Catherine Collier, Aaron Davis, Nicole Flint, Alex Garzon-Garcia, Matthew Griffiths, John Gunn, Rosemary Hill, Petra Kuhnert, Stephen Lewis, Janice Lough, Pethie Lyons, Reinier Mann, Kirsten Maclean, Nadine Marshall, Kevin McCosker, Len McKenzie, Jon Olley, Caroline Petus, Mark Poggio, Cathy Robinson, Amelia Selles, Mark Silburn, Rachael Smith, Terri Sutcliffe, Dieter Tracey, Ryan Turner, Sven Uthicke, Maria VanderGragt, David Waters, Tony Weber, Scott Wilkinson and Jill Windle.

A special thanks to Dieter Tracey for preparing the maps presented in this chapter and to Jane Mellors for the final editing (both from TropWATER, James Cook University).

The chapter was prepared with the support of funding from the Office of the Great Barrier Reef within the Queensland Department of Environment and Heritage Protection and the Department of the Environment and Energy. In-kind support was contributed from the organisations of the authors.

Executive summary

To support the development of the Reef 2050 Water Quality Improvement Plan 2017-2022, a multidisciplinary group of scientists, with oversight from the Reef Independent Science Panel, was established to review and synthesise the significant advances in scientific knowledge of water quality issues in the Great Barrier Reef to arrive at a consensus on the current understanding of the system.

For the 2017 Scientific Consensus Statement, the information and findings in these assessments and in other scientific publications were reviewed and synthesised in four supporting chapters. This fifth and final chapter provides a synthesis of the key findings of these four chapters and, based on this evidence, makes recommendations for future management of water quality in the Great Barrier Reef.

The overarching consensus is that:

> **Key Great Barrier Reef ecosystems continue to be in poor condition. This is largely due to the collective impact of land run-off associated with past and ongoing catchment development, coastal development activities, extreme weather events and climate change impacts such as the 2016 and 2017 coral bleaching events.**
>
> **Current initiatives will not meet the water quality targets. To accelerate the change in on-ground management, improvements to governance, program design, delivery and evaluation systems are urgently needed. This will require greater incorporation of social and economic factors, better targeting and prioritisation, exploration of alternative management options and increased support and resources.**

The evidence base supporting this consensus is provided in a series of four supporting chapters. The main conclusions were:

1. The decline of marine water quality associated with land-based run-off from the adjacent catchments is a major cause of the current poor state of many of the coastal and marine ecosystems of the Great Barrier Reef. Water quality improvement has an important role in ecosystem resilience.
2. The main source of the primary pollutants (nutrients, fine sediments and pesticides) from Great Barrier Reef catchments is diffuse source pollution from agriculture. These pollutants pose a risk to Great Barrier Reef coastal and marine ecosystems.
3. Progress towards the water quality targets has been slow and the present trajectory suggests these targets will not be met.
4. Greater effort to improve water quality is urgently required to progress the substantial pollutant reductions using an expanded scope of tailored and innovative solutions. Climate change adaptation and mitigation, cumulative impact assessment for major projects and better policy coordination are also required to protect the Great Barrier Reef.
5. There is an urgent need for greater investment in voluntary practice change programs, the use of regulatory tools and other policy mechanisms to accelerate the adoption of practice change, and robust monitoring and evaluation programs to measure the rate and effectiveness of adoption.
6. Strengthened and more effective coordination of Australian and Queensland government policies and programs, further collaboration with farmers and other stakeholders, and strong evaluation systems are critical to the success of Great Barrier Reef water quality initiatives.

7. Priorities for reducing pollutant loads are now established at a catchment scale, based on the exposure of coastal and marine ecosystems to land-based pollutants, and should be used to guide investment.
8. A greater focus on experimentation, prioritisation and evaluation at different scales, coupled with the use of modelling and other approaches to understand future scenarios, could further improve water quality programs.

The conclusions above are supported by the following key findings:

1. The decline of marine water quality associated with land-based run-off from the adjacent catchments is a major cause of the current poor state of many of the Great Barrier Reef coastal and marine ecosystems. Additionally, coastal ecosystems have been highly modified and continue to be exposed to a range of pressures from catchment development. The resilience of marine ecosystems was indicated by their ability to at least partially recover from previous losses during periods of low disturbance and reduced catchment pollutant loads. The systems have been severely impacted by a number of recent events—including prolonged periods of extreme sea surface temperatures, tropical cyclones and the progression of the fourth wave of crown-of-thorns starfish population outbreaks. Climate change is predicted to increase the frequency of large-scale bleaching events and the intensity of extreme weather events.
2. The greatest water quality risks to the Great Barrier Reef and coastal ecosystems are from discharges of (i) nutrients, which are an additional stress factor for many coral species, promote crown-of-thorns starfish population outbreaks with destructive effects on mid-shelf and offshore coral reefs, and promote macroalgal growth; (ii) fine sediments, which reduce the light available to seagrass ecosystems and inshore coral reefs; and (iii) pesticides, which pose a toxicity risk to freshwater ecosystems and some inshore and coastal habitats.
3. The main source of excess nutrients, fine sediments and pesticides from Great Barrier Reef catchments is diffuse source pollution from agriculture. Other land uses, including urban areas, contribute relatively small but concentrated pollutant loads which may be important at local scales.
4. Progress towards the Reef Water Quality Protection Plan 2013 targets has been slow and the present trajectory will not meet the targets. This puts the Outstanding Universal Value of the Great Barrier Reef under increasing pressure, especially in the context of other pressures such as climate change. Greater effort to improve reef water quality is urgently required to restore and protect the Great Barrier Reef ecosystems.
5. Current management options to reduce pollutant run-off to the Great Barrier Reef provide a solid foundation for program implementation, but an expanded scope of tailored and innovative solutions is urgently required to progress the substantial pollutant load reductions required to meet the Reef 2050 Water Quality Improvement Plan targets by 2025. There is an urgent need for greater investment in voluntary practice change programs, the use of regulatory tools and other policy mechanisms to accelerate the adoption of practice change, and robust monitoring and evaluation programs to measure the rate and effectiveness of adoption.
6. Great Barrier Reef water quality governance requires a commitment to adaptive, participatory and transdisciplinary approaches, and better use of social, economic and institutional research. There is strong evidence to show where aspects of current water quality management programs can be strengthened. Risks including climate change, major development projects and related policy areas, such as agricultural intensification and coastal development, need to be addressed more directly. Strengthened and more effective coordination of Australian and Queensland government policies and programs, further

collaboration with farmers and other stakeholders, and strong evaluation systems are critical to the success of Great Barrier Reef water quality initiatives.

7. Several catchments contribute to the highest exposure of coastal or marine ecosystems to pollutants, and are considered a high priority for water quality improvement. These include the Mulgrave-Russell, Johnstone, Tully, Herbert, Haughton, Burdekin, Pioneer, Plane, Fitzroy and Mary catchments. Social and economic information is required to prioritise efforts within catchments.
8. Monitoring and modelling of the Great Barrier Reef ecosystems is a strength of the Reef Water Quality Protection Plan 2013 and its programs, with some spatial limitations. However, there has been limited investment in social and institutional research and monitoring, and a lack of systematic evaluation of delivery processes and governance systems. A greater focus on experimentation, prioritisation and evaluation at different scales, coupled with the use of modelling and other approaches to understand future scenarios, could further improve water quality programs.

While a great deal of evidence is available to support the 2017 Scientific Consensus Statement, there are still many important knowledge gaps that need to be addressed to improve our understanding and management of water quality issues in the Great Barrier Reef. Key knowledge gaps and areas for further research are included in each of the first four chapters and highlighted in section 8 of this chapter. These will be incorporated into the updated Reef Water Quality Protection Plan Research, Development and Innovation Strategy.

The writing team has identified the key findings and recommendations (section 9) from the evidence collated for this Scientific Consensus Statement. The main findings highlight the most important areas of the evidence, and the recommendations identify actions that are essential for reversing the decline in Great Barrier Reef ecosystem health due to water quality degradation and modification of coastal ecosystems. The clear message is that greater and more substantial effort to improve water quality is urgently required.

1. Introduction

To support the development of the Reef 2050 Water Quality Improvement Plan 2017-2022, a multidisciplinary group of scientists, with oversight from the Reef Independent Science Panel, was established to review and synthesise the significant advances in scientific knowledge of water quality issues in the Great Barrier Reef and to arrive at a consensus on the current understanding of the system. This is four years after the last Scientific Consensus Statement in 2013 (see Brodie et al., 2013), which concluded that key Great Barrier Reef ecosystems are showing declining trends in condition due to continuing poor water quality, cumulative impacts of climate change and increasing intensity of extreme events. The evidence base was synthesised in a series of five supporting chapters, and the following conclusions in 2013 were based on those detailed reviews:

1. The decline of marine water quality associated with terrestrial run-off from the adjacent catchments is a major cause of the current poor state of many of the key marine ecosystems of the Great Barrier Reef.
2. The greatest water quality risks to the Great Barrier Reef are from nitrogen discharge, associated with crown-of-thorns starfish outbreaks and their destructive effects on coral reefs, and fine sediment discharge which reduces the light available to seagrass ecosystems and inshore coral reefs. Pesticides pose a risk to freshwater and some inshore and coastal habitats.
3. Recent extreme weather—heavy rainfall, floods and tropical cyclones—have severely impacted marine water quality and Great Barrier Reef ecosystems. Climate change is predicted to increase the intensity of extreme weather events.
4. The main source of excess nutrients, fine sediments and pesticides from Great Barrier Reef catchments is diffuse source pollution from agriculture.
5. Improved land and agricultural management practices are proven to reduce the run-off of suspended sediment, nutrients and pesticides at the paddock scale.

Since 2013, several major comprehensive assessments of the condition of Great Barrier Reef coastal and marine ecosystems have been completed. The assessments of the status and risk of current and potential pressures to long-term ecosystem resilience were presented in:

- the Great Barrier Reef Outlook Report (GBRMPA, 2014a)
- the Great Barrier Reef Region Strategic Assessment, jointly conducted by the Queensland and Australian governments (GBRMPA, 2014b; Queensland Department of State Development, 2013)
- the Final Report of the Great Barrier Reef Water Science Taskforce (Great Barrier Reef Water Science Taskforce, 2016)
- the Water Quality Improvement Plans for all six natural resource management regions bordering the Great Barrier Reef.

The Water Quality Improvement Plans also include an assessment of relative risks of degraded water quality at a basin scale, management options and recommendations (Burnett Mary NRM Group, 2015; Cape York NRM and South Cape York Catchments, 2016; Fitzroy Basin Association, 2015; Folkers et al., 2014; NQ Dry Tropics, 2016; Terrain NRM, 2015).

For the 2017 Scientific Consensus Statement, the information and findings in these assessments and in other scientific publications were reviewed and synthesised in four supporting chapters. This fifth and final chapter provides a synthesis of the key findings of these four chapters and, based on this evidence, makes recommendations for future management of water quality in the Great Barrier Reef.

In this chapter, the findings of the supporting chapters are first summarised in five sections:

- the condition of Great Barrier Reef coastal and marine ecosystems and their responses to water quality and disturbances (section 2)
- the sources of sediments, nutrients, pesticides and other pollutants to the Great Barrier Reef (section 3)
- the risk from anthropogenic pollutants to Great Barrier Reef coastal and marine ecosystems (section 4)
- environmental, social and economic values at risk and progress to date (section 5)
- management options for addressing water quality issues and their effectiveness (section 6).

References for the material included in these sections are accessible in the original chapters.

Section 7 identifies spatial priorities for water quality management in the Great Barrier Reef catchment. Priority knowledge gaps and unresolved issues for each chapter are summarised in section 8. Final conclusions and recommendations are presented in section 9.

2. What is the condition of coastal and marine ecosystems of the Great Barrier Reef and what are their responses to water quality and disturbances?

The Great Barrier Reef marine ecosystems and their associated catchments are part of a dynamic, interconnected system. The condition of inshore coral reefs and seagrass meadows marginally improved between 2014 and 2015, but is still rated moderate to poor, depending on the region. The improvement coincided with a period of low tropical cyclonic disturbance and no significant river flood events affecting the Great Barrier Reef in 2014 to 2016, leading to reduced catchment pollutant loads. However, in 2016 and 2017 record warm sea surface temperatures caused a mass coral bleaching event and significant coral mortality.

Research over recent years has improved the understanding of interactive and cumulative pressures as drivers of coastal and marine ecosystem condition and resilience. The global pressures of ocean warming and acidification and local disturbances by tropical cyclones interact with local, anthropogenic pressures such as land run-off. However, predicting future conditions of coastal and marine ecosystems is difficult due to the challenge of untangling and quantifying individual pressure–response relationships, non-linear responses and the complexity of interactions and ecological feedback loops in a changing environment.

Supporting evidence

2.1 Conditions and trends of water quality and coastal and marine ecosystems in the Great Barrier Reef region

2.1.1 Coastal and marine water quality

- Water quality in the inshore waters from the Wet Tropics to the Fitzroy regions remains in moderate to poor condition and is strongly associated with increased land-based run-off.
- Turbidity and photic depth in the Great Barrier Reef lagoon are significantly affected by rainfall and river flow as well as by wave and tidal effects.
- The half-lives of widely used photosystem II inhibiting herbicides (PSII herbicides) are more than 100 days, indicating high persistence and explaining their presence in the Great Barrier Reef year-round.

2.1.2 Coastal and marine ecosystems

Coastal freshwater wetlands and estuarine ecosystems

- The extent of natural and near-natural wetlands has largely been maintained since the 2013 Scientific Consensus Statement at around 85% of pre-development extent (reported in 2013).
- The extent of mapped freshwater swamps (palustrine wetlands) remains at 76% of the estimated pre-development extent, with an overall loss of 59 ha between 2009 and 2013. However, historic loss of floodplain wetlands exceeds 80% of pre-development extent in the lowland areas of some catchments, such as the Herbert.
- Over 90% of the estimated pre-development extent of mangroves and salt marshes remain in most catchments, with an overall loss of 293 ha between 2009 and 2013.

Seagrass ecosystems

- Inshore seagrass meadows remain in poor condition, despite improvements in some seagrass condition indicators in some regions. There were overall improvements in abundance (above-ground percentage cover and biomass); however, reproductive effort declined, indicating a low capacity to recover from disturbances with the available seed resources.

Coral reef ecosystems

- The condition of monitored inshore coral reefs within the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy natural resource management regions has marginally improved between 2014 and 2015, but is still rated moderate to poor, depending on the region.
- Hard coral cover on mid-shelf and offshore reefs south of around Cairns increased between 2012 and 2015, showing very fast recovery during a period of low disturbance.
- Coral cover declined in the Cairns/Cooktown Management Area, associated with the impact of tropical cyclones and crown-of-thorns starfish outbreaks.
- A mass thermal coral bleaching event affected the Great Barrier Reef in 2016 and resulted in significant coral mortality, especially north of Port Douglas.
- Ongoing, warmer-than-average sea temperatures have resulted in a further mass coral bleaching in 2017; this is the first time that bleaching has occurred in the Great Barrier Reef in consecutive years. The 2017 bleaching was widespread but most intense on reefs between Cairns and Townsville. Coral mortality from the 2017 bleaching event is still unfolding and not yet fully quantified.
- In addition, severe tropical cyclone Debbie affected reefs in the Mackay Whitsunday region in 2017 with subsequent flooding affecting the Fitzroy region. Impacts of this cyclone and associated floods on wetlands, seagrass meadows and coral reefs have yet to be quantified.

Dugongs

- Dugong populations in the northern Great Barrier Reef are stable, with current estimates of 4517 animals, but are in severe decline between Rockhampton and Cooktown (central and southern Great Barrier Reef), with 2011 survey estimates of 537 animals.
- Dugong populations immediately outside the Great Barrier Reef World Heritage Area in Torres Strait and Hervey Bay are stable, with current estimates of 102,519 and 1438 animals, respectively.

2.2 Key drivers of the observed changes

- Global pressures such as ocean warming and acidification are affecting the Great Barrier Reef, where sea surface temperatures have warmed by 0.80°C since the late 19th century and will continue to warm.
- Record warm sea surface temperatures were observed on the entire Great Barrier Reef in March, April and May 2016. Temperatures in the northern half of the Great Barrier Reef remained extremely high into late summer and autumn, while temperatures further south were slightly moderated in February 2016 by two tropical lows bringing cloud cover, rain and wind.
- Several tropical cyclones caused local disturbances on the Great Barrier Reef between 2013 and 2015, including three severe cyclones. No further cyclones were recorded until tropical cyclone Debbie crossed the Whitsunday coast in March 2017.
- Local, anthropogenic pressures such as land run-off affected the Great Barrier Reef in several ways. The 2013 water year (October 2012 to September 2013) was the last in a sequence of years with above average river discharge (2007-2013). Total river discharge in the 2014-2016 water years was around or below average and no significant river flood events affected the Great Barrier Reef lagoon. Flooding associated with tropical cyclone Debbie affected the Fitzroy region in 2017.
- The condition of many coastal freshwater wetlands continues to be affected by a range of chronic and acute pressures such as excess nutrient, sediment and pesticide loads; loss of connectivity; changes in hydrology; and invasive species. These modifications have led to secondary impacts such as algal blooms and hypoxia.
- River run-off containing suspended sediments, nutrients (which can trigger phytoplankton blooms) and coloured dissolved organic matter reduce the levels of light reaching inshore seagrass meadows and coral reefs.
- High concentrations of suspended sediment interfere with filter feeding, smother corals with a fine layer of sediment that requires mucus production and energy to clear and affect the reproduction and early life histories of corals.
- The ratio of carbon to nitrogen in seagrass tissue indicates that nitrogen availability remains elevated compared to biological demand.
- The fourth documented crown-of-thorns starfish population outbreak commenced around 2010-2011 and has now progressed south, to reefs at the latitude of about Ingham. The link between high nutrient availability, such as is observed after significant flood events, and primary outbreaks has been further strengthened.

2.3 Ecosystem resilience to environmental pressures and changes

- Great Barrier Reef seagrass meadows continue to recover from losses experienced during the extreme weather of 2009 to 2011. Recovery rates vary spatially and temporally due to varying stressors, reproductive output and availability of seed banks. In some regions, seagrass recovery was hindered with the concomitant loss of ecosystem engineering functions (e.g. seagrasses stabilising the seabed thereby reducing sediment erosion/resuspension), undermining habitat resilience
- The coral reefs on the mid-shelf and outer shelf of the Great Barrier Reef have shown capacity to rapidly recover from recent disturbances, mostly through increase in cover of fast-growing coral species. The recent period of low rainfall and run-off demonstrates the inherent ability of inshore reefs communities to recover from acute disturbances during periods of reduced catchment loads.

- The value of mitigation of local pressures is exemplified by the no-take zones on Great Barrier Reef reefs, which have been associated with greater resistance to disturbance and shorter recovery times of coral cover and reef fish communities after disturbance.
- Limited information exists on the recovery and resilience of coastal wetlands and estuarine ecosystems, including mangroves, because their condition is not systematically monitored.
- The current resilience of coastal and marine ecosystems is indicated by their ability to at least partially recover from previous losses during periods of low disturbance and reduced catchment pollutant loads. While the processes and conditions controlling recovery are not completely understood, improvements in water quality are important.

3. What are the major sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef?

Methods used to estimate river pollutant loads to the Great Barrier Reef lagoon have improved since the 2013 Scientific Consensus Statement. The key findings from the 2013 Scientific Consensus Statement were based on the best available estimates of river pollutant loads derived from catchment modelling and monitoring for the six natural resource management regions. In this review, multiple lines of evidence are presented: (i) monitored pollutant loads data for 32 sites (with up to nine years of data) for sediments, nutrients and pesticides, (ii) updated modelling data (up to 2014-2015) at the 47 management units (or sub-catchment) scale, and (iii) individual research project findings focusing on the last four years (2013-2017).

The results confirm that water discharged from the catchments into the Great Barrier Reef lagoon continues to be of poor quality in many locations. Furthermore, enhanced modelling and monitoring of total suspended solids, nitrogen, phosphorus and pesticides and provenance tracing of sediment have significantly enhanced our knowledge of major sources and processes contributing to these river pollutant loads. The main land uses contributing pollutant loads are rangeland grazing for sediment and particulate nutrients and sugarcane for dissolved inorganic nutrients and photosystem II inhibiting herbicides. Contributions from other land uses including urban areas are relatively minor in comparison to agriculture but can be important at local scales. At the scale of the six natural resource management regions, the Wet Tropics, Burdekin and Fitzroy regions still contribute most to these river pollutant loads. However, at the scale of the 35 basins, basin-specific priorities across the Great Barrier Reef also include some in the Mackay Whitsunday and Burnett Mary regions, emphasising the value of assessments at the basin scale or finer scale.

Supporting evidence

3.1 Sediment

- Catchment modelling estimates that ~9900 kt/yr of fine (silt and clay) sediment is delivered to the Great Barrier Reef, of which 7930 kt/yr is estimated to be anthropogenic and due to changes in land use and management. Compared to estimated pre-development conditions, the modelled mean annual fine sediment loads to the Great Barrier Reef lagoon have increased ~5-fold for the entire Great Barrier Reef catchment, ranging between 3-fold and 8-fold depending on the region.
- Catchment monitoring revealed that fine sediment (under 16 µm) is the fraction most likely to reach the Great Barrier Reef lagoon and is the dominant proportion in monitored fine sediment loads across most regions.
- The Burdekin region contributes ~40% of the anthropogenic fine sediment load to the Great Barrier Reef lagoon, with the Fitzroy (~18%), Wet Tropics (~15%) and Burnett Mary (~15%) the other dominant regions. Within these regions, the top five sediment-contributing basins to the

anthropogenic load are the Burdekin, Fitzroy, Mary, Burnett and Herbert. Within these basins, approximately two-thirds of the specific sediment yield ($t/km^2/yr$) is coming from the top quartile of management units (i.e. 12 out of the 47 management units) when assessed using both modelling and monitoring data.

- Rangeland grazing is the dominant land use contributing sediment, although parts of the Wet Tropics and Mackay Whitsunday regions have high specific yields ($t/km^2/yr$) from other land uses.
- Tracing studies suggest that sub-surface erosion (gully, streambank and deep rill erosion on hillslopes) is the primary source of sediment, contributing ~90% to the end-of-catchment loads. The models show similar ratios for the Burdekin, Fitzroy and Burnett Mary regions and for the Normanby Basin.

3.2 Nutrients

- Catchment modelling estimates that there is ~55 kt/yr of total nitrogen and ~13.4 kt/yr of total phosphorus delivered to the Great Barrier Reef. Approximately 29 kt/yr of total nitrogen and 8.8 kt/yr of total phosphorus is estimated to be anthropogenic and due to changes in land use and management. This is a 2.1-fold increase for total nitrogen (range between 1.2 and 4.7 times, depending on the region) and 2.9-fold increase for total phosphorus (range between 1.2 and 5.3 times).
- Catchment modelling estimates that the various nutrient constituents show different increases in loads delivered to the Great Barrier Reef from pre-development conditions. The dissolved inorganic nitrogen load is ~12 kt/yr, with a 2.0-fold increase (ranging between 1.2 and 6.0, with the exception of Cape York). The particulate nitrogen load is ~25 kt/yr, with a 1.5-fold increase (ranging between 1.2 and 2.2). The particulate phosphorus load is ~10 kt/yr, with a 2.9-fold increase (ranging between 1.2 and 5.3).
- Total nitrogen delivery to the Great Barrier Reef is dominated by the Wet Tropics (30%) and Fitzroy (20%) regions; dissolved inorganic nitrogen is dominated by the Wet Tropics (46%) and Burdekin (21%); and particulate nitrogen is dominated by the Wet Tropics (27%) and Fitzroy (26%) regions. Particulate phosphorus is dominated by the Fitzroy (33%) and the Burdekin (22%) regions.
- Within these six natural resource management regions, hotspot areas exist that contribute disproportionally to the anthropogenic nutrient loads. The top five basins contributing to the anthropogenic dissolved inorganic nitrogen load are the Herbert, Burdekin, Johnstone, Haughton and Mulgrave-Russell. The top five basins contributing to the anthropogenic particulate nitrogen load are the Fitzroy, Mary, Burdekin, Johnstone and Herbert. The top quartile of management units (i.e. 12 out of the 47 management units) contribute ~67% of the total nitrogen, ~87% of the dissolved inorganic nitrogen, 69% of particulate nitrogen, 69% of the total phosphorus and 72% of particulate phosphorus, based on the specific nutrient yields ($t/km^2/yr$).
- Sugarcane areas dominate the source of dissolved inorganic nitrogen loads, and grazing dominates the source of particulate nitrogen loads. In the rangeland grazing areas, sub-surface soil erosion (based primarily on studies undertaken on gullies) may contribute low concentrations but potentially high loads of bioavailable nitrogen, phosphorus and carbon depending on the soil type. Although the spatial location of bioavailable particulate nitrogen sources may differ from that of fine sediment, the management strategies for mitigating export of particulate nitrogen and fine sediment are similar.
- Dissolved and particulate nutrient loads from urban land uses, particularly wastewater discharges, can be important at local scales but generally represent less than 7% of the total load.

3.3 Pesticides and other pollutants

- Catchment modelling estimates that there is ~12,000 kg/yr of photosystem inhibiting herbicides (ametryn, atrazine, diuron, hexazinone, tebuthiuron and simazine) delivered to the Great Barrier Reef.
- The measured pesticide data suggest that most pesticides are found in all regions, even though some are in very small quantities. The results from the end-of-system water quality monitoring suggest that the measured pesticide loads are generally lower than modelled estimates, but that many more pesticides than the five priority photosystem II inhibiting herbicides are present in Great Barrier Reef coastal and marine ecosystems.
- The dominant source of pesticides changes between years and locations. However, in terms of toxic equivalent load, the Wet Tropics, Mackay Whitsunday and Burdekin regions dominate delivery to the Great Barrier Reef.
- The toxic equivalent loads for pesticides are highest from sugarcane for all regions, except the Fitzroy, where loads from grazing dominate. Total toxic equivalent loads are highest from the Plane Creek and Haughton basins.
- Sources of pollutants other than sediment, nutrients and pesticides include both diffuse and point sources. Agricultural land uses are a likely source of metals (through phosphatic fertilisers and fungicides) and pharmaceuticals (such as antibiotics) into aquatic ecosystems. Shipping, along shipping lanes and around anchorage areas, is likely to contribute to chronic antifouling contamination as well as marine debris. The contribution of agricultural land uses and shipping to these pollutant loads has not been quantified. Point sources such as urban centres, waste treatment and disposal (including sewage treatment plants), mines (both abandoned and current), ports and marinas, industrial areas and intensive animal production are all known or likely sources of a range of different pollutants. Compared to diffuse sources, most contributions of such point sources are likely to be relatively small but could be significant locally and over short time periods. Point sources are generally regulated activities; however, monitoring and permit information is not always available to examine ecological risk. In some cases, no monitoring data exist.

4. What is the risk to Great Barrier Reef coastal and marine ecosystems from anthropogenic pollutants?

A combination of qualitative and semi-quantitative assessments was used to estimate the likelihood of exposure and relative risk of water quality constituents to Great Barrier Reef coastal and marine ecosystem health from major sources in the catchments, focusing on agricultural land uses.

The main finding was that increased loads of suspended sediments, nutrients (nitrogen and phosphorus) and pesticides are all important at different scales and different locations in the Great Barrier Reef (Figure 1). However, the risk differs between the individual pollutants, source catchments and the distance from the coast. A number of basins contribute to the high exposure of coastal or marine ecosystems to two or more pollutants. These include the Mulgrave-Russell, Johnstone, Tully, Herbert, Haughton, Burdekin, Pioneer, Plane, Fitzroy and Mary basins.

Supporting evidence

4.1 Fine sediment

- Exposure to fine sediment is most significant in areas of shallow seagrass and coral reefs on the inner shelf adjacent to basins with high anthropogenic fine sediment loads.

- The greatest exposure of coral reef and seagrass to fine sediment is from the Burdekin, Fitzroy, Mary, Herbert, Johnstone and Burnett basins. The Burdekin and Fitzroy basins also contribute the greatest fine sediment risk to seagrass ecosystems.
- The greatest exposure of floodplain wetland ecosystems to sediment pressures is in the Dawson, Isaac and Mackenzie catchments; the greatest exposure of floodplain ecosystems to sediment is in the Dawson and Lower Burdekin catchments.

4.2 Nutrients

4.2.1 Nitrogen

- Exposure to dissolved inorganic nitrogen is significant to all inner shelf areas and the mid-shelf area between Lizard Island and Townsville adjacent to basins with high anthropogenic dissolved inorganic nitrogen loads. The relative importance of dissolved inorganic nitrogen to seagrass ecosystems is still uncertain, but it may influence light availability for deepwater seagrass in areas deeper than 10–12 m due to increased phytoplankton growth.
- The greatest exposure of coral reef and seagrass to dissolved inorganic nitrogen is from the Herbert, Haughton, Johnstone, Mulgrave-Russell, Tully, Plane and Murray basins. The Herbert, Johnstone, Mulgrave-Russell and Tully basins also contribute the greatest dissolved inorganic nitrogen risk to coral reefs and primary crown-of-thorns starfish outbreaks.
- Anthropogenic particulate nitrogen is also likely to be of some importance in the same areas, as well as in the Fitzroy Basin; however, our knowledge on the bioavailability of particulate nitrogen to marine ecosystems relative to that of dissolved inorganic nitrogen is still limited.
- Given the small anthropogenic loads of dissolved organic nitrogen from most basins, and its limited bioavailability, it is considered to be less important than dissolved inorganic nitrogen.
- The greatest exposure of floodplain wetland ecosystems to nutrient pressures is in the Dawson and Lower Fitzroy catchments, and the greatest exposure of floodplain ecosystems to nutrients is in the Belyando and Dawson catchments.

4.2.2 Phosphorus

- Anthropogenic phosphorus loads are considerable from many basins, and although our knowledge of the relative importance of nitrogen and phosphorus is still limited, nitrogen is considered to be the limiting nutrient and hence more important than phosphorus. Hence, phosphorus is not considered to be as important as nitrogen in any form.

4.3 Pesticides

- Only a few basins present a very high – moderate risk to end-of-catchment ecosystems from photosystem II inhibiting herbicides, with diuron presenting the highest risk. These basins are generally characterised as smaller coastal catchments with high proportions of sugarcane land use (i.e. basins within the Mackay Whitsunday region and the Lower Burdekin catchment).
- While the risk assessment only assessed the concentration and temporal exposure of five photosystem II inhibiting herbicides, developments in our understanding of the ecotoxicity of other pesticides detected in Great Barrier Reef catchments has allowed us to examine other pesticides individually.
- The ecotoxicity threshold assessment demonstrated that Great Barrier Reef ecosystems are exposed to a large number of other types of pesticides, some of which were a high risk on their own. Of the pesticides that indicated a risk to ecosystems (i.e. <95% species protection), imidacloprid had a very high-moderate risk in a number of basins, and hexazinone, metolachlor and metsulfuron-methyl had a moderate to high risk in some basins. Including all pesticides in

the multisubstance-Potentially Affected Fraction (ms-PAF) risk metric in future risk assessments will provide a more accurate assessment of the potential risk pesticides have to these ecosystems.

- Pesticides pose the greatest risk to ecosystems closest to the source of the pesticides; that is, freshwater wetlands, rivers and estuaries are exposed to the highest concentrations, followed by coastal ecosystems, seagrass and coral reefs. Our understanding, at this stage, of the spatial exposure of pesticides in the marine environment is very limited.
- The greatest exposure of floodplain wetland ecosystems to pesticide pressures is in the Herbert Basin and Lower Burdekin catchment, and the greatest exposure of floodplain ecosystems to pesticide pressures is in the Herbert, Pioneer and Plane basins and the Lower Burdekin and Belyando catchments.

4.4 Other pollutants

- In a qualitative risk assessment of pollutants other than sediment, nutrients and pesticides, marine plastic pollution poses the highest relative risk to the Great Barrier Reef marine ecosystems, particularly in the Cape York region due to exposure to oceanic and local shipping sources. This is followed by chronic contamination of water and sediments with antifouling paint components and exposure to certain personal care products in regions south of Cape York. The relative risks of other pollutants are likely to be relatively low with some minor differences between regions.

Significant data limitations exist in the Cape York region; therefore, it is difficult to make conclusions about this region with confidence. Enough evidence is available to conclude that, overall, the eastern Cape York catchments currently present a relatively low risk to adjacent coastal and marine ecosystems. This notwithstanding, the Normanby, Hann and Stewart basins are likely to pose a risk to ecosystems in the Princess Charlotte Bay area from degraded water quality, particularly from increased turbidity in wet season conditions. Until the 2016 bleaching event, the coral reef ecosystems in the Cape York region were typically in good condition.

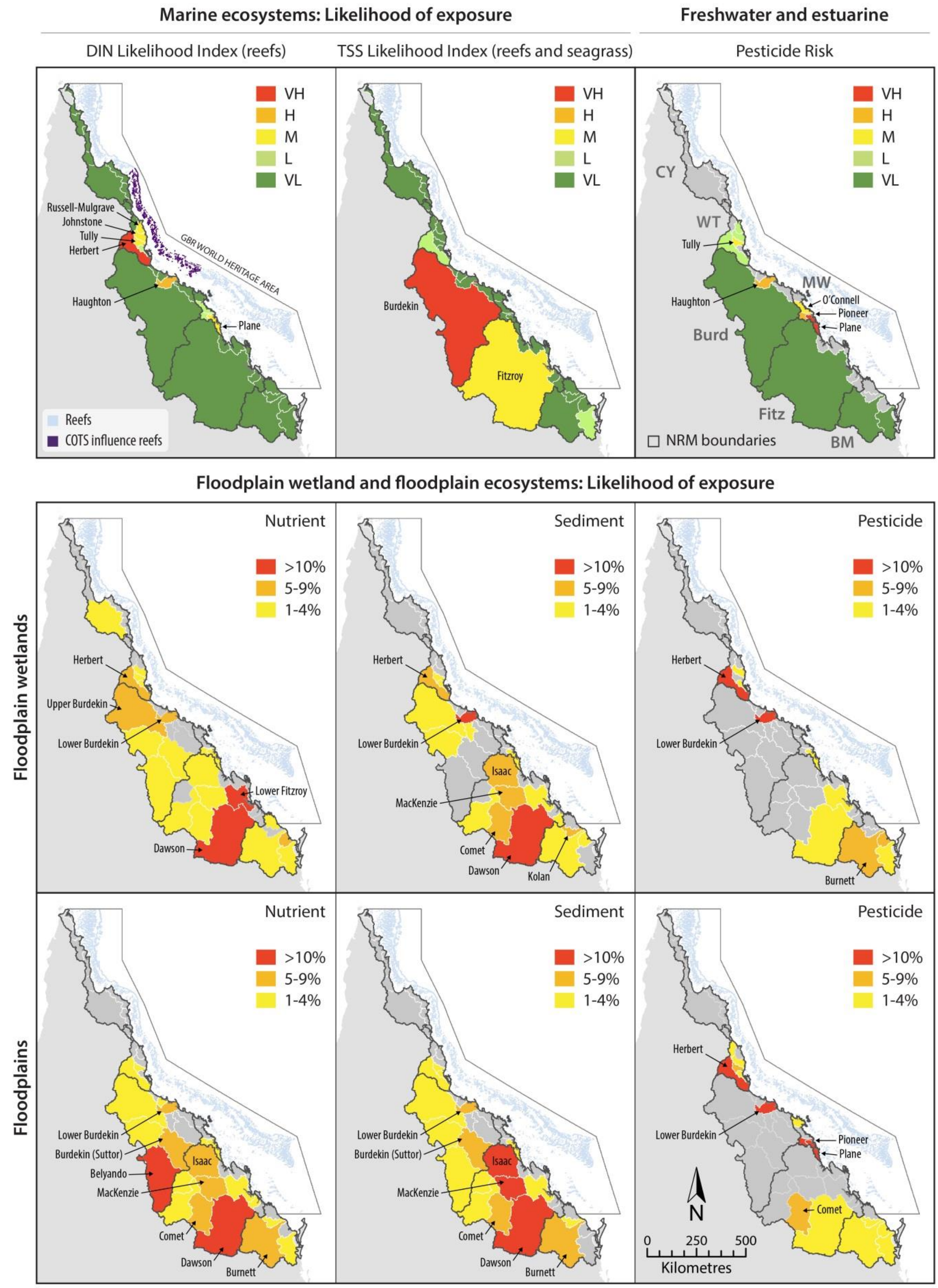

Figure 1: Summary of the results of the assessment of the likelihood of exposure of coral reefs and seagrass to sediments and nutrients, risk of pesticides to freshwater and estuarine ecosystems and the likelihood of exposure of coastal (floodplain wetlands and floodplains) ecosystems to sediments, nutrients and pesticides. *See Chapter 3 for further information.*

5. What does the current state of water quality mean for the environmental, social, economic and cultural values of the Great Barrier Reef?

The Great Barrier Reef is recognised nationally as a location of National Environmental Significance and internationally as a World Heritage Area for its Outstanding Universal Value in relation to four criteria:

- representation of the major stages of the Earth's evolutionary history
- ecological and biological processes
- natural beauty and natural phenomena
- habitats for the conservation of biodiversity.

The Great Barrier Reef supports a large economic base and is important to the maintenance of people's livelihoods and wellbeing. Many of the environmental, social and economic values of the Great Barrier Reef are directly and indirectly are threatened by the water quality risks described above.

The governance of the Great Barrier Reef represents a 'wicked' problem that is resistant to solution because of its inherent complexity. Coordination between governments and government programs is critical to provide clear policy signals and effective action in agricultural land use and management. Collaboration in the delivery of voluntary practice change programs is strong, but regional capacity is fragile. Climate change, ongoing agricultural run-off, major development projects and poorly aligned and coordinated policies represent critical risks to Great Barrier Reef health.

Supporting evidence

5.1 Values at risk

Evidence of the environmental, economic, social and cultural values of the Great Barrier Reef includes:

- The environmental values of the Great Barrier Reef are recognised as globally significant (Outstanding Universal Value) in its World Heritage listing and nationally as a Matter of National Environmental Significance under the *Environment Protection and Biodiversity Conservation Act 1999*.
- Several recent reports document the declining condition of the environmental values of the Great Barrier Reef, and regional Water Quality Improvement Plans summarise information on regional coastal and marine assets.
- The direct economic contribution of the Great Barrier Reef is estimated at $5.68 billion annually, driven largely by tourism. The economic value of agricultural production in Great Barrier Reef catchments is about half this.
- 'Non-use' economic values are likely to be at least as great as the values of the direct economic contribution, if not greater. The Great Barrier Reef holds important cultural values for residents, tourists, commercial fishers, tourism operators and Australians more broadly (particularly aesthetic, heritage, lifestyle and biodiversity values). The broader Australian community perceives the Great Barrier Reef to be a significant contributor to national identity. In many cases, people rate these values higher than direct use values.
- Public debates about water quality impacts on the Great Barrier Reef and its values need to recognise and engage with the social benefits people obtain from the Great Barrier Reef (not only benefits of action to ecological and economic values).

- Recognising Indigenous roles and values in water quality management offers multiple benefits to Indigenous communities and management agencies. Current water quality planning efforts fail to realise these benefits.

5.2 Progress to date

Reef Water Quality Protection Plan 2013 includes land and catchment management targets to address improved agricultural management practices and the protection of natural wetlands and riparian areas. These targets are based on the conceptual understanding of the link between land condition, management practice standards and water quality outcomes.

As described further in Chapter 4 (section 4.7), management practices are classified using the Paddock to Reef Water Quality Risk Framework which attempts to describe what constitutes 'best practice management'. This has progressed from the ABCD framework described in the 2013 Scientific Consensus Statement to become much more specific about the detail of individual practices, which is essential for more accurate monitoring, evaluation and reporting.

Reef Water Quality Protection Plan 2013 management practice and land condition targets to be achieved across the Great Barrier Reef catchments by 2018 are:

- 90% of sugarcane, horticulture, cropping and grazing lands are managed using best management practice systems (soil, nutrient and pesticides) in priority areas
- minimum 70% late dry season ground cover on grazing lands
- extent of riparian vegetation is increased
- no net loss of the extent, and an improvement in the ecological processes and environmental values, of natural wetlands.

Reef Water Quality Protection Plan 2013 targets to be achieved by 2018 include:

- at least a 50% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads in priority areas
- at least a 20% reduction in anthropogenic end-of-catchment loads of sediment and particulate nutrients in priority areas
- at least a 60% reduction in end-of-catchment pesticide loads in priority areas. The pesticides referred to are the PSII herbicides hexazinone, ametryn, atrazine, diuron and tebuthiuron.

The development of basin-specific targets was progressed through each of the recently completed regional Water Quality Improvement Plans (Cape York NRM, 2015; Terrain NRM, 2015; NQ Dry Tropics, 2016; Folkers et al., 2014; Fitzroy Basin Association, 2015; Burnett Mary Regional Group, 2015); however, consistent methodology was not employed for all regions as they were completed at different times (from 2014 to 2016). These are currently being reviewed and updated as part of the Reef Water Quality Protection Plan update (see Brodie et al., 2017).

The annual Great Barrier Reef Report Card reports progress against the Reef Water Quality Protection Plan targets, with the most recent being Report Card 2015, released in 2016, detailing 2014-2015 data (Australian and Queensland governments, 2016). Most of the indicators are reported annually, except for the wetland and riparian extent indicators which are reported every four years (the last report was in 2014). Some of the key indicators are summarised in Table 1. In conclusion:

- The overall condition of the inshore marine environment (water quality, seagrass and coral) remains poor and has not changed greatly since Report Card 2011.

- While there has been good progress of the adoption of some individual management practices across the agricultural industries in the Great Barrier Reef catchments, the data show that a large proportion (in some cases, up to 77%) of agricultural land is managed using practices that are below best management practice for water quality. This demonstrates the challenges associated with facilitating the adoption of improved (lower water quality risk) land management practices as discussed in Chapter 4 and highlights the limited progress towards achieving the management practice adoption targets over the first six years.
- An analysis of the Report Card data to date indicates that the rate of progress towards the targets is slowing. This is partly a consequence of a change to more focused targets. As the understanding of water quality risk has improved, more robust measurement frameworks have been adopted (Australian and Queensland governments, 2013). However, it is unlikely that the current targets will be met on this trajectory.
- Catchment condition targets are tracking positively with very good, good and moderate scores for groundcover, wetland loss and riparian extent respectively.

Table 1: Progress towards targets and assigned scores in Report Card 2015.

Activity	2018 Target[1]	Progress to target as at 2014-2015[2]	Report Card 2015 Score[2]
Marine condition			Overall score: Poor ‘E’ Seagrass: Poor ‘E’ Coral: Moderate ‘D’ Water quality: Moderate ‘D’
Dissolved inorganic nitrogen load	50% reduction	18%	Poor ‘E’
Fine sediment load	20% reduction	12%	Moderate ‘C’
Sugarcane land – managed to best practice standard	90%	23%	Poor ‘D’
Grazing land – managed to best practice standard	90%	36%	Poor ‘D’
Ground cover[3]	Minimum 70% late dry season cover	77%	Very good ‘A’
Wetland loss	No net loss	<1% net loss	Good
Riparian extent	Extent increased	0.4% loss	Moderate

Notes: [1] Load targets are the reduction in anthropogenic loads based on modelled estimation of anthropogenic loads; [2] 2015 ABCDE scoring system (Australian and Queensland governments, 2016). Limited commensurate data are available on actual improvements in water quality. [3] This is absolute ground cover that has not been seasonally adjusted for rainfall.

The ability to measure progress towards the Reef Water Quality Protection Plan targets is also challenged by the vast extent, inter-annual variability and complex governance arrangements of the Great Barrier Reef system. This is addressed more specifically in each of the chapters and, where relevant, highlighted in the limitations and knowledge gaps.

6. What are the management options for addressing Great Barrier Reef water quality issues, and what is their effectiveness?

Slow progress towards water quality targets shows that greater effort to improve water quality is urgently required to restore and protect the Great Barrier Reef ecosystems. Confidence in the Paddock to Reef Water Quality Risk Frameworks used to assess the effectiveness of agricultural practices for water quality is now very high. Research now highlights the benefits of lower nitrogen application rates in reducing water quality risk and the potential of site- and season-specific nitrogen recommendations. Cover management is effective at reducing erosion, but gully and streambank erosion remediation has become a higher priority. Social science insights highlight the importance of tailoring programs to the characteristics of different groups of landholders, as well as the value of working collaboratively with land managers and their networks. Large variations exist in the costs of improving water quality between natural resource management regions, programs and industries, and prioritisation can improve the efficiency and effectiveness of practice change investments.

Unlike previous Scientific Consensus Statements, the 2017 Scientific Consensus Statement has considered non-agricultural water quality management such as wetlands and treatment systems, urban and ports management and the issue of other contaminants. Action in these areas can complement water quality improvement from agricultural lands, but often information about the effectiveness of practices in the Great Barrier Reef is limited.

Supporting evidence

6.1 The effectiveness of agricultural practice change

New research has confirmed existing knowledge about the efficacy of many agricultural management practices in reducing water quality impacts, improving confidence in the Paddock to Reef Water Quality Risk Frameworks used to monitor and evaluate progress against targets. New knowledge that has emerged since the 2013 Scientific Consensus Statement includes:

- Sediment delivery from gullies and streambank erosion is now recognised as more significant than previously thought and requires greater focus.
- Enhanced efficiency fertilisers can increase nitrogen use efficiency in sugarcane, although further work is required to establish the extent to which their use reduces nitrogen losses.
- Better climate forecasting may help to reduce nitrogen losses.
- Tailoring nitrogen recommendations to site-specific conditions is desirable but requires decision support systems that model the behaviour of enhanced efficiency fertilisers against variable soil, climate and management factors.
- Engineered treatment systems can be effective in reducing the concentration of pollutants such as sediment, nutrients and pesticides. Treatment systems include technologies such as constructed wetlands, denitrifying bioreactors, floating wetlands, high efficiency sedimentation basins and algae nutrient removal.

To reduce sediment loss from rangeland grazing, established practices include:

- maintaining ground cover and forage biomass at the end of the dry season
- setting appropriate stocking rates
- excluding stock from riparian and frontage country and from rilled, scalded and gullied areas
- locating and constructing linear features (roads, tracks, fences, firebreaks and water points) using best practice management techniques to help minimise erosion risk
- targeting hotspots of sediment loss.

New insights about reducing sediment loss from grazing lands include:

- increased confidence that reducing stocking rates will improve ground cover and water quality from hillslopes
- increased confidence that cover provided by invasive grass species is less effective in helping productivity and soil infiltration capacity than perennials or native grasses
- the importance of sediments from gully and streambank sources is clearer, and sediments from these sources can contain high concentrations of bioavailable nutrients
- increased confidence that improving land condition on hillslopes above gullies helps reduce gully erosion
- effective remediation of gullies requires substantial actions such as excluding stock, and engineering (e.g. check dams) or bioengineering (slope battering, seed, mulch, gypsum and fertiliser) approaches
- the effectiveness of managing stream bank erosion has still not been demonstrated in Great Barrier Reef catchments.

To reduce sediment loss from cropping lands, research supports existing practices including:

- reducing or eliminating tillage and maximising soil cover (via crop residue retention and grassed inter-rows)
- adopting controlled traffic, opportunity cropping and contour embankments
- increasing irrigation application efficiency and timing to minimise run-off, deep drainage and denitrification losses from the farm.

To reduce nutrient exports from agricultural lands, established practices include:

- minimising the nutrient surpluses from fertiliser application, that is, the difference between inputs and crop off-take, especially for nitrogen
- practices such as split applications and changing the timing of fertiliser applications to avoid irrigation or the chance of rainfall and burying fertiliser also help
- targeting hotspots where nutrient surpluses are high (and hence nutrient use efficiency is low)
- reducing erosion to reduce particulate nutrient losses.

New insights to reducing nutrient exports from agricultural lands include:

- increased confidence that lower nutrient (nitrogen) application rates (reduced to industry best management practice rates) reduce nutrient losses from fields without reducing yield
- enhanced efficiency fertilisers can increase nitrogen use efficiency in sugarcane, which should reduce nitrogen losses if nitrogen application rates are reduced. However, there are only early indications that these fertilisers reduce nitrogen exports. Enhanced efficiency fertilisers need to be targeted according to season, soil and fertiliser technology types
- early indications that seasonal climate forecasting can play a role in optimising nitrogen fertiliser applications to sugarcane
- a current focus on aligning production goals to block or productivity zone yield potential in the Six Easy Steps framework for sugarcane fertiliser management. However, the sugarcane nitrogen requirement in the framework is also spatially and temporally variable. Development of site-specific nitrogen recommendations needs to account for variability in the sugarcane nitrogen requirement as well as yield target.

To reduce pesticides exports, established agricultural practices include:

- reducing the amount applied, for example, banded spraying and adopting integrated pest and/or weed management
- minimising run-off and sediment loss from the farm
- maximising the time between application and likely run-off events
- choosing products with rapid degradation rates (e.g. some 'knockdown' herbicides).

New insights to reducing pesticide loss from agricultural lands include:

- increased confidence that reducing pesticide applications (e.g. through banded spraying) reduces pesticide losses from fields
- increased confidence that avoiding run-off for three weeks after application substantially reduces pesticide losses
- practices for managing losses also apply to the newly released chemicals
- transport of most pesticides is dominated by the dissolved phase, placing greater emphasis on the management of run-off. More pesticides are lost in deep drainage that previously thought, although the total contribution to end-of-system loads is very small
- integrated weed management in sugarcane has demonstrated the successful use of shorter lived herbicides and/or lower application rates
- frameworks to help choose pesticide products (balancing toxicity and run-off and deep drainage potential to reduce risk) are starting to be developed.

Established irrigation practices that reduce water quality risks include:

- increasing irrigation efficiency (i.e. reducing over-application of irrigation), which reduces nutrient and pesticide losses
- delaying irrigation after nitrogen or pesticide applications, which reduces losses.

New insights into the effectiveness of irrigation practices in reducing water quality risks include:

- clearer indications (through modelling) that highly efficient irrigation systems reduce nutrient losses
- increased confidence that avoiding irrigation after nitrogen or pesticide applications substantially reduces losses.

6.2 The social and economic dimensions of agricultural practice change

6.2.1 Social dimensions

Established knowledge about the social dimensions of changing agricultural practices includes:

- The adoption of a new practice is dependent upon landholders' expectations that the practice will allow them to better achieve their own goals. This decision is based on subjective perceptions and is sensitive to timing, local conditions and the personal, family and business circumstances of individual farmers or industry sectors.
- The perceived benefits of adopting a new practice may be focused on profitability, but may also include social recognition, ease of management, meeting family goals or a reduction in regulatory risk. Landholders with strong profitability goals engage more with productivity best management practices, while those with environmental or stewardship goals engage with vegetation or riparian best management practices. Best management practice programs may unintentionally exclude some landholders because of the scope of implied or expressed benefits of the program.

- Different groups of landholders can be identified based on their adoption behaviours, goals, attitudes, norms and socio-economic characteristics. These groups trust different information sources and are more likely to work with some organisations or entities over others. Understanding the character or diversity of these attributes within the landholder target group improves participation and uptake.
- Even if farmers are aware of broader environmental problems or value biodiversity, this does not always translate to recognition or acceptance of management issues on their own properties.

Research insights specific to the social dimensions of agricultural practice change in the Great Barrier Reef include:

- Conflicting messages about reef health, blaming farmers and overemphasising science to the exclusion of local or industry knowledge contribute to low acceptance of environmental responsibility.
- Social barriers to participating in Great Barrier Reef agricultural practice change programs include perceptions of working with government; scheme complexity; lack of social recognition; and practice changes that disrupt relationships with peers, harvesting cooperatives, contractors and suppliers. Designing delivery programs that recognise and leverage these social and cultural preferences improves participation.
- Where local industry, farmers, scientists and natural resource managers work collaboratively to design and evaluate new interventions (e.g. local technical assessment panels or monitoring outcomes of actions at paddock or sub-catchment scales), these processes of joint learning improve trust in decisions and in the data, which underpins support for future action.
- Participation in Great Barrier Reef financial incentive programs will be improved by flexibility to tailor contracts and delivery to producers' circumstances and by working through local, trusted intermediaries (e.g. extension officers).

The recent interest in the use of social marketing, community-based social marketing and improving communication practices as an adjunct to good engagement practices needs to be evaluated. Decision support tools for farmers and extension officers can provide sophisticated support and real-time feedback on crop production and environmental outcomes, but barriers to uptake (including privacy and data-sharing issues) need to be overcome for these benefits to be fully realised.

6.2.2 Economic dimensions

There is now a large body of work that estimates the benefits, costs, adoption drivers and mechanism design relevant to the Great Barrier Reef. Overall, recent economic analysis using a combination of modelling and evaluation data shows that:

- There are large variations in the estimated costs of improving water quality across regions, programs and industries.
- The modelled total costs of meeting water quality targets are very high (much higher than previously considered). As water quality targets are approached, the costs of additional actions are likely to rise sharply.
- Analysis of reef funding programs shows marked variations in estimated cost effectiveness of both management changes and programs.
- Smaller scale prioritisation of investment can improve the efficiency and effectiveness of practice change investments.
- Different mixes of policy mechanisms may be required to accelerate progress towards the water quality targets.

In terms of the costs to farmers of changing management practices for water quality benefits:

- While some farm management changes can be at low (or negative cost), most involve capital investment and/or trade-offs in production and long time frames until benefits are received.
- The cost of management changes and the benefits to the landholder and Great Barrier Reef water quality varies widely, resulting in large differences in the cost effectiveness of actions.
- Risk preferences, transaction costs and other barriers such as complexity are also key drivers for landholder adoption behaviour.

Economic analysis can contribute to more efficient prioritisation of investment and mechanism design:

- A simple focus on individual sources of pollutants, actions or regions is unlikely to be efficient as the cost effectiveness of management practice change varies across industries, regions and farms.
- Prioritisation should consider:
    - environmental (Great Barrier Reef coastal and marine ecosystem health), social and economic benefits
    - risks of practice change to landholders (including financial risks, technical failure and program failure) and the broader community
    - impacts of weather and markets
    - performance of past and current investments, delivery models and delivery partners
    - time lags to implementation, end-of-basin pollutant reductions and benefits to Great Barrier Reef health.
- There needs to be an agreed principles-based methodology for assessing the relative benefits and risks of focusing on protecting reef assets in good health versus repairing degraded areas.

Recent work by Star et al. (2017) demonstrates a more holistic prioritisation process that accounts for marine risk, practice change, adoption rates, costs, time lags and uncertainties. The analysis highlights that for all parameters there are a range of relatively low-cost options that can be prioritised, and that no individual action or catchment is preferred across all the prioritisation criteria.

6.3 The effectiveness of other land management practices in improving water quality

The 2017 Scientific Consensus Statement has included non-agricultural land uses for the first time. The science of agricultural land management for Great Barrier Reef water quality has progressed over the last 15 years of intensive research effort. Unfortunately, our knowledge about the effectiveness of management practices for water quality improvement across other land uses is much less. In particular, there is little Great Barrier Reef–specific information, and this raises doubts about the relevance of research from other areas (particularly outside the tropics and subtropics).

Urban: Established water quality management practices in urban areas include stormwater quality management such as vegetated treatment systems, integrated water cycle management and wastewater management approaches. Integration of water cycle management approaches is critical to improving water quality. Water quality monitoring in Mackay and Townsville indicates high variability of stormwater quality. Some information and guidance is available for the Great Barrier Reef through local governments. Water Quality Improvement Plans have highlighted the opportunities for specific management actions. There are capacity-building programs for stormwater quality management currently underway in the Great Barrier Reef.

Ports: Ports impact water quality through a range of direct and indirect impacts, including run-off and discharge from port facilities and portside activities, shipping movements and associated anchorage areas, construction, capital and maintenance dredging and land reclamation. Water quality monitoring in Queensland ports is variable, and public reporting of results is currently limited.

6.4 Ecosystem protection and remediation and treatment systems

Natural and modified estuarine and freshwater wetlands have many values, including protection from wave action and storms and reducing the impacts of floods, as well as providing important habitat. Wetlands can absorb and transform pollutants and nutrients in catchment run-off, but the capacity of wetlands to improve water quality for the reef is limited by the size and type of wetland (open water, vegetated, etc.), residence time, wetland location and condition and hydrological connectivity. The capacity of wetlands to improve water quality is highest when hydrologic loads are low to intermediate, such as during early and late wet season, in smaller sub-catchments or in the dry season as well in irrigated areas where flows are supplemented.

While acting to filter catchment run-off, poor quality water entering wetlands can affect the provision of values and services from the wetlands and have consequences for wider reef health. The consideration of natural wetlands and treatment systems in relation to water quality improvement needs to be framed within the context of the broader landscape and be part of an overall integrated pollutant management process.

Natural and constructed wetlands can remove nitrogen and phosphorus from the water through denitrification, sediment accumulation and plant growth:

- In the Great Barrier Reef, the capacity of wetlands to mitigate nutrient export from the basin is likely to be variable across catchments and wetland types.
- Temporal variability of hydrological flows, especially during extreme drought or flood events, will strongly influence the ability of wetlands to mitigate nutrient exports. Nutrient uptake may be higher at the beginning and end of the wet season.
- Nutrients are removed primarily through denitrification, storage in soils and vegetation. However, input of excess nutrients can damage wetlands functions and threaten their values.
- Excess nutrients can damage wetlands functions.
- Globally, wetlands have been found to remove nitrogen at a median rate of 93 g/m^2 $yr/^1$ and phosphorus at a rate of 1.2 g m^2/yr^1, with a removal efficiency of 39% and 46% respectively.
- The range of treatment systems available for nutrient removal has expanded and proven to be effective overseas.

Natural and constructed wetlands can facilitate sedimentation by trapping sediment and the carbon and nutrients associated with it:

- Intertidal wetlands in the Great Barrier Reef, especially mangroves, can trap sediment from the water that floods them.
- Excess sediment can be detrimental to wetlands and, in some cases, can destroy them.
- At the landscape level, wetlands can make a substantial contribution to reducing sediment loads to the marine environment in many regions.

Pesticides are being transported as run-off to wetlands of the Great Barrier Reef:

- Natural and constructed wetlands can trap pesticides and accelerate their decomposition.
- In some areas of the Great Barrier Reef, wetlands are accumulating high levels of pesticides. This can damage wetland functions and threaten their values.

6.5 Other pollutants

As well as sediment, nutrients and pesticides, a range of other pollutants are of growing significance in the Great Barrier Reef and elsewhere. These are derived from a range of sources including agriculture, urban, industrial, transport and waste facilities, which complicates management efforts.

The Great Barrier Reef has widespread contamination with marine debris derived from shipping, fishing and industrial and urban sources. Current proposals to ban single-use plastic bags and for container deposit schemes are promising first steps to reduce marine debris, but more significant change is required.

Monitoring of Great Barrier Reef sewage treatment plants has shown that effluent discharges include a wide range of pollutants such as pharmaceuticals and personal care products (as well as nutrients). Comprehensive information about Great Barrier Reef sewage treatment plants and their discharges is not readily available.

6.6 Land-use change and future developments

Recent Australian and Queensland government documents have identified potential areas for expansion and intensification of agriculture in the Great Barrier Reef. Any shift from grazing to fertilised cropping will increase the discharge of dissolved inorganic nitrogen to the Great Barrier Reef.

Urban expansion is also expected along the Great Barrier Reef coast, with population growth and inward migration to the region. Expanding urban areas will increase the urban water quality footprint in the Great Barrier Reef.

Expected land-use intensification and its associated water quality impacts should be incorporated into water quality planning, management strategies and catchment modelling of water quality outcomes. Impacts can be minimised by adoption of best practice systems from the outset. Changes in land use to less intensive options (such as from sugarcane to grazing, wetlands or conservation) is an option that warrants further consideration to accelerate pollutant load reductions. There is currently limited investigation or evidence of these options in the Great Barrier Reef catchment.

6.7 Great Barrier Reef governance and program delivery

There are many learnings about program design and delivery that are coming from new research findings in the Great Barrier Reef and elsewhere. These learnings could benefit the design and implementation of Great Barrier Reef water quality programs. This was not included in the 2013 Scientific Consensus Statement. The literature highlights the need for strengthened intergovernmental coordination and policy alignment and the importance of addressing the significant risks from other policy domains.

The evidence highlights that Great Barrier Reef governance is a wicked policy problem, requiring adaptive, participatory and transdisciplinary approaches:

- **Adaptive** approaches recommend the use of modelling and other tools to build system understanding, encourage experimentation and evaluation and tailor solutions to regional variations. A greater focus on experimentation and evaluation of on-ground works and program delivery would strengthen the adaptive capacity of Great Barrier Reef programs. Current governance arrangements have not effectively supported a culture of innovation for water quality outcomes.

- **Participatory** approaches can bring more knowledge to the debate about solutions, garner support, coordinate effort and reveal value conflicts. Participation and collaboration are features of Great Barrier Reef policy, planning and implementation. Collaboration between natural resource management organisations and industry peak bodies has facilitated coordinated program delivery. Regional capacity is, however, fragile, with changes to natural resource management programs, capacity and funding commitments.
- **Transdisciplinary** approaches recommend using natural and social sciences and stakeholder knowledge to test and evaluate innovative solutions. There has been limited investment in social and institutional research to connect knowledge of land management practice change with different policy instrument mixes and draw on international experience and a lack of systematic evaluation of delivery processes and governance systems to support ongoing improvement.

Additional research insights about the governance of Great Barrier Reef water quality include:

- Climate change, major development projects and poorly aligned and coordinated policies represent critical risks to Great Barrier Reef health.
- Intergovernmental coordination affects all aspects of program design and delivery. Policy alignment (across governments and within government across related policy areas) needs to be improved to provide unambiguous policy signals to stakeholders and deliver greater impact.
- Researchers have called for the new Reef 2050 Long-Term Sustainability Plan, as the overarching intergovernmental document, to have stronger authority and investment, clearer strategies to achieve its targets and vision and better stakeholder engagement.
- Smart regulation (using risk-based compliance and multiple pathways to influence behaviours, such as industry standards, supply chains and financial systems) has potential to harness industry innovation for multiple outcomes.
- Modelling of water quality outcomes is well established as a decision support and reporting tool in the Great Barrier Reef. More use of scenarios and forecasting could help water quality programs anticipate future challenges.

7. Spatial priorities for pollutant management in the Great Barrier Reef catchment

The information summarised in this chapter, supported by further detail provided in the chapters, can be drawn together to identify spatial priorities for managing water quality risks to the Great Barrier Reef. Chapter 3 provides an assessment of the likelihood of ecosystem exposure to anthropogenic pollutants. The results can be used to directly inform spatial priorities for reducing these risks to coastal and marine ecosystems at a basin scale; they are summarised in Table 2. The table shows the proportional contribution of each basin to the total Great Barrier Reef anthropogenic loads for total suspended solids and dissolved inorganic nitrogen to illustrate the areas delivering the highest anthropogenic loads (from Chapter 2) and the primary results from the marine likelihood of exposure and risk assessments from Chapter 3. The results for the assessments within the marine zones, and then across the Great Barrier Reef, are used to assist in interpretation of areas of greatest pollutant exposure within natural resource management regions. The outcomes of the risk assessments for crown-of-thorns starfish and coral reefs and for reduced benthic light for seagrass are also identified. Information related to the current condition of coral reefs and seagrass in these regions (from Chapter 1) is included to assist in the identification of patterns among basins and between pollutants. It is evident that there are ecosystems in parts of the Cape York region that are in better condition, and these are also identified as being likely to have low exposure to pollutants. However, no clear correlation between condition and risk can be readily identified across the Great Barrier Reef at this scale.

The assessment of the likelihood of exposure of coral reefs to dissolved inorganic nitrogen indicated that the Herbert, Haughton, Johnstone, Mulgrave-Russell and Tully basins are the highest contributors across the Great Barrier Reef. The example of the assessment of dissolved inorganic nitrogen risk and crown-of-thorns starfish also indicates that coral reefs in the Wet Tropics region are at greatest risk from dissolved inorganic nitrogen exposure. At a basin scale, the assessment emphasises the contribution of the Herbert Basin to the dissolved inorganic nitrogen risk to coral reefs through crown-of-thorns starfish influence, followed by the Johnstone, Mulgrave-Russell and Tully basins. This is considered for defining management priorities across the Great Barrier Reef (below).

The assessment of the likelihood of exposure of coral reefs and seagrass to fine sediment shows that the Burdekin, Fitzroy and Herbert basins are the highest contributors to coral reef and seagrass exposure across the Great Barrier Reef. The example of the assessment of fine sediment risk to seagrass from benthic light limitations indicates that seagrass in the Burdekin region, followed by the Burnett Mary region, is at greatest risk. At a basin scale the assessment emphasises the contribution of the Burdekin and Fitzroy basins to the fine sediment risk to seagrass.

The assessment of the average ms-PAF risk shows that the Plane, Haughton and Pioneer basins rank the highest.

The assessment of the likelihood of exposure of floodplain wetlands and wetlands to pollutants is not included in Table 2, but showed that:

- Floodplain wetlands in six management units / basins—Dawson, Lower Burdekin, Herbert, Burnett, Burrum and Tully—have high likelihood of exposure to sediment, nutrient and pesticide pressures. The areas of greatest likelihood of exposure of floodplain wetlands to nutrient pressures are in the Fitzroy and Dawson, for sediments the Dawson and Lower Burdekin and for pesticides the Lower Burdekin and Herbert basins.
- Floodplains in seven management units / basins—Tully, Belyando, Plane, Dawson, Comet, Kolan and Burnett—have high likelihood of exposure to sediments, nutrients and pesticides. The areas of greatest likelihood of exposure of floodplains to nutrient inputs are in the Belyando and Dawson; for sediments the Dawson, Isaac and Mackenzie; and for pesticides the Herbert, Lower Burdekin, Belyando, Pioneer and Plane basins.

It is important to note that many mid- and outer shelf parts of the Great Barrier Reef are not impacted to any extent by terrestrial run-off impacts. This is particularly true for the Torres Strait, Cape York, Pompey and Swain sectors, which form a large part of the area of the Great Barrier Reef. While coral reef and seagrass status is reported in Table 2, there is no implication that current status is necessarily associated with terrestrial run-off. The main mid- and outer shelf reef locations directly impacted by terrestrial run-off are those regions located between Lizard Island and Townsville.

This information can also be used to highlight the basins within natural resource management regions that are likely to be linked to the greatest exposure of coral reefs and seagrass to pollutants (Table 3).

Table 2: Summary of the likelihood of exposure and risk assessments for fine sediments, dissolved inorganic nitrogen and pesticides. Colour coding: Marine likelihood of exposure: Very High (red) = Marine Index >0.9; High (orange) = Marine Index 0.4–0.9; Moderate (yellow) = Marine Index 0.15–0.39; Low (green) = Marine Index 0.03–0.14; Minimal (no colour) = Marine Index <0.03. Proportional anthropogenic load contributions (anth. = anthropogenic): No colour = <3%; Green = 3–4%; Yellow: 5–14%; Orange: 15–30%; Red: >30%.

Basin	Current condition		Dissolved inorganic nitrogen				Fine sediments				Pesticides	
				Marine ecosystems: Likelihood of exposure				Marine ecosystems: Likelihood of exposure			Freshwater and estuarine	
											Pesticide risk	
	Coral condition[2]	Seagrass condition[3]	DIN anth. load as % of Great Barrier Reef anth. load	DIN Index within marine zone	DIN Likelihood Index (reefs)	Rank	Fine sediment anth. load as % of Great Barrier Reef anth. load	Fine sediment Index within marine zone	Fine sediment Likelihood Index (seagrass + reefs)	Rank	Average ms-PAF risk: % species affected (2013-2016)	Rank
Jacky Jacky	Variable coral cover (5–70%) on mid- and outer shelf reefs. Note: bleaching in 2016 has reduced coral cover in this region (Hughes et al. 2017).	Poor (note limited spatial coverage of data)	<1%	0.09	0.00	29	1%	0.80	0.00	29		
Olive-Pascoe			<1%	1.00	0.00	29	1%	1.00	0.00	29		
Lockhart			<1%	0.02	0.00	29	1%	1.00	0.00	29		
Stewart			<1%	0.01	0.00	29	1%	0.27	0.00	29		
Normanby			<1%	0.01	0.00	29	2%	0.27	0.00	29		
Jeannie			<1%	0.01	0.00	29	<1%	1.00	0.00	29		
Endeavour			<1%	0.04	0.00	29	<1%	0.89	0.00	29		
Daintree	Inner shelf: moderate coral cover on mid- and outer shelf reefs (Cairns and Innisfail sectors, 2015): 10–30%.	Poor	2%	0.15	0.15*	13	<1%	0.08	0.02	19		
Mossman			2%	0.12	0.12*	16	<1%	0.02	0.00	28		
Barron			1%	0.10	0.10*	17	<1%	0.10	0.02	17		
Mulgrave-Russell			7%	0.48	0.48*	4	2%	0.47	0.11**	7	3.7	6
Johnstone			8%	0.56	0.56*	3	3%	0.79	0.19**	5	1.3	7
Tully			6%	0.43	0.43*	5	1%	0.25	0.06	10	5	5
Murray			4%	0.26	0.26*	7	<1%	0.12	0.03	15		
Herbert			15%	1.00	1.00*	1	4%	1.00	0.24**	3	2	8
Black		Moderate	<1%	0.02	0.02	22	<1%	0.01	0.01	24		

Basin	Current condition		Dissolved inorganic nitrogen				Fine sediments				Pesticides	
				Marine ecosystems: Likelihood of exposure				Marine ecosystems: Likelihood of exposure			Freshwater and estuarine	
											Pesticide risk	
	Coral condition[2]	Seagrass condition[3]	DIN anth. load as % of Great Barrier Reef anth. load	DIN Index within marine zone	DIN Likelihood Index (reefs)	Rank	Fine sediment anth. load as % of Great Barrier Reef anth. load	Fine sediment Index within marine zone	Fine sediment Likelihood Index (seagrass + reefs)	Rank	Average ms-PAF risk: % species affected (2013-2016)	Rank
Ross	Inner shelf: poor coral cover on mid- and outer shelf reefs (Townsville sector, 2015): 20–30%.		2%	0.13	0.13	15	1%	0.02	0.02	22		
Haughton			15%	1.00	0.93*	2	2%	0.06	0.06	12	10.9	2
Burdekin			3%	0.19	0.17	11	35%	1.00	1.00**	1	0.6	10
Don			1%	0.07	0.07	20	2%	0.07	0.07	9		
Proserpine	Inner shelf: moderate coral cover on mid- and outer shelf reefs (Whitsunday and Pompey sectors): 10–30%.	Poor	3%	0.43	0.18	10	1%	0.06	0.03	16		
O'Connell			3%	0.51	0.21	9	3%	0.19	0.08**	8	5.3	4
Pioneer			3%	0.53	0.22	8	2%	0.13	0.06	11	13.5	3
Plane			6%	1.00	0.41	6	1%	0.08	0.03	13	29.3	1
Styx	Inner shelf: poor to very poor coral cover on mid- and outer shelf reefs (Capricorn-Bunker and Swain sectors): 20-60%	Very Poor	<1%	0.02	0.01	24	1%	0.07	0.03	14		
Shoalwater			<1%	0.01	0.00	26	1%	0.05	0.02	18		
Waterpark Creek			<1%	0.01	0.00	27	1%	0.04	0.02	20		
Fitzroy			3%	0.36	0.15	14	16%	1.00	0.46**	2	0.8	9
Calliope River			<1%	0.01	0.01	25	1%	0.04	0.02	23		
Boyne			<1%	0.01	0.00	28	<1%	0.01	0.01	27		

Basin	Current condition		Dissolved inorganic nitrogen				Fine sediments				Pesticides	
				Marine ecosystems: Likelihood of exposure				Marine ecosystems: Likelihood of exposure			Freshwater and estuarine	
											Pesticide risk	
	Coral condition[2]	Seagrass condition[3]	DIN anth. load as % of Great Barrier Reef anth. load	DIN Index within marine zone	DIN Likelihood Index (reefs)	Rank	Fine sediment anth. load as % of Great Barrier Reef anth. load	Fine sediment Index within marine zone	Fine sediment Likelihood Index (seagrass + reefs)	Rank	Average ms-PAF risk: % species affected (2013-2016)	Rank
Baffle	Inner shelf: <10% in many locations (Coppo et al. 2014). Coral cover on mid and outer shelf reefs (Capricorn-Bunker and Swain sectors): 20–60%	Poor	1%	0.09	0.01	23	1%	0.04	0.02	21		
Kolan			1%	0.19	0.03	21	<1%	0.02	0.01	25		
Burnett			3%	0.57	0.09	18	5%	0.33	0.15**	6	0.5	11
Burrum			3%	0.51	0.08	19	<1%	0.01	0.01	26		
Mary			6%	1.00	0.16	12	8%	0.52	0.23**	4	0.5	12

Notes:

1: Seagrass condition: Assessment of coral and seagrass condition is per the Report Card 2015. It is recognised that some areas have experienced further influences since this assessment date, which have led to further decline (see Chapter 1). It is likely that the impacts of tropical cyclone Debbie and coral bleaching in 2017 have reduced coral cover in the Mackay Whitsunday region.

2: Coral reef condition: Inner shelf condition is from the Marine Monitoring Program, Report Card 2015 (Thompson et al., 2016). Condition of mid-shelf and outer shelf coral reefs is based on AIMS Long-term Monitoring Program data to December 2015 or March 2017, which was before the impact of, respectively, the 2016 and 2017 mass coral bleaching events. www.aims.gov.au/docs/research/monitoring/reef/latest-surveys.html

3: Seagrass is from the Marine Monitoring Program, Report Card 2015 (McKenzie et al., 2016).

* Ranked highest dissolved inorganic nitrogen risk to coral reefs from crown-of-thorns starfish; ** Ranked high risk to seagrass from reduced benthic light.

[a] calculated from the average of Haughton River and Barratta Creek ms-PAF risk values

[b] calculated from the average of Russell River and Mulgrave River ms-PAF risk values

[c] calculated from the Johnstone River @ Coquette site 2015-2016 ms-PAF risk values

Table 3: Summary of the basins with the highest likelihood of exposure for fine sediments and dissolved inorganic nitrogen and of pesticide risk within each natural resource management region.

NRM region	Highest DIN Likelihood Index within marine zone for each natural resource management region	Highest TSS Likelihood Index within marine zone for each natural resource management region	Pesticide risk (note that not all basins were assessed)
Cape York	N/A	N/A	N/A
Wet Tropics	Herbert	Herbert	Tully
Burdekin	Haughton	Burdekin	Haughton
Mackay Whitsunday	Plane	O'Connell	Plane
Fitzroy	Fitzroy	Fitzroy	Fitzroy
Burnett Mary	Mary	Mary	Burnett

Prioritisation in relation to management of water quality issues in the Great Barrier Reef requires assessment of the risk of exposure but also of which actions can achieve the largest pollutant load reductions at lowest cost and greatest certainty. Star et al. (2017) have integrated existing spatial datasets to identify where there is scope to achieve the most cost-effective water quality outcomes (informed by Chapter 4) and how that relates to the basin-specific assessment of the likelihood of exposure of pollutants to marine ecosystems (determined in Chapter 3 and outlined above) (Figure 2). The results assess all 47 management units of the Great Barrier Reef catchment to identify the most cost-effective actions and areas for management efforts, also highlighting where there is further scope for improvement. The best available data to date have been used; however, further refinement would improve the precision of the analysis.

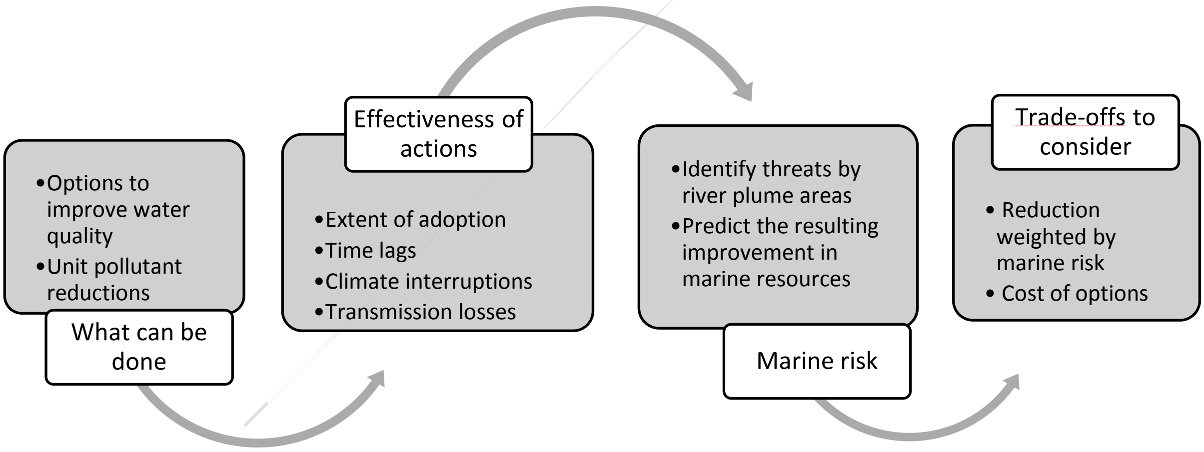

Figure 2: Four main steps considered in the prioritisation approach of Star et al. (2017).

The analysis involves summarising data in four key steps.

The first step is to identify the *Expected pollutant reduction* across the different management changes for the three pollutants by the 47 management units and the different industries involved (grazing and sugarcane). For ease of analysis, these are estimated in terms of potential changes at end of catchment (transmission losses are factored in).

Expected pollutant reduction = Pollutant reduction (on-farm)*transmission rate **1**

The second step is to adjust the loads by an *effectiveness index*, which takes account of the expected management practice adoption, time lags and transmission factors[2] to predict what proportion of potential changes on-farm will lead to pollutant reductions at end of catchment. For example, actions that occur in the upper parts of catchments that have low levels of adoption and long-time lags until pollutant reductions occur will have much lower levels of effectiveness than actions closer to the coast.

Effectiveness Index = Practice adoption rate*Time lags **2A**

Pollutant load reduced = Expected pollutant reduction*Effectiveness Index **2B**

The third step is to take account of the *risks* that might interrupt the predicted projections, including risks that might impact on implementation (socio-political risks), adoption (technical and financial risks) and performance (climate risks).

Pollutant reduction weighted for risk factors = Expected end-of-catchment reductions over time **3**

The fourth step is to compare the pollutant load reduction weighted for marine protection against the cost of the action:

Cost per tonne pollutant reduction weighted for marine likelihood of exposure = Pollutant reduction* marine exposure index / cost **4**

The approach allows the relative benefits of each group of actions to be estimated in turn so that they can be 'stacked' in different ways. The result (cost per tonne of pollutant weighted for marine exposure) provides a measure of cost effectiveness that can be used to rank projects in order of priority.

The assessment includes grazing and sugarcane (excluding grains, horticulture and bananas) and uses the grazing and sugarcane management Paddock to Reef Water Quality Risk Frameworks to determine the effectiveness of different management actions. The pollutant reductions or water quality benefits have been estimated using catchment modelling and weighted by importance based on the associated Marine Likelihood of Exposure Indexes from Chapter 3 (the latter assessed through a combination of eReefs modelling outputs, remote sensing analysis and monitoring data linked to basin end-of-catchment loads). The approach also considers landholder participation and adoption (based on existing uptake), climate variability as a risk to on-ground works, time lags to achieve benefits (greater in grazing lands, but differs by land productivity) and the costs of management change. A number of data limitations have been identified in this assessment; therefore, several assumptions are required to complete the analysis. The Cape York and Burnett Mary regions generally have less data than the other natural resource management regions for all input data.

The results highlight the wide range of costs and the opportunity to target investments. The more cost-effective options initially come from managing hillslope erosion in grazing lands and from various sugarcane management changes, relative to the gully and streambank approaches which have higher costs and longer time frames for recovery. The analysis highlights that for all parameters there is a range of relatively low-cost options that can be prioritised, although these may not necessarily align well with the areas of highest likelihood of pollutant exposure. The results of the integrated prioritisation are useful for assessing investment priorities beyond the initial assessment of relative risks to Great Barrier Reef ecosystems; however, uncertainties in the heterogeneity of the

[2] In the analysis, the loads data provided from Source Catchments modelling incorporated the transmission losses with the data on loads reduction.

adoption, climate and cost estimates of specific practices, and the need to make assumptions in the datasets to extrapolate the data to a basin scale, remain an issue.

Summary results of the prioritisation exercises are shown for sediment and dissolved inorganic nitrogen respectively in Figures 3 and 4. Only actions that achieve at least 1% of total reductions are included, and the actions are graphed in order left to right from the least to most expensive. Cumulative contributions to pollutant reductions are graphed on the horizontal axis.

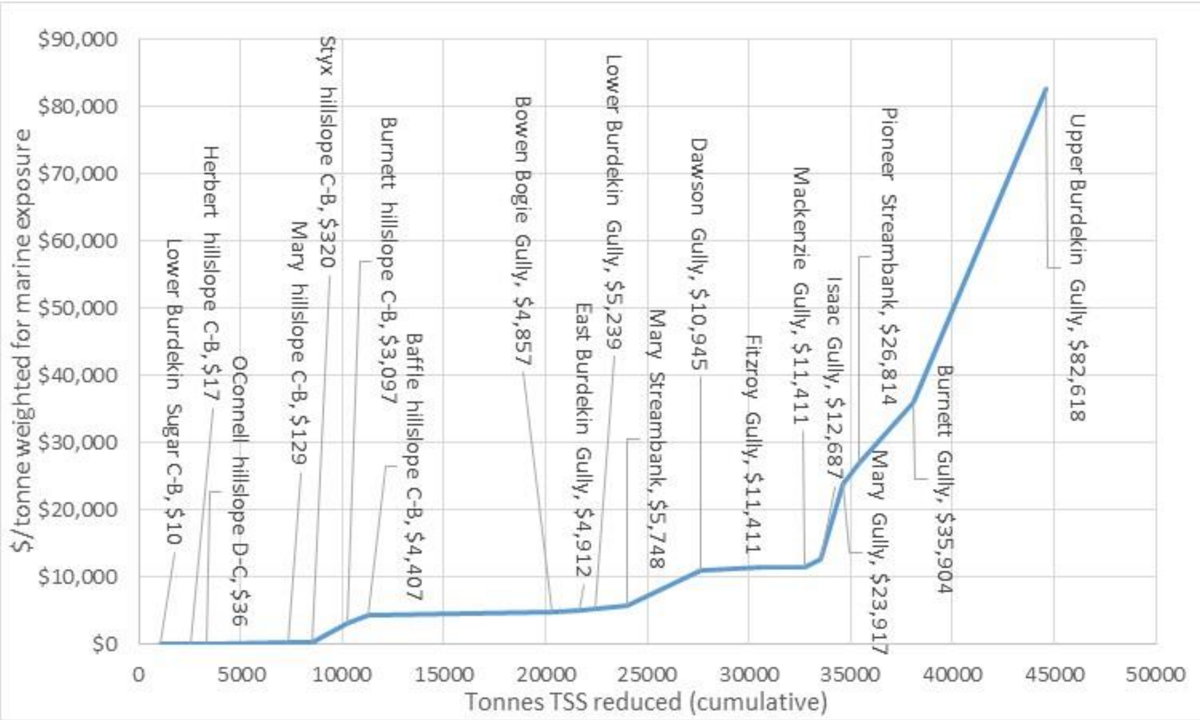

Figure 3: **Sediment prioritisation at management unit level with cumulative sediment reductions on the horizontal axis and the $ per weighted tonne on the vertical axis (only projects >1% of total reduction).** Costs are adjusted by an index for marine exposure for each catchment.

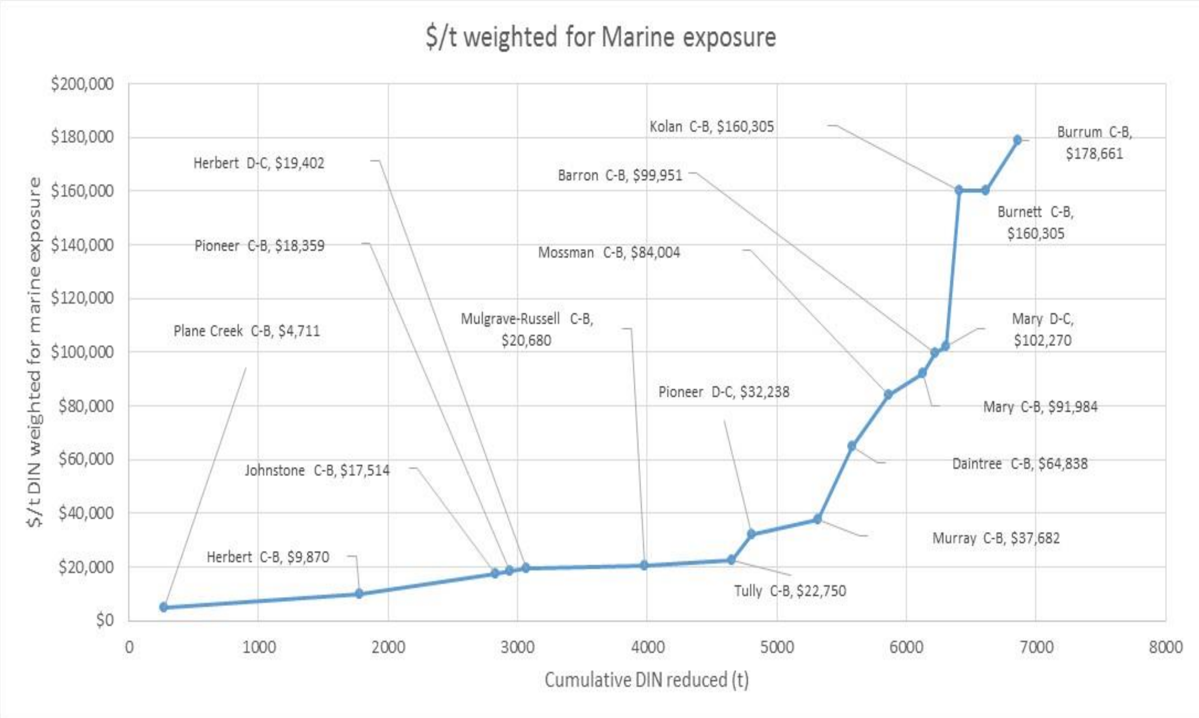

Figure 4: Dissolved inorganic nitrogen prioritisation at management unit level with cumulative dissolved inorganic nitrogen reductions on the horizontal axis and the $ per weighted tonne on the vertical axis (only projects >1% of total reduction).

The results provide an assessment of the trade-offs between potential pollutant reductions and corresponding reductions in marine exposure against the costs involved. The assessments are dependent on the available data and the modelling approach; of particular note is the impact of the marine exposure index which may underweight the contribution of management units that have lower levels of risk to the marine environment.

For sediment, the results show that costs per tonne of reduction rise dramatically from lowest cost to highest cost actions. There are several cost-effective actions that achieve small quantities of pollutant reduction, such as Lower Burdekin sugarcane management shifting from C to B management (Figure 3). After these, the Mary Basin showed the highest effectiveness of sediment reduction, reflecting the high level of landholder participation and management practice adoption and low risk of adverse weather. For the areas with the highest likelihood of fine sediment exposure, the largest pollutant reduction can be achieved from the Bowen Bogie management unit (mid-range in Figure 3), reflecting its very high sediment loads, which offset its low effectiveness score; this relates to currently low participation in management practice adoption, long time lags and high climate risk. In terms of cost effectiveness weighted for marine exposure, the Bowen Bogie management unit ranks behind several actions in the Mary and other management units, but ahead of larger gully reductions in the Fitzroy and other management units.

Results for reducing dissolved inorganic nitrogen highlighted that areas with the highest effectiveness ratings do not align well with the areas of highest likelihood of dissolved inorganic nitrogen exposure. The most cost-effective management units in the Mackay Whitsunday, Burnett Mary and Wet Tropics natural resource management regions for the actions specified only have the capacity to achieve marginal reductions overall. If the marine Likelihood of Exposure Index is the key driver of management decisions, then the focus is dominated by the Wet Tropics region, with the Herbert, Johnstone and Mulgrave-Russell management units having the largest potential load reduction (shown mid-range in Figure 4).

These results have implications for the updated basin-scale targets for the 35 basins for fine sediment, dissolved inorganic nitrogen, particulate nitrogen and particular phosphorus (Brodie et al., 2017). The targets are based on a marine endpoint chosen to meet criteria at which particular species/ecosystems (coral and seagrass only, at this stage) are able to survive with no deleterious effects. As the analysis is performed on a basin scale, it shows those basins that need large reductions in load to reverse the decline in coral or seagrass health in that marine region. These targets correlate with the results of the marine exposure assessment in Chapter 3. Given this, the load targets also identify where intensive management actions will be required to achieve satisfactory coral or seagrass health outcomes.

The regions of the Great Barrier Reef where ecosystems/species populations are still in relatively good condition (see Chapter 1), including northern Cape York (containing high value coral reefs, dugong populations, freshwater wetlands and estuaries) and Hervey Bay (containing high value seagrass meadows and dugong populations), are currently ranked as 'low risk' in terms of anthropogenic threats (see Chapter 3), hence receive low priority for restorative management funding. The Torres Strait (containing high value coral reefs, seagrass meadows and dugong populations) also falls into this category. The ecological integrity of these regions, their potential roles as refuges against climate change and the possibility that they may act as seeding centres for the rest of the Great Barrier Reef give them greater importance than would be indicated based on current risk profiles (Brodie and Pearson, 2016). The southern mid- and outer shelf reefs (south of Townsville (e.g. Pompey and Swain) are also likely to be important in this context.

Given the greater degree of confidence in the assessment of the relative contribution of individual basins to Great Barrier Reef anthropogenic pollutant loads and the likelihood of exposure of ecosystems to pollutants, these results are used to prepare a summary of priorities for managing water quality in the Great Barrier Reef (Table 4, Figure 5). Since the assessment is based on average conditions, a conservative approach was taken to the priority classification and was initially based on the Marine Likelihood of Exposure Indexes for fine sediment and dissolved inorganic nitrogen, where Very high = >0.90; High = 0.4 - 0.90; Moderate = 0.15-0.39 and at least 3% load contribution; Low = 0.02 - 0.15; Minimal = <0.03. In addition, the basins that were assessed as highest fine sediment risk to seagrass (see Chapter 3, Table 18) or highest dissolved inorganic nitrogen risk for the crown-of-thorns starfish influence area (see Chapter 3, Table 15) were ranked higher than other basins. Given the limited confidence in the results for the Cape York region and existing knowledge of load contributions and potential exposure from sediment from the Normanby Basin (see Chapter 3), the Normanby Basin was adjusted from Minimal to Low risk for fine sediment.

The assessment identifies the following highest priority basins for pollutant reduction from a Great Barrier Reef–wide perspective:

- fine sediment and particulate nutrients: Burdekin, Herbert, O'Connell, Mary and Styx basins
- dissolved inorganic nitrogen: Plane, Herbert, Johnstone, Pioneer and Mulgrave-Russell basins
- pesticides: Plane, Pioneer and Haughton basins.

The Cape York basins could also be identified as priority for protection / maintaining current water quality given their relatively low risk contributions and relatively good condition of the adjacent marine ecosystems.

When comparing the highest priority basins against the most cost-effective basins (in $/tonne), the Mary, Herbert, Fitzroy and Burdekin basins offer the most cost-effective management for sediment, while actions in the Burdekin Basin, including the Bowen Bogie catchment, provide the larger scale reductions at higher cost levels. For dissolved inorganic nitrogen, the results are less clear due to limitations in data availability across the Great Barrier Reef but indicate that the Plane, Herbert, Johnstone, Pioneer and Mulgrave-Russell basins are the most cost-effective areas for reducing dissolved inorganic nitrogen loads by improved sugarcane management.

Table 4: Relative spatial priorities for water quality improvement in the Great Barrier Reef basins based on the assessment of pollutant exposure and risk to coastal and marine ecosystems. Note that this is a result of the biophysical assessment only and results for particulate nutrients have been extrapolated from the sediment assessment and not considered independently. Social and economic factors determine priorities within basins.

NRM region	Basin	Relative priority			Dominant contributing land use or process for Low to Very High priority areas^	
		Fine sediment and particulate nutrients	Dissolved inorganic nitrogen	Pesticides	Sediment	Dissolved inorganic nitrogen
Cape York#	Jacky Jacky Creek	Minimal	Minimal			
	Olive-Pascoe River	Minimal	Minimal			
	Lockhart River	Minimal	Minimal			
	Stewart River	Minimal	Minimal			
	Normanby River	Low	Minimal			
	Jeannie River	Minimal	Minimal			
	Endeavour River	Minimal	Minimal			
Wet Tropics	Daintree River	Minimal	Moderate*			Sugarcane
	Mossman River	Minimal	Moderate*			Sugarcane
	Barron River	Minimal	Moderate*			Sugarcane
	Mulgrave-Russell River	Low	High*	Low	Sugarcane	Sugarcane
	Johnstone River	Moderate**	High*	Low	Sugarcane	Sugarcane
	Tully River	Low	High*	Moderate	Sugarcane	Sugarcane
	Murray River	Low	Moderate*		Sugarcane	Sugarcane
	Herbert River	High**	Very High*	Low	Grazing	Sugarcane
Burdekin	Black River	Minimal	Minimal			
	Ross River	Minimal	Low			Sewage treatment plant
	Haughton River	Low	Very High*	High	Grazing	Sugarcane
	Burdekin River	Very High**	Moderate	Low	Grazing	Sugarcane, grazing
	Don River	Low	Low		Grazing	Sugarcane, grazing
Mackay Whitsunday	Proserpine River	Low	Moderate		Grazing, sugarcane	Sugarcane
	O'Connell River	Moderate**	Moderate	Moderate	Sugarcane	Sugarcane
	Pioneer River	Low	Moderate	High	Streambank sources (various land uses)	Sugarcane
	Plane Creek	Low	High	Very High	Sugarcane	Sugarcane
Fitzroy	Styx River	Low	Minimal		Grazing	
	Shoalwater Creek	Minimal	Minimal			
	Waterpark Creek	Minimal	Minimal			
	Fitzroy River	High**	Low	Low	Grazing	Grazing
	Calliope River	Minimal	Minimal			

NRM region	Basin	Relative priority			Dominant contributing land use or process for Low to Very High priority areas^	
		Fine sediment and particulate nutrients	Dissolved inorganic nitrogen	Pesticides	Sediment	Dissolved inorganic nitrogen
	Boyne River	Minimal	Minimal			
Burnett Mary	Baffle Creek	Minimal	Minimal			
	Kolan River	Minimal	Low			Sugarcane
	Burnett River	Moderate**	Low	Low	Streambank sources (various land uses)	Sugarcane
	Burrum River	Minimal	Low			Sugarcane
	Mary River	High**	Moderate	Low	Streambank sources (various land uses)	Sugarcane

Notes:

High level of uncertainty in these results. Grey shading = not assessed.
^ Determined from Source Catchments load estimates for each land use (derived from McCloskey et al., 2017b).
Decision rules: Since we are working with average conditions, a conservative approach was taken: Marine Likelihood of Exposure Index: Very high (red) = >0.9; High (orange) = 0.4–0.9; Moderate (yellow) = 0.15–0.39 and at least 3% load contribution; Low (green) = 0.03–0.14; Minimal (no colour) = <0.03. In addition: **Basins were assessed as highest fine sediment risk to seagrass (see Chapter 3, Table 18) and therefore are ranked higher than other basins. *Basins were assessed as highest dissolved inorganic nitrogen risk for the crown-of-thorns starfish influence area (see Chapter 3, Table 15) and therefore are ranked higher than other basins.

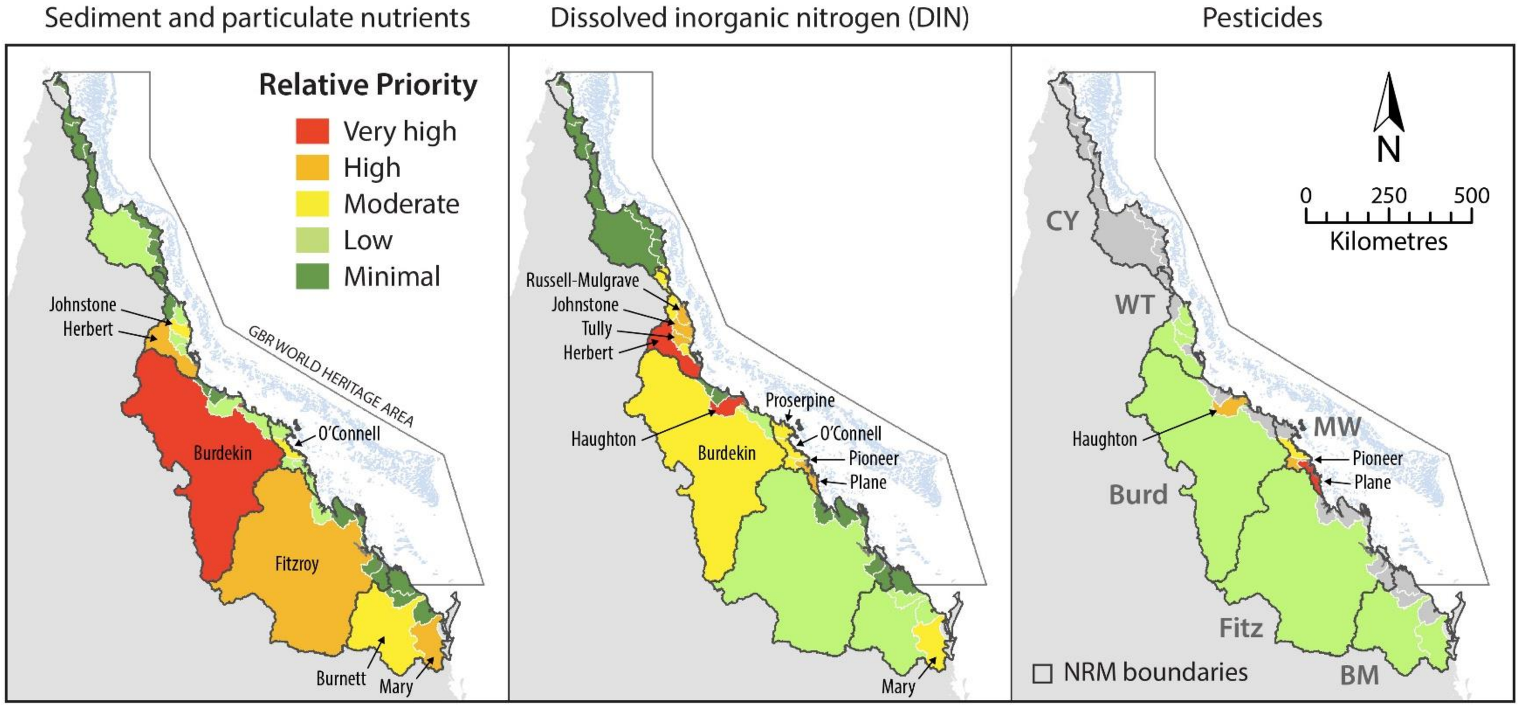

Figure 5: Map illustrating the relative spatial priorities for water quality improvement in the Great Barrier Reef catchments based on the assessment of pollutant exposure and risk to coastal and marine ecosystems. Note that this is a result of the biophysical assessment only, and results for particulate nutrients have been extrapolated from the total suspended solids assessment and not considered independently. Social and economic factors determine priorities within basins.

8. Priority knowledge gaps

While considerable progress has been made in water quality research and management, the key findings in the 2017 Scientific Consensus Statement are similar to those in the 2013 Scientific Consensus Statement (see individual chapters for highlights of the updated findings). However, there are still some knowledge gaps and uncertainties that, if addressed, would improve our ability to manage water quality for Great Barrier Reef ecosystem health outcomes. The key knowledge gaps and areas for further research from each chapter are highlighted below. Note that these are not necessarily in order of priority, but that *the most important knowledge gaps are highlighted in italic text*.

8.1 What is the condition of coastal and marine ecosystems of the Great Barrier Reef and their responses to water quality and disturbances?

There is still appreciable uncertainty in our knowledge of the responses of coastal and marine ecosystems to the cumulative impacts of multiple pressures. To improve assessments of coastal and marine water quality and to attribute responses of ecosystems to critical drivers of ecological changes it is important to:

- *Define desired states of seagrass meadows and coral reefs so that ecologically relevant targets can be set for the management of water quality–related pressures.*
- *Develop the capability to predict future ecosystem condition, resilience and recovery under a changing environment, including improved understanding of (i) recovery processes to inform more targeted management, and (ii) scope and rates of acclimatisation and adaptation.*
- *Inform the mitigation of crown-of-thorns starfish impacts by improving our understanding of the mechanisms and processes by which (i) nutrient run-off, and (ii) predator removal promote crown-of-thorns starfish outbreaks.*
- Refine existing water quality guideline values and improve monitoring through a combination of comprehensive water quality observations and application and continuous improvement of the eReefs biogeochemical model.
- Improve knowledge of water quality and connectivity in coastal ecosystems through (i) monitoring the condition of coastal freshwater wetlands and estuarine ecosystems, and (ii) prioritisation of freshwater and estuarine barriers for mitigation or removal.
- Improve understanding of historic and current rates of sediment accumulation in wetlands to improve understanding of landscape change, sediment exposure and risk to wetlands.
- Improve understanding of the location and ecological function of groundwater-dependent ecosystems.

8.2 What are the major sources of sediments, nutrients, pesticides and other pollutants to the Great Barrier Reef?

Knowledge of the major sources of pollutants to the Great Barrier Reef continues to progress; however, the following aspects should be refined:

- *Develop explicit estimates of confidence to highlight where we have high/medium or low confidence in the various monitoring and modelling datasets.*
- Establish a more robust framework for incorporating new knowledge into Source Catchment modelling and reporting to improve transparency and knowledge integration.

- *Improve understanding of sediments with respect to (i) particle size, (ii) bioavailable nutrient status, and (iii) long-term or pre-agricultural erosion rates. This would allow for more robust targeting of the ecologically threatening anthropogenic sediment.*
- *Improve understanding of nutrient sources evaluated as whole-of-catchment nutrient budgets. This should include sources (land uses, surface and groundwater), transformations and losses. To date, most studies have worked on components of the nutrient budget, but not on all elements in a single multi-land-use catchment.*
- *Refine knowledge of the on-farm application rates and usage of pesticides and farm chemicals and an understanding of the types, concentrations and sources of a range of new pollutants.*

8.3 What is the risk to Great Barrier Reef coastal and marine ecosystems from anthropogenic pollutants?

The ability to assess the risk to Great Barrier Reef coastal and marine ecosystems from anthropogenic land-based pollutants continues to improve through greater monitoring and modelling capacity and through more integrated and spatially explicit assessments. However, there are several key aspects that need to be progressed to provide greater confidence in the results:

- *Scope the availability and acquisition of more consistent temporal and spatial data for all water quality variables (including those not included in the most recent assessment such as phosphorus and particulate nutrients) and their ecological impacts on coastal and marine ecosystems. This will enable improved classification in terms of ecological risk and application of a formal risk assessment framework (which includes assessments of likelihood and consequence).*
- *Improve understanding of the responses of key Great Barrier Reef coastal and marine ecosystem components to cumulative impacts of repeated exposure to poor water quality and the cumulative impacts of multiple water quality pressures.*
- *Extend the habitat assessment of ecological risk beyond coral reefs and seagrass to other marine ecosystems and coastal ecosystems such as floodplain wetlands, floodplains, freshwater wetland and estuarine environments (mangrove and saltpan), fish and non-reef bioregions.*
- *Progress techniques to incorporate the principles of conservation management and the increasing need to protect areas in the Great Barrier Reef and its catchments that are in good condition as many parts of the Great Barrier Reef ecosystem become more degraded.*
- Refine the approach to estimate marine zones of influence for each basin.
- Update the assessment of dissolved inorganic nitrogen contributions from basins in the context of initiation of crown-of-thorns starfish population outbreaks using the new eReefs biogeochemical model. This would assist in refining relative priorities between the Wet Tropics basins. In addition, the potential role of terrestrially sourced particulate nitrogen in contributing to crown-of-thorns starfish outbreaks needs to be examined.
- Investigate scenarios for the influence of variable climate conditions (not just average conditions) on exposure of ecosystems and the implications of future climate scenarios.
- Improve quantified information on the consequences of degraded water quality on coastal aquatic ecosystems.
- Assess the exposure of wetlands to pesticide pollutants via drainage systems in nearshore areas (e.g. irrigation drainage, spoon drains), including mapping of drainage infrastructure carrying pesticide pollutants to nearshore coastal wetlands.
- *Improve understanding of the prevalence and associated effects of other pollutants (e.g. marine debris including microplastics, antifouling paint components, pharmaceuticals and others) on*

Great Barrier Reef species and ecosystems to assess their ecological risk, including relative to sediment, nutrients and pesticides.

8.4 What are the management options for addressing Great Barrier Reef water quality issues, and what is their effectiveness?

While current management options for addressing water quality issues in the Great Barrier Reef catchments have provided a solid foundation for program implementation, there are substantial knowledge gaps about options that will deliver accelerated and large-scale pollutant reductions in the Great Barrier Reef catchments and about the best ways to implement them.

Agricultural management options

- *Expand assessment of the effectiveness, costs and suitability of management techniques to address erosion features in gullies and riparian areas, including physical works and grazing management) in priority areas of Great Barrier Reef grazing lands.*
- *Develop and apply decision support tools that use forage budgeting, forage condition assessment and climate forecasts to set stocking rates across the grazing industry, and conduct research to support this, including understanding the recovery of degraded lands and the relative benefits of different pasture species, systems and stocking rates.*
- *Develop decision support systems to tailor site-specific fertiliser recommendations and conduct supporting research, including:*
  - *the water quality benefits of adopting enhanced efficiency fertilisers and the best management of these fertilisers under different soil and climatic conditions*
  - *the potential for novel interventions (e.g. incorporating climate forecasting into nutrient management decisions) to help farmers reduce nitrogen applications*
  - *improving site-specific recommendations for nitrogen application in sugarcane and nitrogen supply from organic sources and optimising the management of enhanced efficiency fertilisers using the Agricultural Production Systems sIMulator model (APSIM)*
  - *exploring the potential for improved irrigation and fertiliser management and water use efficiency to reduce nutrient loss*
  - *the contribution of organic sources of nutrients (e.g. nitrogen from legumes, nitrogen and phosphorus from mill mud) to nutrient losses (both dissolved and particulate).*
- Improve understanding of the relative and additive toxicity, run-off potential and half-lives of new herbicide products (knockdowns and residuals) and other pesticides.
- *Improve knowledge of how practice improvement for water quality benefits can be encouraged through the broader social and economic networks that influence management (suppliers, contractors, buyers, family members and peers) as well as extension, information and advice provision by public, private and non-government organisation sources.*
- Assess the potential of emerging digital technologies (sensing, information and communication technologies and big data analytics) in enhancing extension strategies, farmer decision-making, monitoring and improvement at different scales (farm to program) and the social and institutional requirements for required data sharing.
- *Improve approaches to estimating overall costs of management options, address modelling constraints and reduce underlying assumptions.*
- *Improve understanding of farmer motivations to change, incorporating costs and risks associated with weather and markets.*

- *Develop consistent prioritisation approaches to take full account of the costs and benefits that can be gained from management practice adoption.*

Other management options

- Quantify the pollutant retention capacity of natural and near natural palustrine, riverine and lacustrine wetlands in the catchments of the Great Barrier Reef, including:
    - the potential to retain/process nutrients and pesticides derived from agricultural practices and other sources
    - identification of wetland characteristics that maximise contaminant removal, supported by data on pollutant assimilation rates, capacity and load/concentration thresholds
    - effectiveness of retention in different locations and under widely variable hydrological regimes
    - consideration of the landscape scale context and effects of pollutants on wetland processes and functions that contribute to water quality improvement.
- *Evaluate the effectiveness, efficiency and costs of using different types of treatment systems to address sediment, nutrients and pesticides in different locations in the Great Barrier Reef.*
- Assess the feasibility of changing land uses to less intensive uses with lower pollutant generation, in terms of the water quality benefits, cost effectiveness and social implications.
- Validate the effectiveness of a larger suite of urban water quality management practices in the Great Barrier Reef.
- Review current and potential future risk of contaminants in sewage treatment plant effluent discharges, with the projected increase in population and urban growth along the Great Barrier Reef coast.
- Evaluate the effectiveness of the schemes to reduce marine debris through monitoring of marine debris and microplastics in coastal and marine environments.
- Review the impacts of ports, particularly in estuaries, and improve the water quality monitoring, assessment and reporting in Great Barrier Reef ports.
- Improve knowledge to support management of the impacts of land-based disposal of dredge material.

Governance and program delivery

- Build a foundation of social research including principles of behavioural change and systematic evaluation of program delivery arrangements to provide clear feedback to policy, programs and Great Barrier Reef stakeholders.
- Explore ‘smart regulation’ options to influence agricultural practices through unconventional pathways such as standards, supply chains and commercial institutions and work collaboratively with growers, supply chain participants and industry groups to design, test and evaluate the effectiveness of these instruments.
- Evaluate the effectiveness of Great Barrier Reef governance arrangements (including policy alignment) and establish clear feedback mechanisms to policy and programs.

Some of these important knowledge gaps are already being addressed through new and ongoing research projects including those in the Queensland Government Reef Water Quality Science Program and the Australian Government National Environmental Science Programme.

9. Conclusions and recommendations

The writing team has identified the key findings and recommendations in Table 5 from the evidence collated for this Scientific Consensus Statement. The main findings highlight the most important areas of the evidence, and the recommendations identify actions that are essential for reversing the decline in Great Barrier Reef ecosystem health due to water quality degradation.

Table 5. Summary of the main findings and recommendations for the 2017 Scientific Consensus Statement. The highest priority recommendations are highlighted in bold text.

Summary of evidence	Recommendations
Overarching consensus **Key Great Barrier Reef ecosystems continue to be in poor condition. This is largely due to the collective impact of land run-off associated with past and ongoing catchment development, coastal development activities, extreme weather events and climate change impacts such as the 2016 and 2017 coral bleaching events.** **Current initiatives will not meet the water quality targets. To accelerate the change in on-ground management, improvements to governance, program design, delivery and evaluation systems are urgently needed. This will require greater incorporation of social and economic factors, better targeting and prioritisation, exploration of alternative management options and increased support and resources.**	
Condition of coastal and marine ecosystems **The decline of marine water quality associated with land-based run-off from the adjacent catchments is a major cause of the current poor state of many of the Great Barrier Reef coastal and marine ecosystems. Additionally, coastal ecosystems have been highly modified and continue to be exposed to a range of pressures from catchment development. The resilience of marine ecosystems was indicated by their ability to at least partially recover from previous losses during periods of low disturbance and reduced catchment pollutant loads. The systems have been severely impacted by a number of recent events—including prolonged periods of extreme sea surface temperatures, tropical cyclones and the progression of the fourth wave of crown-of-thorns starfish population outbreaks. Climate change is predicted to increase the frequency of large-scale bleaching events and the intensity of extreme weather events.**	
• The Great Barrier Reef marine ecosystems and their associated catchments are part of a dynamic, interconnected system. The condition of all parts of the system, including the catchment, is important for the long-term health of the Great Barrier Reef. Each part has its own inherent ecosystem and biodiversity values and provides ecosystem services such as water quality improvement and carbon storage that benefit the receiving marine environment. • Coastal freshwater wetlands continue to be affected by a range of chronic and acute pressures such as excess nutrient, sediment and pesticide loads; loss of connectivity; changes in hydrology and invasive species. • Poor marine water quality associated with pollutant run-off from the adjacent catchments, especially during major floods, affects the condition of many of the key marine ecosystems of the Great Barrier Reef. • Inshore seagrass meadows and coral reefs continue to recover from previous losses due to major run-off events and cyclones, but remain in moderate to poor condition.	• **Implement measures to better anticipate and respond to future changes including climate change, coastal urban growth, and agricultural expansion and intensification. This will require: (i) developing a coherent climate adaptation strategy for the Great Barrier Reef catchments; (ii) modified water quality planning and delivery approaches; (iii) strategies to manage unforeseen impacts of future land-use change (e.g. coastal development or land retirement) including offsets or strict conditioning; (iv) future scenario modelling; and (v) better standards for cumulative impact assessment including climate scenarios for environmental impact assessment of development proposals in the Great Barrier Reef catchments.** • Undertake urgent action to maintain and improve the resilience of the coastal and marine ecosystems of the Great Barrier Reef through implementing more intensive management of catchment water quality and other local pressures, active landscape protection and restoration

Summary of evidence	Recommendations
• Periods of reduced catchment run-off associated with low rainfall demonstrate the inherent ability of inshore reef communities to recover from acute disturbances. This provides a strong case for reducing the pollutant loads being delivered to the Great Barrier Reef. • Mid-shelf and outer shelf reefs in the southern half of the Great Barrier Reef have shown the capacity to rapidly recover from previous disturbances; however, a severe mass thermal coral bleaching event in 2016 resulted in significant coral mortality, especially north of Port Douglas. • Ongoing, warmer-than-average sea temperatures resulted in a further widespread mass coral bleaching event in 2017 which was most intense on reefs between Cairns and Townsville. In addition, a severe tropical cyclone Debbie affected reefs in the Mackay Whitsunday region and subsequent flooding also affected the Fitzroy region. Impacts of these events have yet to be quantified. • Climate change is predicted to increase the intensity of extreme weather events, which are significant in driving impacts to coastal and marine ecosystems.	approaches to maintain as much biodiversity and ecosystem functions as possible, and more effective global climate change mitigation measures. A stronger knowledge base about the role of extreme events and a changing climate on end-of-catchment pollutant loads is essential for developing achievable water quality targets. • Implement a more holistic and coordinated approach to managing wetlands (including rivers) and floodplains and their connections to the Great Barrier Reef by embedding protection of catchment, estuary and floodplain functions and connectivity in Great Barrier Reef policy. This should also include increased efforts to understand how multiple and cumulative environmental pressures (including water quality) affect recovery processes, to help refine predictions of future condition and resilience of coastal and marine ecosystems.
Risk to coastal and marine ecosystems **The greatest water quality risks to the Great Barrier Reef and coastal ecosystems are from discharges of: (i) nutrients, which are an additional stress factor for many coral species, promote crown-of-thorns starfish population outbreaks with destructive effects on mid-shelf and offshore coral reefs, and promote macroalgal growth; (ii) fine sediments, which reduce the light available to seagrass ecosystems and inshore coral reefs, and (iii) pesticides, which pose a toxicity risk to freshwater ecosystems and some inshore and coastal habitats.**	
A combination of qualitative and semi-quantitative assessments were used to estimate the relative risk of water quality pollutants to Great Barrier Reef coastal aquatic and marine ecosystem health. • Increased loads of fine sediments, nutrients (nitrogen and phosphorus) and pesticides were all found to be important at different scales and different locations in the Great Barrier Reef. However, the risks differ between the individual pollutants, source catchments and distance from the coast. • Exposure to fine sediment is most significant for areas with shallow seagrass and coral reefs on the inner shelf adjacent to basins with high anthropogenic fine sediment loads. The greatest coral reef and seagrass exposure to fine sediment is from the Burdekin, Fitzroy, Mary, Herbert, Johnstone and Burnett	• Use the Great Barrier Reef catchment-specific pollutant load reduction targets to guide actions to minimise water quality risks to the Great Barrier Reef.

Summary of evidence	Recommendations
catchment areas. The Burdekin and Fitzroy catchments also contribute the greatest fine sediment risk to seagrass ecosystems. • Exposure to dissolved inorganic nitrogen is most significant for all inner shelf areas and the mid-shelf area between Lizard Island and Townsville adjacent to catchments with high anthropogenic dissolved inorganic nitrogen loads. The relative importance of dissolved inorganic nitrogen to seagrass ecosystems is still uncertain, but it may influence light availability for deep water seagrass in areas deeper than 10 to 15 metres due to increased phytoplankton growth. • The greatest coral reef and seagrass exposure to dissolved inorganic nitrogen is from the Herbert, Haughton, Johnstone, Mulgrave-Russell, Tully, Plane and Murray catchment areas. The Herbert, Johnstone, Mulgrave-Russell and Tully also contribute the greatest dissolved inorganic nitrogen risk to coral reefs and primary crown-of-thorns starfish outbreaks. Anthropogenic particulate nitrogen is also likely to be of some importance in the same catchment areas, as well as in the Fitzroy; however, our knowledge on the bioavailability of particulate nitrogen to the marine ecosystems in relation to that of dissolved inorganic nitrogen is still limited. • Anthropogenic phosphorus loads are considerable from many catchment areas. Knowledge of the relative importance of nitrogen and phosphorus is limited, but nitrogen is considered to be the limiting nutrient and, hence, more important in any form than phosphorus. • Pesticides pose the greatest risk to ecosystems closest to the source of the pesticides; i.e. freshwater wetlands, rivers and estuaries; followed by coastal ecosystems, seagrass and coral. Catchments within the Mackay Whitsunday region and the Lower Burdekin present a very high to moderate risk to end-of-catchment ecosystems from pesticides, with diuron presenting the highest risk. • Marine plastic pollution was found to be the highest priority among emerging pollutants. This is particularly an issue in the Cape York region due to exposure to oceanic and local shipping sources. Additionally, chronic contamination of water and sediments with antifouling paints, and exposure to certain personal care products, has been assessed as a risk in regions south of Cape York. All other emerging contaminants were assessed as relatively low risk, with some minor differences between regions.	
Sources of land-based pollutants	

Summary of evidence	Recommendations
The main source of excess nutrients, fine sediments and pesticides from Great Barrier Reef catchments is diffuse source pollution from agriculture. Other land uses, including urban areas, contribute relatively small but concentrated pollutant loads, which may be important at local scales.	
• Water discharged from the catchments into the Great Barrier Reef lagoon continues to be of poor quality in many locations. Knowledge of the major sources and processes contributing to these river pollutant loads has significantly improved due to better modelling and monitoring. • Sugarcane areas are the largest contributors of dissolved inorganic nitrogen and pesticides, while grazing contributes the largest proportion of sediment and particulate nutrients to the Great Barrier Reef primarily through sub-surface (gully, streambank and rill) erosion. Contributions from other land uses, including urban, are relatively minor in comparison to agriculture, but can be important locally. • At the regional scale, the Wet Tropics, Burdekin and Fitzroy regions contribute most of these river pollutant loads. However, at the catchment scale, areas within the Mackay Whitsunday and Burnett Mary regions are also important contributors, illustrating the value of identifying management priorities at the catchment or finer scale. • Catchment modelling shows that mean-annual fine sediment, nutrient and pesticide loads delivered to the Great Barrier Reef lagoon have increased substantially since pre-development conditions. They include an: approximate 5.0 fold increase in fine sediment for the entire Great Barrier Reef catchment (range 3.0 to 8.0 fold depending on the region); approximate 2.0 fold increase in dissolved inorganic nitrogen (range 1.2 to 6.0 fold, with the exception of Cape York); approximate 1.5 fold increase in particulate nitrogen (range 1.2 to 2.2 fold) and approximate 2.9 fold increase in particulate phosphorus (range 1.2 to 5.3 fold). • The mean-annual loads of prevalent pesticides (ametryn, atrazine, diuron, hexazinone, tebuthiuron and simazine) are estimated (modelled) to be around 12,000 kg per year across the Great Barrier Reef. The measured pesticide data suggest that most pesticides are found in all regions, even though some are in very small quantities. The catchments that contribute the most pollutants have remained reasonably consistent over the past 10 years. • Expansion of agriculture in the Great Barrier Reef catchment (e.g. under the Northern Australian Development Plan), major development projects and	• **Continue to prioritise agricultural sources of pollutants in Great Barrier Reef catchment management. Information on the pollutant contributions from non-agricultural sources (e.g. urban, industrial and ports) and other pollutants should be compiled as a priority to support whole-of-catchment management approaches.**

<table>
<tr><th>Summary of evidence</th><th>Recommendations</th></tr>
<tr><td>anticipated growth in coastal populations of the Great Barrier Reef will increase pollutant loads delivered to the Great Barrier Reef.</td><td></td></tr>
<tr><td colspan="2">Progress to targets
Progress towards the Reef Water Quality Protection Plan 2013 targets has been slow and the present trajectory will not meet the targets. This puts the Outstanding Universal Value of the Great Barrier Reef under increasing pressure, especially in the context of other pressures such as climate change. Greater effort to improve water quality is urgently required to restore and protect the Great Barrier Reef ecosystems.</td></tr>
<tr><td>• The Reef Water Quality Protection Plan 2013 included land and catchment management targets to address improved agricultural management practices and the protection of natural wetlands and riparian areas. These targets were based on the conceptual understanding of the link between land condition, management practice standards and water quality outcomes.
• The annual Great Barrier Reef Report Card reports progress against the Reef Water Quality Protection Plan targets, with the most recent report card providing 2014-2015 data. Most of the indicators are reported annually, except for the wetland and riparian extent indicators which are reported every four years (the last report was in 2014).
— The overall condition of the inshore marine environment (water quality, seagrass and coral) remains poor, and has not changed greatly since Report Card 2011.
— While there has been good progress in adopting improved management practices across the agricultural industries in the Great Barrier Reef catchments, a large proportion (in some cases, up to 77%) of agricultural land is managed using practices which are below best management practice for water quality. This demonstrates the challenges associated with facilitating the adoption of improved (lower water quality risk) land management practices, and highlights the limited progress towards achieving the management practice adoption targets since 2009.
— An analysis of the Great Barrier Reef Report Card data indicates the rate of progress towards the targets is slowing and it is unlikely the targets will be met on the current trajectory.</td><td>• The recommendations for these findings are combined with those for ‘Efforts to improve Great Barrier Reef water quality’. The key message is that there is a need to urgently implement more targeted and substantial effort to improve water quality in the Great Barrier Reef.</td></tr>
</table>

Summary of evidence	Recommendations
— Catchment condition targets are tracking positively, with very good, good and moderate scores for ground cover, wetland loss and riparian extent, respectively. • The adoption of existing best management practices for agricultural land will not be sufficient to achieve the water quality targets and additional management options need to be urgently trialled and validated in the Great Barrier Reef context and then implemented.	
Efforts to improve Great Barrier Reef water quality **Current management options to reduce pollutant run-off to the Great Barrier Reef provide a solid foundation for program implementation, but an expanded scope of tailored and innovative solutions is urgently required to progress the substantial pollutant load reductions required to meet the Reef 2050 Water Quality Improvement Plan targets by 2025. There is an urgent need for greater investment in voluntary practice change programs, the use of regulatory tools and other policy mechanisms to accelerate the adoption of practice change, and robust monitoring and evaluation programs to measure the rate and effectiveness of adoption.**	
• There is very high confidence in the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program water quality risk frameworks which are used to assess the effectiveness of agricultural practices for water quality. New research has highlighted the benefits of lower fertiliser (nitrogen) application rates, and site and season-specific fertiliser recommendations, in reducing water quality risk. In grazing, land cover management has been found to be effective at generally reducing erosion. However, gully and streambank erosion remains a major problem and remediation has become a higher priority. • The adoption of new agricultural practices depends upon many factors including individual goals and circumstances, local context, perceived profitability and risk and ease of management. Farmers are diverse, with different goals, motivations and information sources. Conflicting messages about Great Barrier Reef health, blaming farmers and the over-emphasis on science (to the exclusion of local or industry knowledge) have been found to contribute to low acceptance of environmental responsibility. • Collaborative processes to deliver interventions and improve trust in decisions and data are essential. Local, trusted intermediaries and flexible incentives need to be fostered to improve participation in reef water quality programs.	• **Develop and implement cost-effective techniques to manage gullies and riparian erosion; further develop and implement new approaches to fertiliser management in cropping lands (including the use of enhanced efficiency fertilisers, site-specific fertiliser management, and considering seasonal climate forecasts); and investigate methods to reduce catchment run-off as a result of extreme climatic events.** • **Introduce tailored practice change programs that target different groups of landholders and involve collaboration with landholders, industry organisations and service providers to design and deliver programs. Include programs that involve knowledge exchange between farmers, scientists and others; address perceptions of risk; provide trusted and diverse advisory services; and deliver adequate financial, cultural and social rewards.** • **Develop and implement a broader range of management options for pollutant reduction from all land uses considering costs, water quality benefits, other trade-offs and policy instruments. In particular: (i) test and validate the water quality effectiveness of wetland and treatment systems in specific locations to support their broader application; (ii) review options for voluntary land use change to less intensive uses which support water quality improvement; and (iii) incorporate total**

Summary of evidence	Recommendations
• Wetland and floodplain protection, management and restoration, as well as engineered treatment systems are required to complement on-farm practices to reduce nutrient, sediment and pesticide run-off. • Additional water quality benefits can be achieved from non-agricultural lands such as urban areas and ports, although our understanding of the effectiveness of different practices for water quality in the Great Barrier Reef is limited. • Changes in land use to less intensive options (such as from sugarcane to grazing, wetlands or conservation) warrants further consideration to accelerate pollutant load reductions. There is currently limited investigation or evidence of these options in the Great Barrier Reef catchments. • Large variations exist in the costs of improving water quality between natural resource management regions, programs and industries. Investments can be better prioritised to improve the efficiency and effectiveness of practice change programs. The costs of meeting the water quality targets has been shown to be very high; much higher than previously thought. As water quality targets are approached, the costs of additional actions are likely to rise sharply. • Better prioritisation of investments should take into account the cost-effectiveness of agricultural management options including adoption rates, costs, time lags and climatic influences, as well as risks to the marine environment. The areas where the most cost-effective management options can be achieved are not necessarily the areas that generate the most pollutants.	**water cycle management in expanding urban areas and quantify benefits at local scales. Encourage adoption of proven applications.** • Undertake a more comprehensive and systematic evaluation of existing and proposed policies and programs to improve their effectiveness in accelerating adoption. Additionally, ensure that an economic assessment of projects, in terms of public costs and private benefits, is undertaken to better judge cost-effectiveness and likely adoption before proceeding. • Implement regulatory and market mechanisms to favour selection of lower cost projects and faster practice change, supported by voluntary approaches to meet the pollutant reduction targets. A variety of regulatory tools already exist, and others e.g. 'smart regulation' should be considered.
Governance and program delivery arrangements **Great Barrier Reef water quality governance requires a commitment to adaptive, participatory and transdisciplinary approaches, and better use of social, economic and institutional research. There is strong evidence to show where aspects of current water quality management programs can be strengthened. Risks including climate change, major development projects and related policy areas, such as agricultural intensification and coastal development, need to be addressed more directly. Strengthened and more effective coordination of Australian and Queensland government policies and programs, further collaboration with farmers and other stakeholders, and strong evaluation systems are critical to the success of Great Barrier Reef water quality initiatives.**	
• Overall, the governance of the Great Barrier Reef is inherently complex. Coordination between governments and government programs is critical to provide clear policy signals and ensure effective management actions.	• **Evaluate the effectiveness, efficiency and outcomes of Great Barrier Reef programs and share learnings at Great Barrier Reef and regional levels to drive improvement in program governance, design, delivery and implementation. Incorporate learnings from social research and**

Summary of evidence	Recommendations
• There has been a lack of systematic evaluation of program design and implementation, and limited use of social, economic and institutional research to find and test new solutions and improve program delivery. • Great Barrier Reef governance requires adaptive, participatory and transdisciplinary approaches: — **Adaptive** approaches use modelling and other tools to build system understanding, encourage experimentation and evaluation, and tailor solutions to regional variations. A greater focus on experimentation and evaluation of on-ground works and program delivery would strengthen the adaptive capacity of Great Barrier Reef programs. Current governance arrangements have not effectively supported a culture of innovation for water quality outcomes. — **Participatory** approaches can bring more knowledge to the debate about solutions, garner support, coordinate effort and reveal value conflicts. Participation and collaboration are features of Great Barrier Reef policy, planning and implementation. Collaboration between natural resource management organisations and industry peak bodies has facilitated coordinated program delivery. Regional capacity is, however, fragile with changes to natural resource management programs, capacity and funding commitments. — **Transdisciplinary** approaches use natural and social sciences and stakeholder knowledge to test and evaluate innovative solutions. • Climate change, the cumulative impact of major development projects and uncoordinated policies represent critical risks to Great Barrier Reef health. • Intergovernmental coordination and policy alignment must be improved as they affect all aspects of program design and delivery. Related policy areas, such as agricultural intensification, drought relief and water resource development, and poor alignment with other regional planning and management efforts can have perverse impacts on Great Barrier Reef water quality outcomes.	**international case studies, and commission locally relevant research, to support formal Great Barrier Reef policy review cycles.** • **Address the significant risks to Great Barrier Reef ecosystems from other policy areas by implementing measures to reduce greenhouse gas emissions, assess the cumulative impacts of major projects on the Great Barrier Reef, and influencing related policy areas such as agricultural intensification and coastal development that may increase risks to the Great Barrier Reef.** • Develop stronger alignment between Great Barrier Reef management programs, wetland and floodplain management, and other regional planning and management activities such as land-use planning, development assessment and floodplain management. • Encourage and invest in core natural resource management activities such as local partnerships, planning and community engagement to strengthen the regional, catchment and property-scale delivery network. Longer term funding commitments tied to performance outcomes will provide flexibility to tailor approaches to local contexts. • Encourage experimentation and innovation by scientists working with local stakeholders to develop, test and evaluate potential new solutions. • Strengthen intergovernmental coordination to ensure effective management of the Great Barrier Reef. The Reef 2050 Long-Term Sustainability Plan needs a greater authority and investment, clearer strategies and better stakeholder engagement.

<table>
<tr><td colspan="2">Catchment-scale management priorities
Several catchments contribute to the highest exposure of coastal or marine ecosystems to pollutants, and are considered a high priority for water quality improvement. These include the Mulgrave-Russell, Johnstone, Tully, Herbert, Haughton, Burdekin, Pioneer, Plane, Fitzroy and Mary catchments. Social and economic information is required to prioritise efforts within catchments.</td></tr>
<tr><td>• The highest priority areas for the reduction of fine sediments, dissolved inorganic nitrogen and pesticides loads delivered to the Great Barrier Reef are:
— fine sediment and particulate nutrients: Burdekin, Herbert, Fitzroy and Mary catchments
— dissolved inorganic nitrogen: Herbert, Haughton, Mulgrave-Russell, Johnstone, Tully and Plane catchments
— pesticides: Plane, Pioneer and Haughton catchments.
• The Cape York catchments could also be a priority for protection and for maintaining current water quality given their relatively low risk contributions and relatively good condition of the adjacent marine ecosystems.
• Comparing the highest priority catchments for pollutant reduction against those with the most cost-effective management options (in $/tonne) shows:
— The Mary, Herbert and Fitzroy and Burdekin catchments offer the most cost-effective management for sediment, while actions in the Burdekin, including the Bowen-Broken-Bogie catchment, provide the larger scale reductions at higher cost levels.
— The results are less clear for dissolved inorganic nitrogen due to limitations in data availability across the Great Barrier Reef but indications are the Plane, Herbert, Tully and Johnstone catchments are the most cost-effective areas for reducing dissolved inorganic nitrogen loads through improved sugarcane management.</td>
<td>• Develop a detailed, comprehensive and costed water quality management plan, drawing on the existing regional water quality improvement plans, to guide strategic investment in priority areas and ensure the updated water quality targets for the Great Barrier Reef are achieved.
• Undertake finer scale spatial prioritisation of management and allocate resource effort across and within the Great Barrier Reef catchments, using (i) biophysical catchment characteristics and the likelihood of exposure of coastal and marine ecosystems to pollutants to identify priority areas at a catchment scale, supported by (ii) current practice adoption, and social and economic factors to inform the most cost-effective areas for increased management effort and the choice of policy mechanisms, and (iii) a range of agricultural management practice, landscape remediation and/or land conversion management scenarios. Incorporate risks to landholders and partners, climate, markets and time lags. Industries such as horticulture and broadacre cropping require further attention as they present an opportunity for cost-effective outcomes in short timeframes.
• Target funding for improved land management and remediation to the priority catchments identified in the 2017 Scientific Consensus Statement. Areas of lower priority for remediation still need to be maintained or improved.</td></tr>
<tr><td colspan="2">Monitoring and modelling
Monitoring and modelling of the Great Barrier Reef ecosystems is a strength of the Reef Water Quality Protection Plan 2013 and its programs, with some spatial limitations. However, there has been limited investment in social and institutional research and monitoring, and a lack of systematic evaluation of delivery processes and governance systems. A greater focus on experimentation, prioritisation and evaluation at different scales, coupled with the use of modelling and other approaches to understand future scenarios, could further improve water quality programs.</td></tr>
<tr><td>• The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) commenced in 2009 and is the central program for</td>
<td>• Expand the scope of the Paddock to Reef Integrated Monitoring, Modelling and Reporting program to:</td></tr>
</table>

evaluating progress towards the Reef Water Quality Protection Plan management practice, catchment condition, pollutant reduction targets, as well as marine water quality and ecosystem health condition. The scope of the program does not currently include social (except for management practice adoption reporting), economic or governance indicators. There is also limited marine condition assessment in the northern (Cape York) and southern (Burnett Mary) regions. • Almost 10 years of data collected under the Paddock to Reef program provides the basis for assessing catchment management effectiveness and catchment and marine water quality and ecosystem condition. • Regional reporting partnerships have been established involving a broad range of stakeholders. Access to monitoring data outside of the Paddock to Reef program will become more important with the scope of the Reef 2050 Water Quality Improvement Plan 2017-2022 expanded to include non-agricultural land uses. • The ability to quantitatively attribute changes in catchment activities and end-of-catchment water quality to coastal and marine water quality and ecosystem condition remains limited due to climate variability, sparse monitoring and incomplete operational models. Overall, catchment and marine monitoring and modelling approaches to support evaluation and reporting of the progress towards targets continue to improve. There are still challenges with the lack of data for all indicators in the Cape York and Burnett Mary regions. • There has been very little investment in social, economic and institutional research, or monitoring, evaluation and reporting of indicators related to Great Barrier Reef water quality management, and this constrains the ability to improve the effectiveness of programs.	— include condition reporting of coastal aquatic ecosystems — address the lack of monitoring data, validation of models and the estimation of water quality risks and ecosystem condition in the Cape York and Burnett Mary regions — incorporate a formal social and economic monitoring and modelling component — address the lack of monitoring data from other pollutants, e.g. marine debris, microplastics and personal care products. • Expand and improve public reporting of water quality data from all land uses and whole-of-catchment efforts to support broader community engagement. • Develop the capacity to model the cumulative impacts of water quality and other pressures (major projects, coastal development) under a range of climate and other scenarios to better inform policy, planning and assessment processes. • Develop a systematic approach to program evaluations that incorporates social, economic, governance and programmatic dimensions to inform program delivery efforts and support innovation.

10. Reference list

Australian and Queensland governments, 2013. Reef Plan Paddock to Reef Water Quality Risk Framework. Australian and Queensland governments, Brisbane, Australia.

Australian and Queensland governments, 2016. Great Barrier Reef Report Card 2015 Reef Water Quality Protection Plan. Queensland Government, Brisbane, Australia.

Brodie, J., Pearson, R.G., 2016. Ecosystem health of the Great Barrier Reef: Time for effective management action based on evidence. Estuarine, Coastal and Shelf Science 183, 438-451.

Brodie, J., Waterhouse, J., Schaffelke, B., Kroon, F., Thorburn, P., Rolfe, J., Johnson, J., Fabricius, K., Lewis, S., Devlin, M., Warne, M., McKenzie, L., 2013. 2013 Scientific Consensus Statement. Land use impacts on Great Barrier Reef water quality and ecosystem condition. The State of Queensland, Reef Water Quality Protection Plan Secretariat.

Brodie, J., Baird, M., Mongin, M., Skerrat, J., Waterhouse, J., Robillot, C., Smith, R., Mann, R., Warne, M., 2017. Development of basin specific ecologically relevant water quality targets for the Great Barrier Reef. Final Report for Project EHP16055 – Update and add to the existing 2013 Scientific Consensus Statement to incorporate the most recent science and to support the 2017 update of the Reef Water Quality Protection Plan.

Burnett Mary NRM Group, 2015. Water Quality Improvement Plan for the Burnett Mary 2015, Burnett-Mary Regional Group, Bundaberg, Australia. 171 pp. www.bmrg.org.au/resources/publications/water-quality-improvement-plans/

Cape York NRM and South Cape York Catchments, 2016. Eastern Cape York Water Quality Improvement Plan. Cape York Natural Resource Management and South Cape York Catchments, Cooktown, Queensland, Australia.

Coppo, C., Brodie, J., Butler, I., Mellors, J., Sobtzick, S., 2014. Status of Coastal and Marine Assets in the Burnett Mary Region. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Report No. 14/36, Townsville. 89 pp.

Fitzroy Basin Association, 2015. Fitzroy Water Quality Improvement Plan. Fitzroy Basin Association, Rockhampton, Australia. Online. www.fba.org.au/wqip.

Folkers, A., Rohde, K., Delaney, K., Flett, I. 2014. Mackay Whitsunday Water Quality Improvement Plan 2014-2021. Reef Catchments and Australian Government. reefcatchments.com.au/files/2015/06/WATER-QUALITY-IMPROVEMENT-PLAN-MACKAY-WHITSUNDAY-ISAAC-2014-2021_DRAFT.pdf

GESAMP 2001. Protecting the Oceans from Land-based Activities. Land-based sources and activities affecting the quality and uses of the marine, coastal and associated freshwater environment. UNEP. 168 pp.

GBRMPA (Great Barrier Reef Marine Park Authority), 2014a. Great Barrier Reef Outlook Report 2014, Commonwealth of Australia, Townsville.

GBRMPA (Great Barrier Reef Marine Park Authority), 2014b. Great Barrier Reef Region Strategic Assessment, Commonwealth of Australia, Townsville.

GBRWST (Great Barrier Reef Water Science Taskforce), 2016. Great Barrier Reef Water Science Taskforce Final Report May 2016. Office of the Great Barrier Reef, Department of Environment and Heritage Protection, Brisbane.

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., 2017. Global warming and recurrent mass bleaching of corals. Nature, 543(7645), 373-377.

Kroon, F.J., Berry, K.L.E., Brinkman, D.L., Davis, A., King, O., Kookana, R., Lewis, S., Leusch, F., Makarynskyy, O., Melvin, S., Müller, J., Neale, P., Negri, A., O'Brien, D., Puotinen, M., Smith, R., Tsang, J., van de Merwe, J., Warne, M., Williams, M., 2015. Identification, impacts, and prioritisation of emerging contaminants present in the GBR and Torres Strait marine environments. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns. 138 pp.

McCloskey, G.L., Waters, D., Baheerathan, R., Darr, S., Dougall, C., Ellis, R., Fentie, B., Hateley,L., 2017a. Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments: updated methodology and results – Technical Report for Reef Report Card 2014, Queensland Department of Natural Resources and Mines, Brisbane, Queensland.

McCloskey, G.L., Waters, D., Baheerathan, R., Darr, S., Dougall, C., Ellis, R., Fentie, B., Hateley, L., 2017b. Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments: updated methodology and results – Technical Report for Reef Report Card 2015, Queensland Department of Natural Resources and Mines, Brisbane, Queensland.

McKenzie, L.J., Collier, C.J., Langlois, L.A., Yoshida, R.L., Smith, N., Waycott, M., 2016. Marine Monitoring Program—Inshore Seagrass, Annual Report for the sampling period 1st June 2014 – 31st May 2015. Centre for Tropical Water & Aquatic Ecosystem Research, James Cook University, Cairns.

NQ Dry Tropics, 2016. Burdekin Region Water Quality Improvement Plan 2016. Better Water for the Burdekin. NQ Dry Tropics, Townsville. www.nqdrytropics.com.au/wqip2016/

Queensland Department of State Development, Infrastructure and Planning, 2013. Great Barrier Reef Coastal Zone Strategic Assessment. Strategic Assessment Report, State of Queensland, Brisbane.

Star, M., Rolfe, J., Pringle, M., Shaw, M., McCosker, K., Ellis, R., Waters, D., Tindal, D., Turner, R., 2017. Targeting for pollutant reductions in the Great Barrier Reef management units. Central Queensland University, Rockhampton, Australia.

Terrain NRM, 2015. Wet Tropics Water Quality Improvement Plan 2015-2020. Terrain NRM, Innisfail. www.terrain.org.au/Projects/Water-Quality-Improvement-Plan

Thompson, A., Costello, P., Davidson, J., Logan, M., Gunn, K., Schaffelke, B., 2016. Marine Monitoring Program. Annual Report for Coral Reef Monitoring: 2014 to 2015. Australian Institute of Marine Science, Townsville.