2017 Scientific Consensus Statement

CHAPTER TWO

Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef

Rebecca Bartley
CSIRO

David Waters
Queensland Department of Natural Resources and Mines

Ryan Turner
Queensland Department of Science, Information Technology and Innovation

Frederieke Kroon
AIMS

Scott Wilkinson
CSIRO

Alex Garzon-Garcia
Queensland Department of Science, Information Technology and Innovation

Petra Kuhnert
CSIRO

Stephen Lewis
James Cook University

Rachel Smith
Queensland Department of Science, Information Technology and Innovation

Zoe Bainbridge
James Cook University

Jon Olley
Griffith University

Andrew Brooks
Griffith University

Jo Burton
Queensland Department of Science, Information Technology and Innovation

Jon Brodie
James Cook University

Jane Waterhouse
James Cook University

Citation:

Bartley, R., Waters, D., Turner, R., Kroon, F., Wilkinson, S., Garzon-Garcia, A., Kuhnert, P., Lewis, S., Smith, R., Bainbridge, Z., Olley, J., Brooks, A., Burton, J., Brodie, J., Waterhouse, J., 2017. Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. 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

DIP = dissolved inorganic phosphorus

DON = dissolved organic nitrogen

GBR = Great Barrier Reef

NPI = National Pollutant Inventory

NRM = natural resource management

PN = particulate nitrogen

PP = particulate phosphorus

PSII = Photosystem II

TN = total nitrogen

TP = total phosphorus

TSS = total suspended sediment

Units

d-eq. kg = diuron-equivalent in kilograms

kg = kilograms

km = kilometres

kt/yr = kilotonnes per year

mg/L = milligrams per litre

t = tonnes

t/ha = tonnes per hectare

$t/km^2/yr$ = tonnes per square kilometre per year

t/km^2 = tonnes per square kilometre

t/yr = tonnes per year

µm = micrometres (microns)

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 is one 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 (7 management units) and Fitzroy (7 management units) basins.

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 from (directly or indirectly) 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 have evolved to live in or on sediment.

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. The regions include Cape York, Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary.

Sub-catchment: An internal drainage area within a catchment.

Acknowledgements

This chapter was led by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) with contributions from several representatives from the Department of Natural Resources and Mines (DNRM) (Queensland), Department of Science, Information Technology and Innovation (Queensland) (DSITI), Australian Institute of Marine Science (AIMS), James Cook University (JCU) and Griffith University (GU).

We would like to thank Dr Andrew Ash (CSIRO), for his contribution to Section 2.1.4, and Dr Christian Roth and Dr David Post (CSIRO), for formal reviews on earlier versions of this document. We would also like to thank Reiner Mann and Rohan Wallace (DSITI), John Bennett and Nyssa Henry (OGBR) and several of the catchment modelling team (Rob Ellis) for comments on previous versions. Finally, we thank ISP members Dr Bronwyn Harch (QUT), Dr Jenny Stauber (CSIRO), Dr Graham Bonnet (CSIRO) and Dr Roger Shaw (ISP Independent Chair) for constructive comments on earlier versions.

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 from the Department of the Environment and Energy and in-kind support from the organisations of the authors.

Thank you to Jane Mellors (TropWATER JCU) for final editing.

Executive summary

This chapter provides an up-to-date review of the state of knowledge relating to the source of sediment and nutrients as well as pesticides and other pollutants delivered to the Great Barrier Reef from adjacent catchments. The strengths and limitations of the various datasets are also discussed. Collectively, sediment, nutrients, pesticides and other pollutants (e.g. petroleum hydrocarbons, pharmaceuticals) are described as 'pollutants'. This chapter is focused on defining the major source areas of these pollutants across the Great Barrier Reef, how these sources have varied in space and time, the major processes (e.g. hillslope, gully and streambank erosion) delivering these pollutants, their relative loads to the Great Barrier Reef and a summary of the main drivers in terms of land use, land condition and agricultural practices. Plot- and paddock-scale studies, including the effectiveness of remediation approaches, are summarised in Chapter 4.

Acknowledging that all forms of data used to estimate pollutant loads to the Great Barrier Reef have constraints and limitations, this review uses a 'multiple lines of evidence' approach and draws on data from three main sources. These include the Queensland Government load monitoring data, the latest Queensland Government whole of Great Barrier Reef Source Catchments modelling results (which underpin the Report Card 2015) as well as a summary of the numerous individual research projects and synthesis reports published over the last four years. Data and information are included that was published, publicly available and that had undergone a peer review process. In a few cases, grey literature (e.g. consulting reports) and journal publications currently in review are included.

A synthesis of the broad findings of this chapter are outlined below and in Table 1. A detailed description of what has changed since the last Scientific Consensus Statement is provided in Table 20.

Summary of findings

Sediment

- Catchment modelling predicts 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 pre-European conditions, the modelled mean annual river fine sediment loads to the Great Barrier Reef lagoon have increased ~5-fold for the entire Great Barrier Reef catchment, ranging between 3- and 8-fold depending on the region.
- 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 catchment contributes ~40% of the anthropogenic total suspended sediments load to the Great Barrier Reef lagoon, with the Wet Tropics (~15%), Fitzroy (~18%) and Burnett Mary (~15%) the other dominant regions. Within these regions, the top five sediment-contributing basins 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.
- Grazing lands are the dominant land-use contributing sediment, although parts of the Wet Tropics and Mackay Whitsunday regions have high specific yields (t/km^2/yr).
- 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.

Nutrients

- Catchment modelling estimates that there is ~55 kt/yr of total nitrogen and ~13.4 kt/yr 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).
- Modelled dissolved inorganic nitrogen load to the Great Barrier Reef is ~12 kt/yr, which is a 2.0-fold increase from pre-development conditions (ranging between 1.2 and 6.0, with the exception of Cape York). For particulate nitrogen the modelled load is ~25 kt/yr, a 1.5-fold increase (ranging between 1.2 and 2.2). For particulate phosphorus the modelled load is ~10 kt/yr, which is a 2.9-fold increase (ranging between 1.2 and 5.3) from pre-development conditions.
- 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%) regions; particulate nitrogen is dominated by the Wet Tropics (27%) and Fitzroy (20%) regions; particulate phosphorus is dominated by the Fitzroy (33%) and the Burdekin (22%) regions.
- Within these regions, hotspot areas exist. The top five basins contributing to the dissolved inorganic nitrogen load are the Herbert, Burdekin, Johnstone, Haughton and Mulgrave-Russell. The top five basins contributing to the 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 phosphate and 72% of particulate phosphorus based on the specific nutrient yields ($t/km^2/y$).
- Sugarcane farming dominates dissolved inorganic nitrogen river loads, and grazing dominates the source of particulate nitrogen in river loads. In the grazing lands, 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 total suspended solids, the management strategies for mitigating export of particulate nitrogen and total suspended solids are similar.
- Dissolved and particulate nutrient loads from urban land uses, particularly wastewater discharges, can be important at local scales, but generally represent <7% overall.

Pesticides and other pollutants

- Mean annual loads of photosystem II–inhibiting herbicides, namely ametryn, atrazine, diuron, hexazinone, tebuthiuron and simazine, are estimated to be ~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 results from the end-of-system water quality monitoring suggest that the measured pesticide loads are generally lower than modelled estimates.

- The dominant source of pesticides does change 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 grazing dominates. Total toxic equivalent loads are highest in Plane Creek and Haughton management units.
- Other sources of pollutants to the Great Barrier Reef lagoon include point sources such as intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, military areas and shipping. Compared to diffuse sources, most contributions of such point sources are 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. In some cases, no monitoring data exist.

Research recommendations

- Explicit estimates of confidence are required to highlight where we have high, medium or low confidence in the various datasets.
- A more robust framework for incorporating new knowledge into Source Catchment modelling and reporting would improve transparency and knowledge integration.
- We need improved knowledge on 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.
- We need improved knowledge on 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.
- There is a need for improved knowledge on 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.

Table 1: A synthesis of the broad findings presented in this chapter

Questions	Sediments	Nutrients	Pesticides	Other contaminants
Where are the pollutants coming from?	Total sediment delivery is dominated by the Burdekin catchment (primarily the Bowen Bogie) and grazing land more generally (~70%). Unit area anthropogenic loads (t/km^2/yr) are also high in the Wet Tropics (e.g. Johnstone, Mulgrave-Russell) and Mackay Whitsunday (O'Connell and Pioneer, Cattle Creek).	Dissolved inorganic nitrogen delivery to the Great Barrier Reef is dominated by catchments with a large proportion of sugarcane (e.g. Herbert, Burdekin and Johnstone). Intensive cropping generally exports higher unit area loads of dissolved inorganic nitrogen (e.g. sugarcane and bananas). Particulate nitrogen is highest from the Fitzroy, Mary and Burdekin basins.	The dominant source of pesticides does change between years and locations. However, in terms of toxic equivalent load, sugarcane areas in the Wet Tropics, Mackay Whitsunday and Burdekin regions dominate delivery to the Great Barrier Reef.	Pollutants are derived from a range of diffuse and point sources including agriculture (including intensive animal production), manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, coastal/marine tourism, military areas and shipping.
How do the sources of the pollutant vary in space and time?	There has been a quantified anthropogenic increase in erosion from the Bowen Bogie and Upper Burdekin management units compared with long-term (>1000 year) rates. Nuclide tracers suggest that some parts of the Wet Tropics have high natural sediment loads.	Particulate and dissolved organic nutrients comprise the majority of the end of catchment loads to the Great Barrier Reef but very little is known of their sources, losses or transformation as they are transported from terrestrial to marine systems. Dissolved forms of nutrients may move via surface and sub-surface pathways.	Pesticides are not naturally occurring in the environment and therefore any variability is generally due to human use (rather than factors such as geology or soil type). The variation in loads is generally proportional to application rates.	Compared to diffuse sources, most contributions of point sources are relatively small but could be highly significant locally and over short time periods.
What processes are responsible for the excess pollutant?	Gully erosion and to a lesser extent riverbank erosion are the dominant erosion sources. Scald or rill erosion can also contribute sediment when ground cover is low.	Fertilised crops are directly responsible for increased dissolved inorganic nitrogen loads; however, erosion processes (hillslope, gully and streambank) in grazing lands are likely to be contributing higher bioavailable nutrient loads than currently estimated using models.	Diffuse load losses were highest from intensive agriculture. The total and toxic equivalent loads for pesticides are greatest from sugarcane for all regions.	The processes contributing pollutants are highly variable and depend on the source.
What are the drivers of the anthropogenic pollutant?	Poor land cover and surface condition within grazing areas lead to high run-off and erosion. Poor land cover is also a strong driver of gully erosion, although factors such as soil type are also important. Poor or low riparian vegetation cover is the main anthropogenic or management lever contributing to bank erosion.	Fertiliser application rates and the timing of application and lateral drainage of irrigation water are important drivers of dissolved inorganic nitrogen loss. Management of particulate sources by reducing both surface and sub-surface erosion may be more important than initially estimated. This will require a combination of direct (gully stabilisation) and indirect (cover and run-off management) techniques.	Excessive use of chemicals (application rates) drives pesticides losses, particularly prior to run-off or irrigation events (which relates to the timing of application).	Point sources are generally regulated activities; however, monitoring and permit information is not always available. Data for most pollutants are poor.

1. Introduction

Suspended sediments and nutrients play an important role in freshwater and marine biogeochemical processes and food webs (Krumins et al., 2013; Wood and Armitage, 1997). However, there is general agreement that excessive amounts of sediments, nutrients, pesticides and other pollutants are impacting on the ecological health of the Great Barrier Reef (De'ath et al., 2012; McCulloch et al., 2003a) and other adjacent habitats such as seagrass beds (Waycott et al., 2005). Collectively, these excess sediments, nutrients, pesticides and other pollutants (e.g. petroleum hydrocarbons, pharmaceuticals) are described as 'pollutants'.

The Great Barrier Reef has changed considerably in the past (8500-year record) independently of anthropogenic impact (Browne et al., 2012) and many reefs have coexisted with poor water quality conditions such as high turbidity for millennia (Larcombe et al., 1995). Therefore, quantifying the source and amount of excess or anthropogenic pollutant delivered from agricultural land-use change since European settlement, against the high variability of natural loads in tropical rivers, is challenging. It is easier to identify the anthropogenic source of some pollutants (e.g. pesticides) that did not exist prior to human settlement, than for other pollutants (e.g. sediments and particulate nutrients) that naturally occur in the landscape. Few studies have been able to trace single pollutants from the catchment source through to the marine receiving waters, accounting for all erosion, deposition and transformation processes, particularly in large (>100,000 km^2) catchments (Douglas et al., 2006a; Takesue et al., 2009). Generally, a range of approaches and techniques are required to understand how pollutants move from their source to the marine system (Bartley et al., 2014a). A 'multiple lines of evidence' approach is needed to help understand and represent the numerous complex processes.

Previous Scientific Consensus Statements (e.g. Kroon et al., 2013) provided a review of the various studies that have contributed to the multiple lines of evidence approach. Since the 2013 Scientific Consensus Statement, additional published literature and synthesis reports have become available. The purpose of this chapter is to provide an up-to-date review of available information published since 2013. The chapter reviews information on the pollutants of relevance in the Reef Water Quality Protection Plan targets, namely fine or total suspended sediments (TSS), dissolved inorganic nitrogen (DIN), particulate nitrogen (PN), particulate phosphorus (PP), and photosystem II inhibiting herbicides (PSII herbicides). The chapter also reviews information on other pollutants (e.g. petroleum hydrocarbons, pharmaceuticals). This chapter is broken into four sections. Firstly, the synthesis process and questions to be answered are outlined in the remainder of Section 1. Section 2 provides a synthesis of the most recent research. Section 3 and Table 20 summarise the overall findings, and Section 4 provides a discussion of key research needs.

1.1 Synthesis process

The studies, data and information included in this chapter can be broadly broken into three groups:

1. **Catchment loads monitoring:** The Department of Natural Resources and Mines (DNRM) loads monitoring program has up to nine years of measured data (starting from 2006) from ~32 gauging stations across the Great Barrier Reef catchments. It is acknowledged that water quality and pollutant load data are available for some sites prior to 2006; however, these data were not included due to issues related to data access and measurement consistency. It is important to point out that monitoring load estimates are also a form of modelling as they use relationships (or models) between intermittent pollutant concentration samples and flow to calculate a pollutant load upstream of the sampling point. The variability or error associated with these estimates can be formally quantified (using standard deviation or standard error), and the processes that contribute to that error are generally known (Harmel et al., 2006). Therefore, there is

considerable confidence in these data. As such, they are often considered the point of truth for quantifying pollutant fluxes. Monitoring is, however, expensive and currently has several limitations. These include (i) that it can take many years to capture the flow and pollutant concentration variability at a site. It is estimated that a ~25-year flow period is suitable for measuring changes in run-off (Chiew and McMahon, 1993), and up to 50 years is needed for pollutant loads (Darnell et al., 2012), (ii) it is often difficult to isolate the effects of land use (as discussed in Bartley et al., 2012), (iii) it is difficult to differentiate the contribution from natural and anthropogenic sources using pollutant loads alone; however, when used in conjunction with different isotope and geochemical approaches it can provide important insights into the relative ratios (e.g. Bartley et al., 2015a; Verburg et al., 2011), and (iv) it is challenging to monitor the smaller coastal catchments due to the influence of tides and pollutant transformations (Tappin, 2002), and therefore it is difficult to measure the true loads reaching marine waters. There will never be sufficient measured data and information to estimate the loads and sources of pollutants across the entire Great Barrier Reef; however, there is a need for a consistent approach to estimating end-of-catchment loads and their sources so that decisions can be made regarding remediation investments. For the reasons outlined above, modelling is the primary tool used to estimate end-of-catchment loads to the Great Barrier Reef.

2. **Catchment modelling:** The Source Catchments model applies algorithms that represent processes (e.g. hillslope, gully or bank erosion) across the entire Great Barrier Reef region using site-specific input data (e.g. terrain, soil type, run-off). The strength of catchment modelling is that it can provide an estimate of the constitute load for all of the 35 catchments along the Great Barrier Reef coast and also at smaller scales if required (although predictive confidence generally decreases with decreasing scale) (Wilkinson, 2008). The models utilise all available flow-gauging data and can therefore estimate loads over longer time periods (~28 years). They can also estimate loads from different land uses and provide estimates of the proportion of the load that has come from the current land use, compared to natural or pre-development conditions. The main challenge with the modelling data is the difficulty in undertaking a rigorous quantification of the error or uncertainty associated with many of the data inputs. Therefore, our confidence in the model output is hard to measure, and thus confidence in the modelling output is generally lower than for the monitoring data. The 2015 external modelling review (Bosomworth and Cowie, 2016) DNRM, 2015) identified that 'only a few of the many sources of uncertainty can be formally quantified' and therefore recommended that qualitative terms be used to describe levels of confidence in results. Performance indices outlined by Moriasi et al. (2015) were used to quantify model performance against the measured end-of-catchment discharge and pollutant load estimates and are described in McCloskey et al. (2017a, 2017b). Evaluation of the confidence in all of the input data against independent datasets (e.g. tracing and dating data) has been undertaken where appropriate. In Waters et al. (2014) monitored-loads data were used for validation but not for calibration. However, in the most recent modelling the increased monitoring record allowed some, but not all, of the model's parameters (e.g. delivery ratios and gully cross-sectional area) to be adjusted to better align with monitored loads. The model results will be the key datasets used to estimate pollutant delivery to the Great Barrier Reef; however, the model results are most robust when used to compare results from the 35 basins in relative terms (e.g. Waters et al., 2013).

3. **Research project data** were collected at a range of sites across the Great Barrier Reef using various techniques (e.g. isotopes, geochemical analysis, optically stimulated luminescence dating, run-off flumes and laboratory and field analysis). These studies provide insights into the processes or sources of a particular pollutant in that area. A brief description of the influence of pasture and trees on pollutant loads is also presented.

This report attempts to find consensus between the various datasets. Where conflict does occur, it will be noted as a potential area of further research. In this report, information is included that was published, publicly available and that had undergone a peer review process. Peer review means that someone other than an author, who has domain or discipline knowledge, has read and commented on the report to check for accuracy in terms of the methods, results and interpretation of the data. Detailed descriptions of the methods and results are not included; only a summary of the findings is presented. Readers are encouraged to access the cited literature for specific details. The review focused on new literature or studies published since 2013; however, where earlier (pre-2013) work was important for answering the questions outlined below, it was included. In some cases, relevant research published outside of the Great Barrier Reef area was also incorporated.

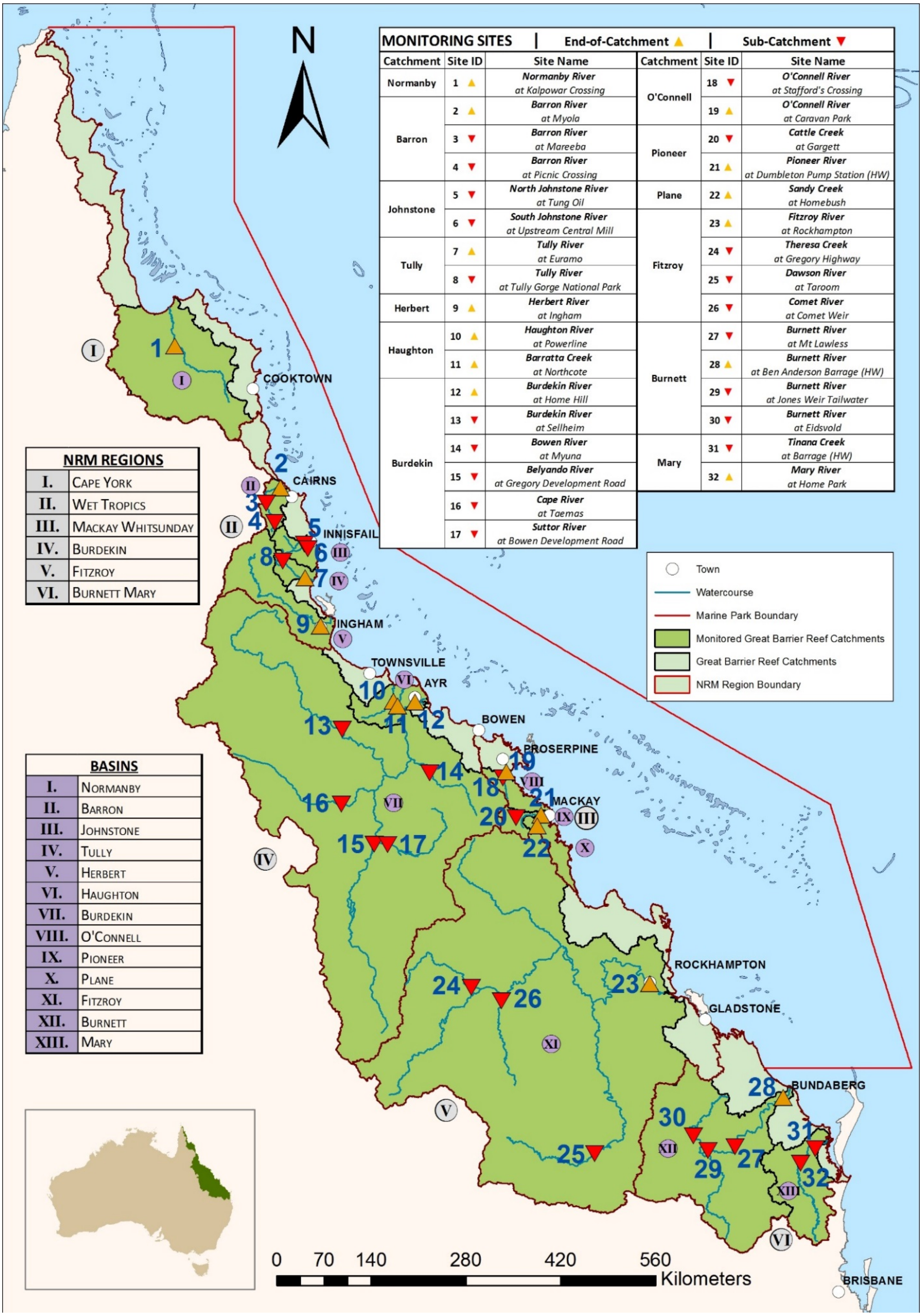
1.2 The questions this chapter addresses

By the end of this chapter, readers should be able to answer the following questions:

- Where are the pollutants coming from (between and within catchments)?
- How do the pollutant sources vary in both space and time?
- What are major processes (e.g. hillslope, gully and streambank erosion) delivering these pollutants?
- What are the dominant drivers of the processes (land use, climate, etc.)?

This chapter **does not**:

- provide a detailed critique of any of the methods used in this report, including the modelling approach. Recent reviews of the Source Catchments models have been undertaken by an independent panel of experts (see the response from the Queensland Government in Bosomworth and Cowie, 2016). A full description of the Source Catchments model can be found in Waters et al. (2014) and the more recent changes and updates can be found in McCloskey et al. (2017a, 2017b). The strengths and weaknesses of the Reef Programme have been discussed elsewhere (Queensland Audit Office, 2015)
- provide a thorough comparison of modelled and measured datasets. This is not the role of the Scientific Consensus Statement. It will, however, attempt to highlight where there is common overlap and where there are differences. In many cases it is difficult to directly compare modelled and measured pollutant flux as the modelled outputs represent net pollutant delivery to the coast which includes trapping in dams and floodplains
- replace the information presented in the Regional Water Quality Improvement Plans and supporting study documents (see Burnett Mary NRM Group 2015; Cape York NRM and South Cape York Catchments, 2016; Fitzroy Basin Association Inc., 2015; Folkers et al., 2014; NQ Dry Tropics, 2016; Terrain NRM, 2015). The Water Quality Improvement Plans describe priorities at a finer spatial scale and include detailed regionally specific information that will not be repeated here. Instead, this chapter will present a whole of Great Barrier Reef synthesis of the most recent information related to understanding the source of pollutants delivered to the Great Barrier Reef
- evaluate changes in pollutant yield due to changes in land-use management. These changes are presented in Chapter 4.



MONITORING SITES | End-of-Catchment ▲ | Sub-Catchment ▼

Catchment	Site ID	Site Name
Normanby	1 ▲	Normanby River at Kalpowar Crossing
Barron	2 ▲	Barron River at Myola
	3 ▼	Barron River at Mareeba
	4 ▼	Barron River at Picnic Crossing
Johnstone	5 ▼	North Johnstone River at Tung Oil
	6 ▼	South Johnstone River at Upstream Central Mill
Tully	7 ▲	Tully River at Euramo
	8 ▼	Tully River at Tully Gorge National Park
Herbert	9 ▲	Herbert River at Ingham
Haughton	10 ▲	Haughton River at Powerline
	11 ▲	Barratta Creek at Northcote
Burdekin	12 ▲	Burdekin River at Home Hill
	13 ▼	Burdekin River at Sellheim
	14 ▼	Bowen River at Myuna
	15 ▼	Belyando River at Gregory Development Road
	16 ▼	Cape River at Taemas
	17 ▼	Suttor River at Bowen Development Road
O'Connell	18 ▼	O'Connell River at Stafford's Crossing
	19 ▲	O'Connell River at Caravan Park
Pioneer	20 ▼	Cattle Creek at Gargett
	21 ▲	Pioneer River at Dumbleton Pump Station (HW)
Plane	22 ▲	Sandy Creek at Homebush
Fitzroy	23 ▲	Fitzroy River at Rockhampton
	24 ▼	Theresa Creek at Gregory Highway
	25 ▼	Dawson River at Taroom
	26 ▼	Comet River at Comet Weir
Burnett	27 ▼	Burnett River at Mt Lawless
	28 ▲	Burnett River at Ben Anderson Barrage (HW)
	29 ▼	Burnett River at Jones Weir Tailwater
	30 ▼	Burnett River at Eidsvold
Mary	31 ▼	Tinana Creek at Barrage (HW)
	32 ▲	Mary River at Home Park

NRM REGIONS	
I.	Cape York
II.	Wet Tropics
III.	Mackay Whitsunday
IV.	Burdekin
V.	Fitzroy
VI.	Burnett Mary

BASINS	
I.	Normanby
II.	Barron
III.	Johnstone
IV.	Tully
V.	Herbert
VI.	Haughton
VII.	Burdekin
VIII.	O'Connell
IX.	Pioneer
X.	Plane
XI.	Fitzroy
XII.	Burnett
XIII.	Mary

○ Town
Watercourse
Marine Park Boundary
🟩 Monitored Great Barrier Reef Catchments
Great Barrier Reef Catchments
🟥 NRM Region Boundary

Figure 1: Location of monitoring sites presented in this Chapter.

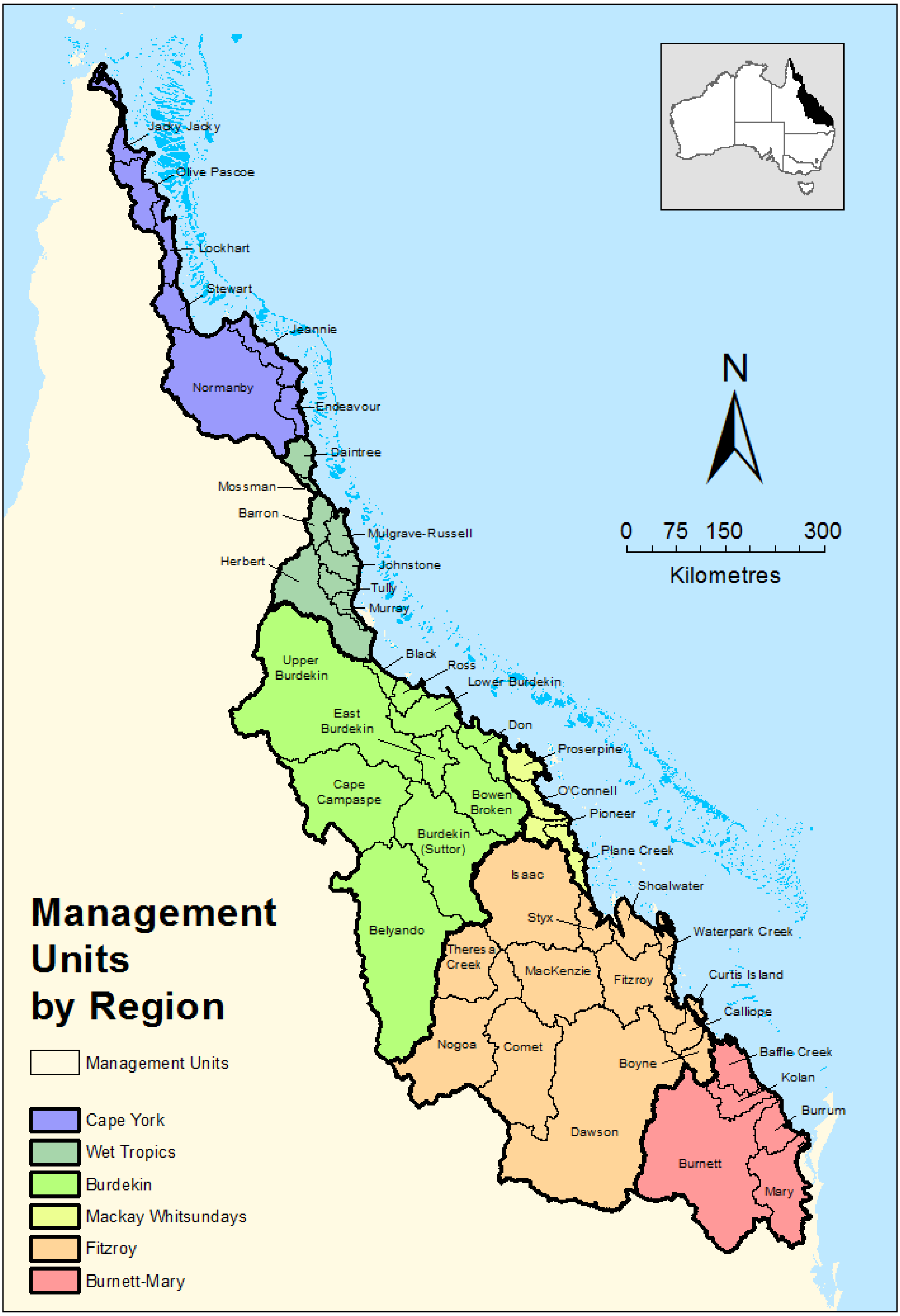


Figure 2: Location of Great Barrier Reef regions, the basins within the regions and the 47 management units used in the modelling.

1.3 Definitions and clarifications

Modelling

- The modelling results presented in this chapter are based on the most recent Report Card 2015 baseline modelling predictions (State of Queensland 2016). These data represent average annual pollutant delivery to the Great Barrier Reef for the 1986–2014 (28-year record) period. The land-use and land-management data are for the 2012–2013 period. A static land-use layer was used over the model run period, which was based on the latest available Queensland Land Use Mapping Program data in each natural resource management (NRM) region (McCloskey et al., 2017a; McCloskey et al., 2017b).
- The modelling results presented in this chapter represent pollutant delivery to the coast only. It is important to highlight that pollutant generation (or erosion) and delivery are very different processes, as are transformations in estuarine and marine environments. The modelling calculates erosion, deposition, transformation and delivery of pollutants from river catchments. Only the delivery estimates are presented in this report. A full budget that describes the modelled source, deposition and transformation of each of the pollutants can be found in McCloskey et al. (2017a).
- The data presented in this chapter may be used to (i) inform marine risk assessment and receiving water models (see Chapters 3 and 5), (ii) identify hotspot areas to guide on-ground investment prioritisation (e.g. Water Quality Improvement Plans, Reef Trust), (iii) compare the relative ratios of different data types and so on. Due to the various uses for the data and information, the results have been presented using a range of units, and explanation of these terms is given in Table 2.
- In this chapter, 35 basins that drain to the Great Barrier Reef are described. Within a basin there may be several streams or rivers (e.g. the Johnstone Basin includes the North Johnstone and South Johnstone rivers). When evaluating delivery to the coast, using data from the 35 basins is sufficient. However, this is not necessarily suitable for identifying hotspots, particularly in the larger Fitzroy and Burdekin basins (>130,000 km^2). To provide a more equitable spatial resolution for comparing hotspot areas, the modelling data were broken into 47 management units (Figure 3**Error! Reference source not found.**). The additional management units include seven areas in the Burdekin basin and seven in the Fitzroy basin. Noting that the Haughton and Lower Burdekin have been merged for this analysis. Using the language adopted in the Water Quality Improvement Plans, these 47 areas will be termed 'management units' for the remainder of this report. Note there are some slight variations in the load numbers when evaluating loads according to the 35 basins compared to the 47 management units (mainly in the Burdekin). This is due to slight variations in catchment boundaries, dam trapping and extractions. The differences are generally <3%. The load estimates from the 47 management units are also based on their load contribution to the coast.

Monitoring

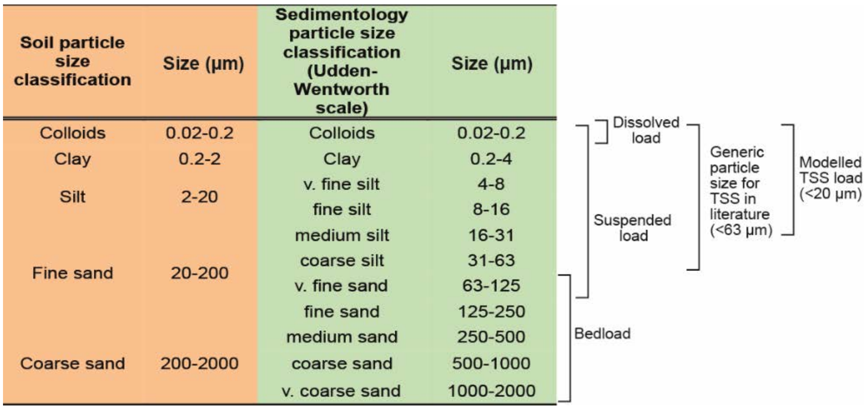
- The gauging and monitoring stations are generally above the tidal influence, and in many basins this is also upstream of large areas of agricultural land (mainly sugarcane). This means that in places like the Wet Tropics and Mackay Whitsunday, the load data do not represent the complete delivery of pollutants to the marine system (McCloskey et al., 2017b). The agricultural areas along the coastal fringe are not directly captured using monitoring. This makes direct comparison of monitoring and modelling data inappropriate in many areas, as the modelling has been adjusted to accommodate the ungauged area.

Definition of sub-surface material

- In this chapter the term 'sub-surface' is used to represent the source of material that is not from the grassed hillslope or paddock surfaces. Sub-surface material may be from gullies (hillslope or alluvial), streambanks, cane drains or deep rills on the hillslope. The term relates to the fallout radionuclide methods used to distinguish between different erosion sources. A more detailed discussion of the results using these methods is given in Section 2.1.3.

Particle size

- Throughout this document various terms are used to describe the particle size of sediment. Not all sediment or particle size fractions present the same risk to the Great Barrier Reef, with fine (<16 µm) sediment moving furthest into the marine environment (Bainbridge et al., 2012).
- The particle size characteristics of rivers are highly variable in both time and space (Walling and Moorehead, 1989). A stream's dissolved load is generally the material that is transported in solution and is <0.02 µm. It is driven by the chemical weathering of rocks and can include sea salts dissolved in rainwater and organic acids from vegetation (Gordon et al., 1992). Suspended sediment (sometimes referred to as 'wash load'), is primarily the product of erosion and comprises clays, silts and fine sands. In many rivers, ~95% of the suspended sediment is <63 µm which is the clay and silt component (Walling et al., 2000); however, this can vary considerably with discharge and soil type. 'Bed load' is the material that moves along the bed but can be transported in suspension, depending on flow conditions.
- Amos et al. (2004) determined that for a large event on the lower Burdekin River the sediment moving during a flood event as suspended material included clay; very fine, fine and medium silt; and some medium and coarse sand. In a more recent study Bainbridge et al. (2014) found that >70% of the suspended sediment collected at the end of the major sub-catchments in the Burdekin was <16 µm, acknowledging that sand-sized fractions may have been under-represented using their approach. Packett et al. (2009) found that for 10 flood events in the Fitzroy, 90% of samples had particle sizes <14 µm, and Turner et al. (2013) found that all event samples collected comprised 90% silt and clay (i.e. <63 µm).
- Between the last freshwater gauge and the coastal zone, most of the sand-sized sediment is deposited and only the very fine clay and silt fractions (<16 µm) are transported more than 3 km offshore (Bainbridge et al., 2012; Webster and Ford, 2010).
- Based on the above data, as well as the soil property data used to model soil erosion, the catchment models conceptually estimate the particle size of their fine or TSS load to be <20 µm (Waters et al., 2014). All discussions relating to modelled sediment loads in this document represent TSS. Coarse or bed load fractions are not included in the end-of-catchment load estimates.
- Sediment tracing studies generally focus on the <10 µm material.



Soil particle size classification	Size (µm)	Sedimentology particle size classification (Udden-Wentworth scale)	Size (µm)
Colloids	0.02-0.2	Colloids	0.02-0.2
Clay	0.2-2	Clay	0.2-4
Silt	2-20	v. fine silt	4-8
		fine silt	8-16
Fine sand	20-200	medium silt	16-31
		coarse silt	31-63
		v. fine sand	63-125
		fine sand	125-250
Coarse sand	200-2000	medium sand	250-500
		coarse sand	500-1000
		v. coarse sand	1000-2000

Figure 4: Description of the size grades of particles based on soil science (The National Committee on Soil and Terrain, 2009) and sedimentology (Leeder, 1982). The transport mechanism and associated particle size are shown in the right-hand side. Modelled TSS load refers to the Source Catchments model**.**

Table 2: A description of the various formats and units used to represent the modelled pollutant loads.

Term	Units	Description	Comments	Application
Total load	Tonnes (t) or kilograms (kg)	The 2015 modelling uses the 2012-2013 baseline land use and management layer. The total load is equal to the sum of the pre-development + anthropogenic load (see below).	Total loads, in some cases, can be compared with monitoring data where monitoring sites are co-located with a management unit boundary (noting that different flow periods may be represented). Modelled data represent delivery to the coast, so dam trapping has been taken into consideration.	Total load is most useful for estimating the total delivery of material to the marine system. Using this metric, the large basins (Burdekin and Fitzroy) will generally always dominate due to their large run-off. This metric is most useful for linking with marine impact and risk. Total load is the baseline run used in the eReefs model.
Total specific load	t/km^2 or t/ha	This is the 2012-2013 baseline modelling run divided by basin or catchment area.	As above	Specific load is most useful when looking for hotspot areas in the catchment. Specific load will highlight high delivery from small areas.
Pre-development load	Tonnes (t) or t/km^2	The pre-development land use scenario is based on estimates of pre-development vegetation cover. The pre-development run retains all water storages, weirs and water extractions as represented in the post-development model. There is no change from the baseline scenario hydrology (McCloskey et al., 2017a). Therefore, where dams exist, the model is likely to underestimate pre-development loads.	The logic of using pre-development conditions is to isolate where there has been a significant change in loads due to agricultural development only. To achieve this, hydrology or run-off remained the same as the baseline scenario. The only variables adjusted in the pre-development scenario runs are ground cover (increased to 95%), riparian cover (set to 100%) and gully erosion (reduced by 90%).	These data are not generally presented on their own. These data are used to represent the pre-development run in the eReefs model.
Total anthropogenic load	Tonnes (t) or t/km^2	This is the 2012-2013 baseline modelling run minus the pre-development load.	This is the total load minus the pre-development load. These data cannot be compared directly with monitoring data as they represent the anthropogenic load only.	Areas with a higher anthropogenic load would, in theory, have a greater load reduction potential compared to areas with high natural, or pre-development, loads.

2. Sources of pollutants—an update of research from 2013 to 2016

2.1 Sediments

2.1.1 Where are the sediments coming from?

Determining the dominant source and delivery of pollutants in a basin requires a combination of techniques including catchment modelling, direct flux monitoring, geochemical tracing and sediment dating. This section provides an update on the recent findings using each of these approaches.

A summary of the Great Barrier Reef measured run-off and TSS loads based on monitoring data is presented in Table 3 and Table 4, respectively. Out of the 32 sites monitored, 29 have between three and nine years of data. Three sites (Haughton River at Powerline, Mary River at Home Park and Tinana Creek at Barrage Head) have only two years of data; however, they were included to provide a complete set of end-of-system monitoring sites. There is a reasonably strong relationship between sediment loads (t) and run-off (ML) for all monitored sites ($r^2 = 0.73$) (data not shown). This suggests that while land cover and condition have an important influence on erosion, rainfall and run-off have a strong and important influence on total sediment loads delivered to the Great Barrier Reef. Based on the end-of-sub-catchment specific loads (t/km^2/yr), the **monitoring** results from the top quartile ($n = 8$) of sites contribute 64% of the sediment load (Table 4).

Based on the 2015 Source Catchments modelling, the TSS load estimated to be delivered to the Great Barrier Reef lagoon for the 1986–2014 modelling period is ~9900 kt, of which ~80%, or ~7900 kt, is considered to be due to land-use change (Table 5). The delivery of sediment is not uniform across the catchments but varies across the different regions, basins and management units in the Great Barrier Reef (Table 5; Figure 5). The models predict that there has been a 3–8-fold increase in TSS across the Great Barrier Reef depending on the region. The Burdekin region delivers more than double the TSS load of any other region. The Wet Tropics, Fitzroy and Burnett Mary basins deliver similar total suspended sediment amounts; however, the Wet Tropics Basin has the highest per unit area delivery (t/km^2/yr). Based on the specific loads (t/km^2/yr), the **modelling** results from the top quartile ($n = 12$) of management units contribute 60–64% of the TSS load (Table 5).

There is a reasonable degree of consistency between modelling and monitoring in terms of identifying the management units with higher specific loads (t/km^2/yr), despite the different time frames between modelling (28 years) and monitoring (typically 3–9 years) data. While monitoring and modelling of catchment loads provide multiple lines of evidence, some of the catchment model parameters are adjusted to align with monitored loads.

Table 3: *Gauged flow data* used to generate average loads for each of the 32 sites in the Great Barrier Reef basins. Data managed and supplied by Queensland Government (Garzon-Garcia et al., 2015; Joo et al., 2011; Turner et al., 2013; Turner et al., 2012; Wallace et al., 2015; Wallace et al., 2014).

NRM region	Basin	Basin area (km^2)	% captured by monitoring	Gauging station	River and site name	Monitored catchment area (km^2)	Flow period represented in load calculations	Average annual discharge for the monitored period (ML)	Start of flow gauge record (used up to 2015)	Long-term annual average discharge for the entire gauge record (ML)
Cape York	Normanby	24,408	62	105107A	Normanby River at Kalpowar Crossing	15,030	2006-2015	2,600,000	2005	2,700,000
Wet Tropics	Barron	2,188	89	110001D	Barron River at Myola	1,945	2006-2015	810,000	1957	760,000
				110002A	Barron River at Mareeba	836	2006-2009	380,000	1915	340,000
				110003A	Barron River at Picnic Crossing	228	2006-2009	150,000	1925	140,000
	Johnstone	2,325	41	1120049	North Johnstone River at old Bruce Highway Bridge (Goondi)*	959	2006-2015	2,000,000	1966	1,800,000
				112101B	South Johnstone River at Upstream Central	400	2006-2015	870,000	1974	790,000
	Tully	1,683	86	113006A	Tully River at Euramo	1,450	2006-2015	3,600,000	1972	3,100,000
				113015A	Tully River at Tully Gorge National Park	482	2010-2015	1,000,000	2009	1,000,000
	Herbert	9,844	87	116001F	Hebert River at Ingham	8,581	2006-2015	4,800,000	1915	3,400,000
Burdekin	Haughton	4,051	44	119003A	Haughton River at Powerline	1,773	2013-2015	140,000	1970	390,000
			19	119101A	Barratta Creek at Northcote	753	2009-2015	250,000	1974	160,000
	Burdekin	130,120	99	120001A	Burdekin River at Home Hill	129,939	2006-2015	15,000,000	1973	9,500,000
				120002C	Burdekin River at Sellheim	36,290	2006-2015	6,700,000	1968	4,600,000
				120302B	Cape River at Taemas	16,074	2006-2013	1,400,000	1968	650,000
				120301B	Belyando River at Gregory Development Road	35,411	2006-2013	1,300,000	1976	620,000
				120310A	Suttor River at Bowen Development Road	50,291	2006-2013	740,000	2006	630,000
				120205A	Bowen River at Myuna	7,104	2012-2015	600,000	1960	960,000
Mackay Whitsunday	O'Connell	850	97	1240062	O'Connell River at Caravan Park	825	2007-2009 2013-2015	310,000	1976	720,000
				124001B	O'Connell River at Stafford's Crossing	340	2006-2009	210,000	2005	190,000
	Pioneer	1,572	94	125013A	Pioneer River at Dumbleton Pump Station	1,485	2006-2015	1,200,000	1977	760,000
				125004B	Cattle Creek at Gargett	326	2006-2009	500,000	1967	310,000

NRM region	Basin	Basin area (km²)	% captured by monitoring	Gauging station	River and site name	Monitored catchment area (km²)	Flow period represented in load calculations	Average annual discharge for the monitored period (ML)	Start of flow gauge record (used up to 2015)	Long-term annual average discharge for the entire gauge record (ML)
	Plane	2,539	13	126001A	Sandy Creek at Homebush	325	2009-2015	290,000	1966	170,000
Fitzroy	Fitzroy	142,552	98	1300000	Fitzroy River at Rockhampton	139,159	2006-2015	9,500,000	1964	4,900,000
				130302A	Dawson River at Taroom	15,846	2010-2015	1,300,000	1911	400,000
				130206A	Theresa Creek at Gregory Highway	8,500	2007-2012 2014-2015	480,000	1956	260,000
				130504B	Comet River at Comet Weir	16,450	2007-2015	1,300,000	2002	810,000
Burnett Mary	Burnett^	33,207	99	136014A	Burnett River at Ben Anderson Barrage	32,891	2006-2015	2,100,000	1910	1,400,000
				136106A	Burnett River at Eidsvold	7,117	2007-2013	790,000	1960	170,000
				136094A	Burnett River at Jones Weir Tail Water	21,700	2006-2013	1,600,000	1981	360,000
				136002D	Burnett River at Mt Lawless	29,395	2006-2015	1,900,000	1909	1,000,000
	Mary	9,466	72	138014A	Mary River at Home Park	6,845	2013-2015	830,000	1982	1,500,000
				138008A	Tinana Creek at Barrage Head	1,284	2013-2015	150,000	1970	270,000

* Combination site, North Johnstone River at Tung Oil North 2006-2013 moved downstream to Johnstone River at Old Bruce Highway Bridge (Goondi) 2013-2015; area increase <4% of monitored catchment.

^ No discharge occurred in the Burnett River between 2006 and 2009.

Table 4: Average annual monitored total suspended sediment (TSS) loads for each of the 32 sites in the Great Barrier Reef basins. (Garzon-Garcia et al., 2015; Joo et al., 2011; Turner et al., 2013; Turner et al., 2012; Wallace et al., 2016; Wallace et al., 2015; Wallace et al., 2014). The datasets were measured during events over three–nine years; sites with an * are based on two years only. Catchments highlighted in blue are in the top quartile (n = 8) for measured specific TSS delivery (t/km^2/y). Standard deviation (SD) in brackets.

NRM region	Basin	Gauging station	River and site name	Years of data	Number of samples	Annual average TSS loads (tonnes) with SD in brackets	Sediment load (t/km^2/y)
Cape York	Normanby	105107A	Normanby River at Kalpowar Crossing	9	264	130,000 (± 75,000)	8.6
Wet Tropics	Barron	110001D	Barron River at Myola	9	590	190,000 (± 120,000)	98
		110002A	Barron River at Mareeba	3	60	39,000 (± 29,000)	47
		110003A	Barron River at Picnic Crossing	3	371	8,300 (± 6,300)	36
	Johnstone	1120049	North Johnstone River at Tung Oil	9	306	170,000 (± 120,000)	177
		112101B	South Johnstone River at Upstream Central Mill	9	492	72,000 (± 53,000)	180
	Tully	113006A	Tully River at Euramo	9	1,491	100,000 (± 60,000)	69
		113015A	Tully River at Tully Gorge National Park	5	311	20,000 (± 20,000)	42
	Herbert	116001F	Herbert River at Ingham	9	420	400,000 (± 460,000)	47
Burdekin	Haughton	119003A	Haughton River at Powerline*	2	37	17,000 (± 16,000)	9.6
		119101A	Barratta Creek at Northcote	6	649	39,000 (± 65,000)	52
	Burdekin	120001A	Burdekin River at Home Hill	9	436	4,870,000 (± 4,010,000)	38
		120002C	Burdekin River at Sellheim	9	171	4,340,000 (± 4,230,000)	120
		120302B	Cape River at Taemas	7	367	350,000 (± 240,000)	22
		120301B	Belyando River at Gregory Development Road	7	452	160,000 (± 120,000)	4.5
		120310A	Suttor River at Bowen Development Road	7	182	120,000 (± 60,000)	2.4
		120205A	Bowen River at Myuna	3	112	990,000 (± 950,000)	139
Mackay Whitsunday	O’Connell	1240062	O’Connell River at Caravan Park	4	86	80,000 (± 70,000)	97
		124001B	O’Connell River at Stafford’s Crossing	3	55	37,000 (± 12,000)	109
	Pioneer	125013A	Pioneer River at Dumbleton Pump Station	9	657	230,000 (± 230,000)	155
		125004B	Cattle Creek at Gargett	3	39	130,000 (± 83,000)	399
	Plane	126001A	Sandy Creek at Homebush	6	262	27,000 (± 20,000)	83
Fitzroy	Fitzroy	1300000	Fitzroy River at Rockhampton	9	338	2,300,000 (± 2,300,000)	17

NRM region	Basin	Gauging station	River and site name	Years of data	Number of samples	Annual average TSS loads (tonnes) with SD in brackets	Sediment load (t/km^2/y)
		130206A	Theresa Creek at Gregory Highway	6	75	340,000 (± 400,000)	40
		130504B	Comet River at Comet Weir	6	104	770,000 (± 500,000)	47
		130302A	Dawson River at Taroom	4	109	300,000 (± 410,000)	19
Burnett Mary	Burnett	136014A	Burnett River at Ben Anderson Barrage HW	9	457	729,000 (± 1,320,000)	22
		136002D	Burnett River at Mt Lawless	6	396	660,000 (± 1,200,000)	23
		136094A	Burnett River at Jones Weir Tail Water	6	297	340,000 (± 580,000)	16
		136106A	Burnett River at Eidsvold	5	220	73,000 (± 130,000)	10
	Mary	138014A	Mary River at Home Park*	2	176	160,000 (± 190,000)	23
		138008A	Tinana Creek at Barrage Head*	2	146	4,000 (± 200)	3.1

Table 5*: Modelled* end-of-basin annual average total suspended sediment (TSS) loads for each of the 35 Great Barrier Reef basins including the 14 sub-catchments in the Burdekin and Fitzroy basins (in grey text). The modelling represents an annual average based on the 1986-2014 flow period. Note that the * and ** highlight that the sub-catchment totals for the Burdekin and Fitzroy are within 3% and 1% of the basin loads. The data in this table are Queensland Government modelling outputs. The data were rounded to the nearest 10. Catchments highlighted in red are in the top quartile (n = 12) for anthropogenic total load (kt/yr) of TSS. Catchments highlighted in pink are in the top quartile (n = 12) for anthropogenic specific load of TSS (t/km^2/yr).

Region	Basin #	Basin/Catchment name	Basin area (km^2)	Total TSS load exported to the coast (kt/yr)	Total specific load exported to the coast (t/km^2/yr)	Anthropogenic TSS export to the coast (kt/yr)	Total specific Anthropogenic TSS export to the coast (t/km^2/yr)
Cape York	101	Jacky Jacky	2,990	50	20	40	10
	102	Olive Pascoe	4,172	70	20	50	10
	103	Lockhart	2,873	70	20	50	20
	104	Stewart	2,770	50	20	40	10
	105	Normanby	24,380	190	10	150	10
	106	Jeannie	3,637	40	10	30	10
	107	Endeavour	2,186	60	30	30	10
		REGIONAL TOTAL	**43,008**	530		400	
Wet Tropics	108	Daintree	2,105	100	50	30	10
	109	Mossman	477	20	40	10	10
	110	Barron	2,188	60	30	30	10
	111	Mulgrave-Russell	1,975	250	130	160	80
	112	Johnstone	2,317	380	160	260	110
	113	Tully	1,668	160	90	80	50
	114	Murray	1,125	70	70	40	30
	116	Herbert	9,852	480	50	330	30
		REGIONAL TOTAL	**21,707**	1,520		940	
Burdekin		Upper Burdekin	40,413	950	20	830	20
		Cape Campaspe	20,255	40	0	40	0
		Belyando	35,352	60	0	50	0
		Suttor	18,577	90	5	80	0
		Bowen Bogie	11,718	1,660	140	1,400	120
		East Burdekin	3,299	290	90	240	70
		Subtotal (Burdekin)*	**130,120**	3,090		2640	
	120	Burdekin	130,120	3,260	30	2,790	20
	117	Black	1,057	60	60	30	30
	118	Ross	1,707	60	40	50	30
	119	Haughton (Lower Burdekin)	4,051	180	50	160	40
	121	Don	3,736	210	60	180	50
		REGIONAL TOTAL	**140,671**	3,780		3,210	
	122	Proserpine	2,513	130	50	80	30

Region	Basin #	Basin/Catchment name	Basin area (km²)	Total TSS load exported to the coast (kt/yr)	Total specific load exported to the coast (t/km²/yr)	Anthropogenic TSS export to the coast (kt/yr)	Total specific Anthropogenic TSS export to the coast (t/km²/yr)
Mackay Whitsunday	124	O'Connell	2,305	310	140	240	100
	125	Pioneer	1,664	230	140	170	100
	126	Plane	2,547	150	60	100	40
		REGIONAL TOTAL	**9,029**	820		590	
Fitzroy		Comet	17,290	70	<5	60	<5
		Dawson	50,734	340	10	300	10
		Isaac	22,226	170	10	140	10
		Mackenzie	13,128	190	10	160	10
		Nogoa	19,196	20	<5	20	<5
		Theresa Creek	8,473	40	<5	30	<5
		Fitzroy River – lower	11,339	690	60	620	50
		Subtotal (Fitzroy)**	**142,387**	1,510		1,330	
	130	Fitzroy	142,144	1,510	10	1,330	10
	127	Styx	2,997	100	30	100	30
	128	Shoalwater	3,614	70	20	60	20
	129	Water Park	1,846	60	40	60	30
	132	Calliope	2,416	60	20	50	20
	133	Boyne	2,498	20	10	20	10
		REGIONAL TOTAL	**155,515**	1,820		1,610	
Burnett Mary	134	Baffle	4,101	80	20	50	10
	135	Kolan	2,891	40	10	30	10
	136	Burnett	33,274	550	20	430	10
	137	Burrum	3,346	30	10	20	10
	138	Mary	9,420	770	80	670	70
		REGIONAL TOTAL	**53,031**	1,460		1,190	
		TOTAL Great Barrier Reef	***422,961***	**9,930**		**7,940**	

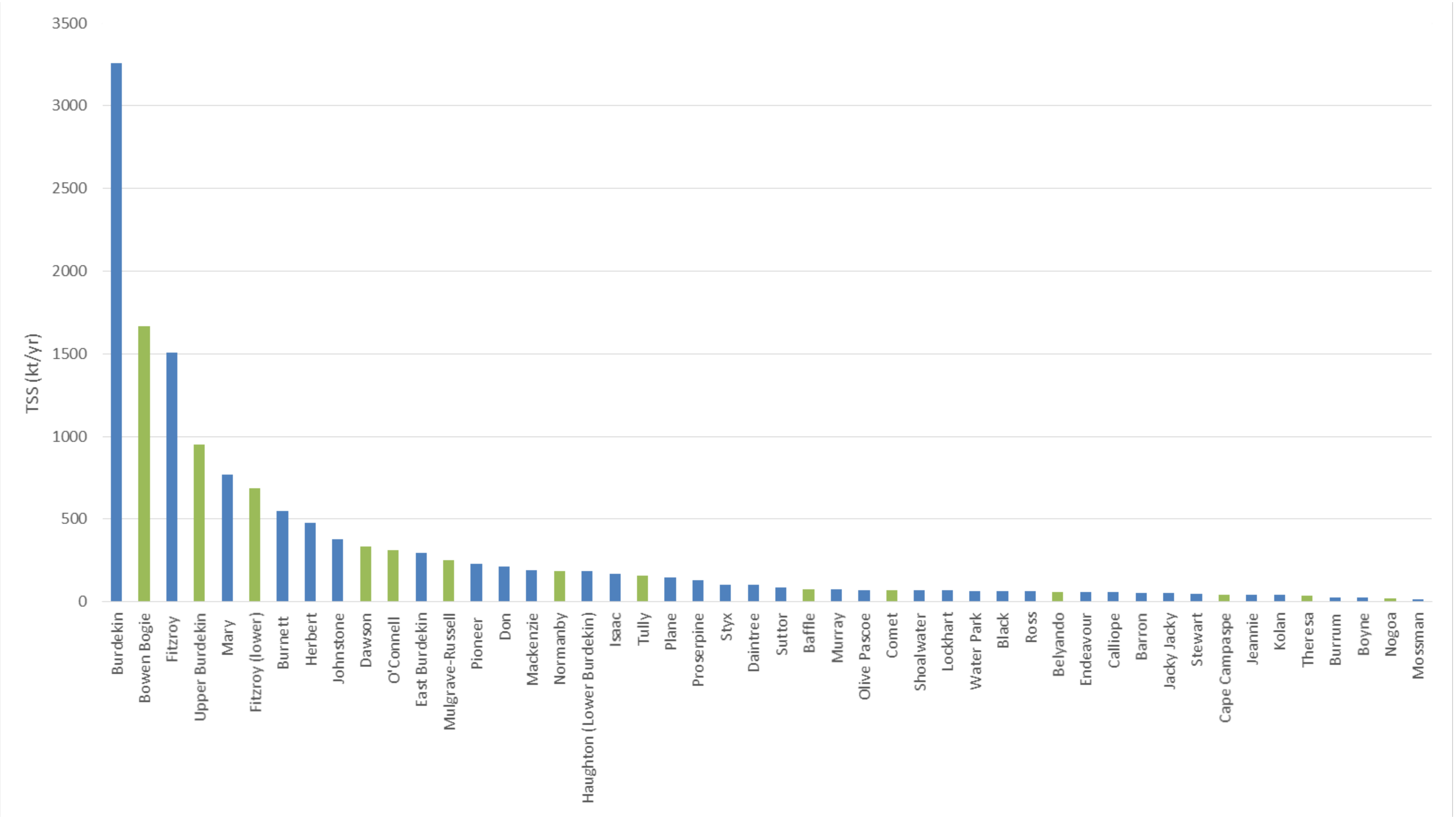

3500
3000
2500
2000
1500
1000
500
0
TSS (kt/yr)
Burdekin
Bowen Bogie
Fitzroy
Upper Burdekin
Mary
Fitzroy (lower)
Burnett
Herbert
Johnstone
Dawson
O'Connell
East Burdekin
Mulgrave-Russell
Pioneer
Don
Mackenzie
Normanby
Haughton (Lower Burdekin)
Isaac
Tully
Plane
Proserpine
Styx
Daintree
Suttor
Baffle
Murray
Olive Pascoe
Comet
Shoalwater
Lockhart
Water Park
Black
Ross
Belyando
Endeavour
Calliope
Barron
Jacky Jacky
Stewart
Cape Campaspe
Jeannie
Kolan
Theresa
Burrum
Boyne
Nogoa
Mossman

Figure 5: Ranking of the *modelled* end-of-basin annual average total suspended (fine) sediment (TSS) delivery (kt/yr) for each of the 35 Great Barrier Reef basins (in blue) plus the additional 14 sub-catchments in the Burdekin and Fitzroy (in green). The modelling represents an annual average based on the 1986-2014 flow period.

2.1.2 How does the source of sediments vary over time and space?

Bainbridge et al. (2012) determined that it is only the fine (<16 µm) and organic-rich suspended sediment that is transported long distances in riverine flood plumes, with coarser fractions being deposited closer to the river mouth. This fine material also influences water clarity on the inshore and mid-shelf of the Great Barrier Reef (Lewis et al., 2015a; Lewis et al., 2015b; Lewis et al., 2014a). Recent research using paired optical and radiocarbon dating on sediment cores from key depositional areas off the Burdekin River showed that most fine sediment is held within 20 km of the river mouth and is not transported as far offshore as previously thought (Lewis et al., 2014a). This finding has been subsequently supported by 3D modelling of river discharges, sediment transport and deposition (Delandmeter et al., 2015). A re-examination of sediment budgets from the Fitzroy River and adjacent Keppel Bay (Brooke et al., 2006) also indicate that the majority of sediment delivered from the Fitzroy River is largely retained near the river mouth (Lewis et al., 2015b).

Identifying the source of the excess fine sediment requires new and innovative approaches that evaluate how sediment sources have changed over time and space. Terrestrial cosmogenic nuclides are increasingly being used in other parts of the world to quantify the contribution of human activity against the natural variability of landscape sediment yields (e.g. Hewawasam et al., 2003) and have recently been applied in the Barron (Nichols et al., 2014) and Burdekin Basin (Croke et al., 2015). In the Burdekin Basin the data were also used to benchmark short-term (~5 year) measurements of contemporary sediment yield against the natural geological erosion rates (~100 to >10,000 years) (Bartley et al., 2015a). In the Barron catchment study, the data indicate that the pre-European or long-term sediment yields (43 t/km^2/y) are similar to the current or contemporary rates (45 t/km^2/y). In the Burdekin catchment, however, two of the five major sub-catchments in the Burdekin (Bowen and Upper Burdekin) were found to have accelerated erosion rates 7.5 and 3.6 times the long-term natural geological erosion rates (Bartley et al., 2015a).

Techniques to identify the spatial sources of sediment have been applied in the Burdekin, Fitzroy and Normanby catchments. In the Burdekin Basin, monitoring of the TSS export from the five main sub-catchments (Upper Burdekin, Cape, Belyando, Suttor and Bowen), the Burdekin Falls Dam overflow and end of basin (Clare gauge) suggests that the Upper Burdekin, Bowen and Lower Burdekin/Bogie sub-catchments dominate the TSS load and deliver ~27%, 45% and 26% of the annual fine (<63 µm) sediment load over a five-year study period (Bainbridge et al., 2014). The same sub-catchments are also the dominant source of the clay and fine silt <16 µm sediment fraction based on sediment geochemistry (Furuichi et al., 2016) and clay mineralogy (Bainbridge et al., 2016). The clay mineral tracing data suggest that the expandable clay group sourced to basaltic terrains travels furthest in the marine environment (Bainbridge et al., 2016; Douglas et al., 2006b; McCulloch et al., 2003b). The clay data suggest that the expandable clays group becomes further enriched in the sediments further offshore, although it is unclear which geological source (and sub-catchment) has produced these clays (Bainbridge et al., 2016). A similar finding has been observed in the Fitzroy Basin where it was found that smectite clays (part of the expandable group) were preferentially transported in the Great Barrier Reef (Douglas et al., 2006b). Smectite clays are commonly abundant as a weathering process of basaltic rocks. The science on the preferential transport of clay minerals in the marine environment is currently unresolved and complicated in field settings. For example, laboratory-based studies which can isolate different processes show that the relatively higher cation exchange capacity of smectite clays should result in them settling out preferentially compared to most other clay minerals (Hillier, 1995). However, other properties of smectites such as a finer particle size and a lower charge density ratio are favourable for them to travel further in the marine environment (Hillier, 1995). Other biological factors including terrestrial organic matter and plume-related production also appear to play a key role in sediment aggradation/flocculation. Hence in a field setting where all these processes are occurring it is difficult to determine the dominant process that drives the transport of sediments in the marine environment. Further work is required to classify the clay components within the expandables group (i.e. pure smectite, montmorillonite, mixed/interstratified layer/mineralogy clays, etc.) as these can have vastly different properties which strongly influence dispersion and flocculation (see Shaw, 1995). Furuichi et al. (2016) found an additional contribution of fine sediment from the Belyando sub-catchment during the 2012 water year, which is currently the focus of further geochemical investigation. The estimates made in the Burdekin account for the dam trapping influence of the Burdekin Falls Dam, which was determined to be between 50% and 85% of fine sediment delivered annually to the dam (Cooper et al., 2016; Lewis et al., 2013). Overall, it is estimated that the Burdekin Dam has reduced the TSS load from the Burdekin River by ~35% compared to pre-dam conditions (Lewis et al., 2009).

In the northern Great Barrier Reef catchment area draining to Princess Charlotte Bay, Brooks et al. (2013) used sediment geochemistry to show that the sediments deposited in the bay are dominated by three components: marine-derived carbonates, quartz silt/sand and terrestrially derived silt-clays. The terrestrially derived silt-clays constitute about 46% of the sediments in the bay. A geochemical mixing model incorporating all of the major terrestrial sources indicates that the terrestrial component is dominated (81 ± 1%) by sediment derived from the coastal plain and the Bizant River. From the data presented they concluded that erosion of the coastal plain is the dominant source of terrestrial sediments deposited in the bay over long (geological) timescales. This largely reflects tidal sources. However, Brooks et al. (2013) noted that these percentages do not necessarily represent the relative proportion or variability of sediment sources transported in flood plumes delivering sediment to the reefs surrounding Princess Charlotte Bay. Analysis of the terrestrial contributions from flood plumes over the 2011-2012 and 2012-2013 wet season is ongoing but suggests the source of sediment is from the upper catchment. More research is required to unravel the interaction between sediment delivered to the nearshore zone in Princess Charlotte Bay by tidal currents and sediment delivered to reefs in flood plumes.

Most of the sediment source tracing in the Fitzroy Basin has been captured in previous consensus statements; however, a recent review of the evidence from the Fitzroy Basin (Lewis et al., 2015a) revealed conflicting contributing sources between geochemical tracing results (Douglas et al., 2006a; Douglas et al., 2006b; Douglas et al., 2008; Smith et al., 2008), catchment monitoring (Packett et al., 2009) and modelling data (Dougall et al., 2014). The Fitzroy Basin is particularly challenging to assess due to the large catchment area, relatively flat terrain and large number of weirs and dams in the catchment. There are estimated to be ~57 unregulated and 39 regulated impoundments in the Fitzroy (Sinclair Knight Mertz, 2012) that can interrupt sediment erosion and delivery pathways. The 2015 modelling data indicates a smaller load from the Fitzroy Basin and less sediment delivery from management units further upstream within the basin relative to previous analyses. This is a result of accounting for these impoundments more thoroughly than in previous modelling. The latest available data suggest the average ‘current’ suspended sediment load exported from the Fitzroy River is between 1.5 and 2.0 million tonnes per year (Lewis et al., 2015b). Consistent with earlier geochemical tracing results (Douglas et al., 2008), recent studies have identified that the dominant source of the fine sediment and nutrients are the cropping areas on basalt lithology. In contrast, catchment modelling continues to identify grazing land as the largest sediment source in the Fitzroy region (Table 9). Broadscale cropping occurs on large areas in the Theresa Creek, Nogoa and Comet management units and to a lesser degree (based on area contribution) in the Callide and Dawson sub-catchments. Cropping also occurs on the floodplains of most streams in the Fitzroy where black soil alluvium is found (Lewis et al., 2015b). The Connors management unit also contributes a high number of large floods on a long-term annual average basis, and maintaining and improving ground cover should be a priority for this area (Lewis et al., 2015b).

Understanding how rivers have adjusted to variations in past climate and associated sediment supply is critical for understanding and predicting how these systems may respond to future changes in climate and rainfall. Alluvial terraces provide information on how catchments have adjusted over time. Hughes et al. (2015) described the spatial preservation of terraces in five catchments in the Wet Tropics. Leonard and Nott (2015a) used optically stimulated luminescence chronologies combined with a detailed sedimentary analysis to determine that floodplain stripping is a major, and relatively unrecognised, source of sediment on the Daintree River. Rates of floodplain accretion are far greater than has been previously estimated, and much higher volumes of sediment are being redistributed within the catchment than previously considered. Similar sediment dating studies on the Normanby (Pietsch et al., 2015) and Fitzroy Rivers (Hughes et al., 2009a; Hughes et al., 2009b; Hughes et al., 2009c) have determined that within stream sediment, storage of fine sediment can be considerable (up to 55% by volume of bench material) in some areas. Pietsch et al. (2015) also demonstrated that in-channel storage of fine sediment within benches can exceed deposition on floodplains, with sediment residence time typically greater than a century. The Source Catchments model can account for fine sediment storage within channels, and this functionality is represented in a number of regional models where relevant data were available to constrain the model (e.g. Fitzroy). As new research data become available across the Great Barrier Reef, models will be updated and refined to provide more reliable long-term estimates of fine sediment deposition and re-entrainment.

Recent studies using annual luminescent lines derived from mid-shelf coral cores were used to reconstruct the Burdekin River flow from 1648 to 2011 (see Figure 5; Lough et al., 2015). The reconstruction showed a shift to higher flows and increased run-off variability in the latter half of the 19th century. This change occurred from around 1860, which also coincided with early European settlement in the region. A change in climate, as well as changes to land use, may therefore be responsible for the increase in sediment yields delivered to coral reefs (McCulloch et al., 2003a). Recent work by Lewis et al. (in review) shows a stronger correlation with freshwater discharge than sediment load, which suggests that the Ba/Ca (Barium/Calcium) ratios in coral cores that were used to provide evidence of an increase in sediment due to land use may in fact be partially due to changes in climate and run-off. A number of studies were undertaken in Queensland following catastrophic flooding in 2011 and 2013 that also highlighted that much of the sediment erosion, and delivery, occurs during large events (Simon, 2014; Thompson and Croke, 2013).

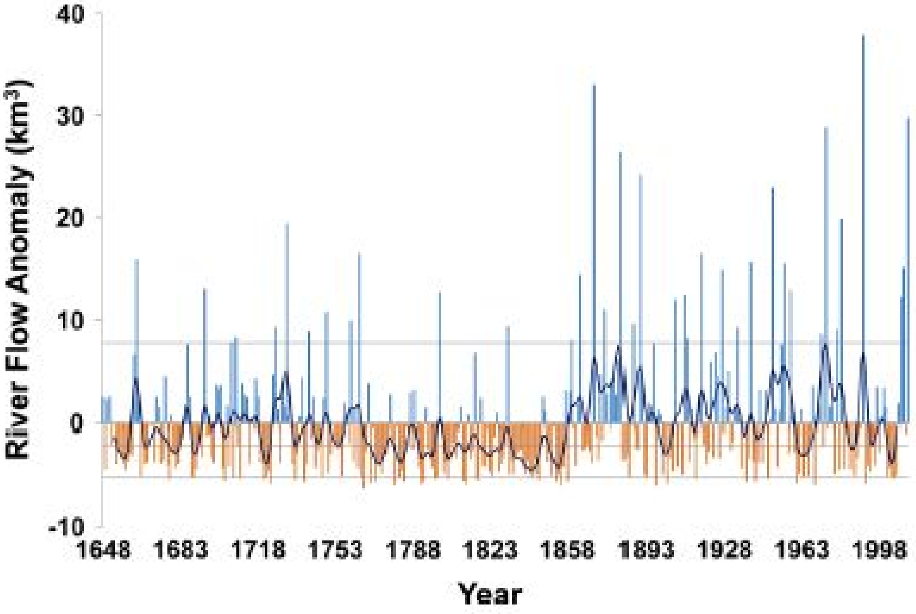


Figure 6: Reconstructed Burdekin River flow as anomalies from 1648 to 2011 average. Dark blue line is 10-year Gaussian filter. Horizontal grey lines are 90th percentile, median and 10th percentile relative to whole record length (Reproduced with permission from Lough et al., 2015).

2.1.3 What processes are responsible for the excess sediment?

Following the identification of the major geographic sources of sediment, it is important to determine which erosion process is responsible for the sediment loss so that appropriate restoration strategies can be implemented. In the simplest terms, sediment can be eroded from hillslopes or paddocks, which is known as surface erosion. Sediment can also be eroded from deep rills, gullies or riverbanks, which, when combined, is considered as sub-surface erosion. Following the erosion of sediment, there are numerous opportunities for sediment to be deposited within the catchment before a small proportion of the eroded material is delivered to the marine system. Contributions from wind erosion have not been considered here.

Sheetwash or hillslope erosion generally dominates sediment budgets in cultivated areas (Hughes et al., 2009b). Visser et al. (2007) measured sediment loss within a sugarcane floodplain setting and demonstrated that plant cane and water furrows are a sediment source, while water headlands and minor cane drains generally act as a sediment sink or trap. Sediment loss from cultivated floodplains can be between 2 and 5 t/ha/yr (Visser et al., 2007). Although hillslope erosion can dominate fine sediment loads in rangeland areas during drought years when ground cover is low (Bartley et al., 2014b; Bartley et al., 2006; Karfs et al., 2009; Roth, 2004; Silburn et al., 2011), sub-surface erosion dominates sediment yields in the longer term (see below). Hillslope erosion rates, and contributions to end-of-catchment sediment flux, have been demonstrated to be low in the Normanby catchment (Brooks et al., 2014a; Brooks et al., 2014b). The addition of gully mapping data (Brooks et al., 2014a) for the Normanby catchment into the catchment models indicates that gully and streambank erosion contribute over 80% of the total sediment export from the Normanby Basin.

Fallout radionuclides (^{137}Cs and ^{210}Pb$_{ex}$) have been widely used to determine the relative contributions of surface and sub-surface erosion (Table 6). Fallout radionuclides are concentrated in the surface soil, therefore sediments derived from sheet and rill erosion will have high concentrations of nuclides. Sediment eroded from gullies or riverbanks have little or no fallout nuclides present. By measuring the concentration in suspended sediments moving down the river, and comparing them with concentrations in sediments produced by the different erosion processes, the erosion process generating the sediment can be determined.

In a study by Hughes et al. (2009b) in a headwater catchment of the Fitzroy River in the dry tropics of central Queensland, surface soil erosion was found to produce less than 20% of the river sediment in non-cultivated parts of the catchment. Catchment modelling showed good agreement with this study, indicating that surface soil erosion contributes approximately 20% of the total export load from the Fitzroy River (Table 6).

In the wet/dry tropical Herbert River catchment in central Queensland, Bartley et al. (2004) used ^{137}Cs to determine that about 50% of the sediment in the lower river originated from surface soils. The Bartley et al. (2004) estimate was not corroborated by Tims et al. (2010), who did a follow-up study in the same catchment using ^{239}Pu. Like ^{137}Cs, ^{239}Pu is a product of atmospheric testing of nuclear weapons, but it can be measured with greater sensitivity. They sampled the Herbert River catchment after a greater than one-in-five-year flood, and their results showed that surface soils were the minor contributor to river sediment everywhere except in some sugarcane cultivation and forested areas. Catchment modelling suggests that surface soil erosion contributes approximately 30% of the total export load from the Herbert Basin (Table 6). Similarly, Wilkinson et al. (2013) showed that subsoils were also the dominant source of the sediments in the Bowen and Upper Burdekin. In a follow-up study Wilkinson et al. (2015a) showed that subsoils were also the dominant source of sediments across the entire Burdekin Basin. Olley et al. (2013) showed that this was also the case for rivers draining into Princess Charlotte Bay on the Northern Cape.

However, traditional tracing techniques generally only discriminate between surface (grassed hillslope) and sub-surface (riverbank, gully wall, deep rill or scald) erosion. A recent tracing study in the Bowen River catchment of the Burdekin Basin addressed this limitation by using additional sediment tracers (^{7}Be) to discriminate between horizontal and vertical surfaces of subsoil. It found that 50% of fine sediment was from vertical surfaces (gully walls and riverbanks), 40% from horizontal surfaces of subsoil (hillslope scalds, rills and gully floors) and 10% from topsoil or grassed hillslopes (Hancock et al., 2014). Interestingly, the proportion of sediment coming from sub-surface erosion in the Upper Burdekin catchment appears to be similar for sites that have had minimal grazing when compared to sites that have been severely overgrazed (Wilkinson et al., 2013). This suggests that tracers are useful for identifying the dominant erosion process in a catchment, but on their own they are not necessarily suitable for identifying the influence of land management on those processes. Catchment modelling suggests that approximately three-quarters of the fine sediment exported from the Burdekin Basin was sourced from sub-surface erosion (Table 6).

Based on the most recent 2015 Source Catchments modelling, hillslope erosion dominates sediment sources in the Wet Tropics, Mackay Whitsunday and Cape York (with the exception of the Normanby Basin); however, sub-surface erosion dominates end-of-basin sediment delivery in the Burdekin, Fitzroy and Burnett Mary regions (

Table 7). The ratio of sediment sources based on tracing data (Table 6) is comparable to the modelled estimates (

Table 7) for the Burdekin and Fitzroy. For other areas, there are still large discrepancies between the ratio of sediment sources based on the various datasets. Previous gully mapping in the Great Barrier Reef was based primarily on the National Land and Water Resources Audit (NLWRA) gully erosion mapping (Hughes et al., 2001), which has been found to have large uncertainties (Kuhnert et al., 2007) and under-predicted the amount of gully erosion to varying degrees, especially in grazed catchments. Mapping gully location and extent is a slow and time-consuming process and has only been completed in detail in some areas, such as the Burdekin (Tindall et al., 2014) and Normanby (Brooks et al., 2013) basins. Improved gully mapping is ongoing in a number of regions (Darr, unpublished data), but it will be several years before there are consistent high-resolution gully maps incorporated into each model for all Great Barrier Reef catchments.

Table 6: Summary of erosion process studies using fallout radionuclide tracers (bold) and catchment modelling (in grey text) estimates in the basins and catchments draining into the Great Barrier Reef.

Region	Catchment	Mean surface soil contribution %	Technique/Tracer	Reference
Cape York	**Princess Charlotte Bay rivers (Normanby catchment; pasture, grazing)**	**16 ± 2**	**^{137}Cs and ^{210}Pb$_{ex}$**	**Olley et al. (2013)**
	Normanby catchment	15	Source Catchments modelling	McCloskey et al. (2017b)
Wet Tropics	**Berner Ck (Johnson catchment)**		**^{137}Cs and ^{210}Pb$_{ex}$**	**Wallbrink et al. (2001)**
	Cultivated cropping	**79 ± 14**		
	Non-cultivated	**19 ± 5**		
	Herbert catchment	**52**	**^{137}Cs**	**Bartley et al. (2004)**
	Herbert catchment	**20 ± 2**	**^{239}Pu**	**Tims et al. (2010)**

Region	Catchment	Mean surface soil contribution %	Technique/Tracer	Reference
	Forest	**83 ± 8**		
	Pasture	**12 ± 2**		
	Pasture	**6 ± 1**		
	Sugarcane	**31 ± 3**		
	Sugarcane	**58 ± 6**		
	Herbert catchment	32		McCloskey et al. (2017b)
Burdekin	**Bowen and Upper Burdekin (Pasture, grazing)**	**13 ± 5 to 65 ± 14 (depending on sub-catchment)**	**^{137}Cs, ^{210}Pb$_{ex}$, ^{7}Be**	**Wilkinson et al. (2013),** **Hancock et al. (2014)**
	Burdekin (Pasture, grazing)	**0 ± 1 to 14 ± 1 (depending on sub-catchment)**	**^{137}Cs**	**Wilkinson et al. (2015a)**
	Bowen Bogie	24	Source Catchments modelling	McCloskey et al. (2017b)
	Upper Burdekin	18	Source Catchments modelling	McCloskey et al. (2017b)
	Burdekin River	24	Source Catchments modelling	McCloskey et al. (2017b)
Fitzroy	**Theresa Ck (Fitzroy catchment)**		**^{137}Cs and ^{210}Pb$_{ex}$**	**Hughes et al. (2009c)**
	Cropping	**43-50**		
	Pasture	**12**		
	Theresa Ck	32	Source Catchments modelling	McCloskey et al. (2017b)

Table 7: *Modelled* contribution to end-of-basin total suspended sediment (TSS) export by erosion source (%) based on the 2015 modelling results. Note: Hillslope + gully + streambank = ~100% and surface and sub-surface = ~100%.

Region	*Hillslope (surface) %*	Gully %	Stream bank %	*Gully + streambank (sub-surface) %*
Cape York*	*64*	29	6	*35*
Wet Tropics	*70*	3	27	*30*
Burdekin	*23*	60	16	*76*
Mackay Whitsunday	*68*	2	31	*33*
Fitzroy	*31*	30	38	*68*
Burnett Mary	*27*	11	62	*73*

* For the Normanby Basin, NLWRA gully density data layer was replaced with data derived from gully mapping. Gully TSS contribution for Normanby Basin is 72%.

The Great Barrier Reef catchments contain more than 87,000 km of gully erosion features (Thorburn and Wilkinson, 2013). However, the contributions of gully erosion to fine sediment exports to the Great Barrier Reef lagoon vary between catchments, due to different densities of gully erosion and variable transport connectivity from catchment management units through the river network to the Great Barrier Reef coast (Wilkinson et al., 2015b). Eight of the 4 Great Barrier Reef catchment management units (Bowen Bogie, East Burdekin, Lower Burdekin, Don, Fitzroy, Mackenzie, Normanby and Theresa Creek) together contain 27,000 km of gullies and contribute 54% of all the sediment derived from gully erosion, from just 19% of the total Great Barrier Reef catchment area

(Wilkinson et al., 2015c). The area occupied by gullies is estimated to have increased ~10-fold since European settlement in parts of northern Australia (Shellberg et al., 2010). Erosion rates have been estimated for several alluvial gully complexes in the Normanby (Brooks et al., 2016) and Mitchell catchments (Shellberg et al., 2016), showing that head-cut retreat can be upwards of tens of metres per year in some areas. Significant amounts of sediment have also been shown to be coming from the overburden piles and tailings dams that are the legacy of tin mining in the Upper Herbert catchment (Little, 2014).

Stream bank erosion, or river channel change, is the least understood of the major erosion processes contributing sediment to the Great Barrier Reef. Using the Shuttle Radar Terrain Mission–derived digital elevation model, it is estimated that there are ~300,000 km of major and minor stream lines draining to the Great Barrier Reef (Bartley et al., 2016a). The channel types, and associated erosion processes, vary enormously. A review of streambank erosion and channel change in the Great Barrier Reef catchments by Bartley (2016b) suggests that rates can vary from 0.01 m to 5 m/yr depending on the size of the catchment, the method used to estimate change and the time period of the study. High erosion rates (~5 m/yr) generally occur following major flood events such as on the Burnett River in 2011 (Simon, 2014) and Lockyer catchment (Thompson et al., 2013). Outside of these major events, channel erosion in the Great Barrier Reef catchments is relatively low by world standards (0.01–0.1 m/yr) (Bainbridge, 2004; Hooke, 1980).

Brooks et al. (2014b) suggested that bank erosion was a key erosion process in most Queensland rivers; however, Leonard and Nott (2015b) used historical maps and geomorphological techniques and suggested that while bank erosion may look like a major source of sediment, there is little evidence for excessive bank erosion in some areas (e.g. the Mulgrave River). Hence, bank erosion is likely to be a significant sediment source in some, but not all, catchments. Identifying where there has been an increase in bank erosion is important for helping prioritise remediation investment, and areas without riparian vegetation should be a priority. Bartley et al. (2015b) identified the dominant controls of bank erosion as stream power, riparian vegetation, bank material and channel confinement. The Source Catchments streambank erosion model incorporates all of these variables.

Based on a study of three Queensland rivers (Brisbane, O'Connell and Normanby), Brooks et al. (2014c) concluded that there was a poor relationship between bank erosion and both stream power and bend curvature, and that in-channel deposition (of coarse bed load) is a better predictor of bank erosion. This suggests that the current bank erosion rule used within the Source Catchments modelling may not accurately reflect bank erosion rates for some stream types (e.g. the anastomosing stream types found in the Fitzroy as studied by Amos et al., 2008). Brooks et al. (2014c) also showed that having >30% woody vegetation within the channel zone can reduce erosion rates by an order of magnitude. The key gap in our understanding is knowledge of the best place for returning riparian vegetation in the landscape. A review of the literature from other parts of the world suggests that the timescales and magnitude of water quality effectiveness following the revegetation of riparian zones can vary significantly and may take many decades (Bartley et al., 2015b).

2.1.4 What are the drivers and land uses delivering the anthropogenic sediment loss?

After identifying the major geographical sources of sediment, and the erosion process contributing that sediment, it is useful to identify the causes or drivers of the erosion. Factors such as geology and soil type, landscape gradient and climate are all important drivers of erosion. These factors are, however, generally not considered to be within our immediate control. The main contemporary factors that govern sediment erosion that are within our control are land use and land condition. Importantly, however, it is largely the landscape and climatic factors that govern sediment delivery.

Modelling estimates that the land uses that deliver most of the sediment to the Great Barrier Reef are grazing in the Burdekin, Fitzroy and Burnett Mary regions; sugarcane in the Wet Tropics and Mackay Whitsunday regions; and nature conservation areas on Cape York region (Figure 7; Table 8). For the Cape York region, most of the nature conservation areas were grazed historically and still carry large numbers of feral cattle.

Event mean concentration data derived from water quality measurements taken in the Great Barrier Reef catchments as well as other parts of Australia suggest that the highest median TSS concentrations are generally from mining (~50,000 mg/L), horticulture (~3000 mg/L), dryland cropping (~2000 mg/L), cotton (~600 mg/L) and grazing on native pastures (~300 mg/L) (Bartley et al., 2012). It is important to point out that these are median values, and concentrations can vary considerably at any given location. For example, TSS concentrations measured in the Bowen catchment are commonly greater than 5000 mg/L, and this is dominated by grazing on native pastures (Wilkinson et al., 2013). A study of erosion from unsealed roads in Cape York (Gleeson, 2012) indicated that the average event mean concentration from unsealed roads was around 1800 mg/L, and that unsealed roads and other linear disturbance features were the largest intensive land use in the Cape (Spencer et al., 2016), being double the area of all other intensive land uses combined.

Based on a six-year study in the Johnstone catchment, Hunter and Walton (2008) also found that for a given mean annual precipitation, specific fluxes of TSS from beef pastures, dairy pastures and unsewered residential areas were similar to those from rainforest, while fluxes from areas of sugarcane and bananas were 3–4 times higher. However, because grazing occupies most of the Great Barrier Reef catchment areas (~75%) it dominates sediment delivery to the Great Barrier Reef (McCloskey et al., 2017b). Sediment concentrations from alluvial gully erosion, which is a key sediment source in grazing land, have been measured in the range of 10,000–100,000 mg/L (Shellberg et al., 2013).

The influence of trees vs. pasture in terms of run-off and sediment loss from catchments and paddocks

It is well established that ground cover and soil surface condition play a significant role in controlling the rates of run-off (e.g. Connolly et al., 1997; McIvor et al*.,* 1995a; McIvor et al., 1995b; Pressland et al., 1991) and sediment loss (Bartley et al., 2006; McIvor, 2001; McIvor et al., 1995a; Pressland et al., 1991; Roth, 2004; Silburn et al., 2011) in savanna landscapes. Soil loss from grazed hillslopes increases as vegetation cover decreases, with the rate decreasing sharply as cover increases beyond 40% (Bartley et al., 2010; McIvor et al., 1995a; Scanlan et al., 1996). Ground cover can be very patchy in savanna landscapes (Ludwig et al., 2007) and this results in large variability in sediment yields even for hillslopes under the same management regime (Bartley et al., 2006). Patchy vegetation on erodible soils within riparian zones can also lead to the initiation of alluvial gullies and scald features (Shellberg et al., 2010). Adequate ground cover, on both hillslopes and riparian zones, needs to be maintained to reduce the potential for gully formation (Wilkinson et al., 2014a). A review of the role of ground cover in reducing run-off and erosion is provided in Bartley et al. (2014a).

The effect of tree clearing on rangeland ecosystem structure and the resultant changes in water and sediment yield have not been well studied in Australia; however, studies in semi-arid rangeland areas in Queensland suggest that converting (Brigalow) forest to pasture can increase run-off by ~80% at sub-catchment scales (Thornton et al., 2007) and ~40% for river basin scales (Siriwardena et al., 2006). Essentially, clearing of forest can result in a doubling of run-off (Cowie et al., 2007; Thornton et al., 2007). Cropped and grazed catchments export higher quantities of sediment and phosphorus than the virgin Brigalow catchments (Elledge and Thornton, 2017). Trend analysis of recent stream-flow records (1920-2007) using pre- and post-clearing river flow data in the Upper Burdekin suggest that there has been a decrease in base flow following tree clearing and an increase in event storm flow during large rainfall events (Peña-Arancibia et al., 2012). Storm flow is largely responsible for erosion and delivery of sediments from rangelands. In general, if tree clearing and any associated land use change expose and/or disturb the soil surface, then water and sediment loss are likely to increase.

Once improved sown pastures are fully established following clearing, which can take a number of years, run-off may be similar to natural woodlands (McIvor et al., 1995a). Removing trees generally enhances pasture productivity with the benefits being greatest in woodlands with high canopy cover (Scanlan, 2002), which most commonly occur in southern and central Queensland. The benefits of tree clearing on pasture production diminish in lower tree-cover areas of northern and western Queensland.

The pasture production benefits of clearing can be partially offset by a reduction in pasture quality. Given the beneficial effect of trees on soil nutrients, tree removal may also have longer term negative implications for soil nutrient dynamics, soil fertility, pasture production and biomass (Jackson and Ash, 1998; Jackson and Ash, 2001). A recent study by Gowen and Bray (2016) used bioeconomic modelling to evaluate the trade-offs between an existing central Queensland grazing operation, which has been using repeated tree clearing to maintain pasture growth, and an alternative carbon and grazing enterprise in which tree clearing is reduced and the additional carbon sequestered in trees is sold. The results showed that ceasing clearing in favour of producing offsets produces a higher net present value over 20 years. In addition to the biophysical effects of reduced cover, there are numerous negative ecological implications of tree clearing in rangelands (Ludwig and Tongway, 2002; Martin and McIntye, 2007).

The influence of trees vs. pasture in terms of erosion and sediment loss in the riparian zone

There is an enormous amount of literature demonstrating that vegetation in riparian zones has positive benefits in terms of reduced channel erosion. Based on international research, Beeson and Doyle (1995) found that bends without riparian vegetation were 30 times more likely to undergo major bank erosion than vegetated bends, and Smith (1976) found that in aggrading river conditions, heavily vegetated banks were 20,000 times more resistant to erosion than non-vegetated banks. Micheli et al. (2004) did a comparison of migration rates and bank erodibilities between 1949 and 1997 on the Sacramento River (USA) and found that reaches bordered by agriculture were 80–150% more erodible than reaches flanked by riparian forest.

A study conducted in the Daintree catchment demonstrated that erosion rates on banks with riparian vegetation were 6.5 times (or 85%) lower than on sites without riparian vegetation (Bartley et al., 2008). Olley et al. (2015) determined that sediment yield per unit area from a catchment containing no remnant vegetation is predicted to be between 50 and 200 times that of a fully vegetated channel network. It is between 25 and 60 times greater for total phosphorus (TP) and between 1.6 and 4.1 times greater for total nitrogen (TN), compared with a fully vegetated channel network (Olley et al., 2015).

Riparian vegetation also has different influences at different spatial scales (Curran and Hession, 2013), and it has different impacts on stream processes depending upon its position down a catchment (Abernethy and Rutherfurd, 1998). The presence of riparian vegetation is useful for all types of erosion, but its specific influence may vary within the catchment (Bartley et al., 2015b). For example, in headwater areas, trees can provide woody debris in the channel that increases the hydraulic resistance of the channel and banks. In middle reaches, the main role of riparian vegetation is to strengthen the bank substrate by tree roots. In lower reaches, where channels are often wider and banks higher, vegetation maintains steeper bank geometries. Riparian vegetation has benefits for both mechanical and hydrological processes as well as local climate, and a combination of woody and grass species is likely to offer the greatest benefit in terms of bank stabilisation (Simon and Collison, 2002). In many Queensland rivers the extent of vegetation within the channel itself, as well as on the banks, is a key determinant of the extent of channel erosion per unit imposed stream power (Brooks et al., 2014c).

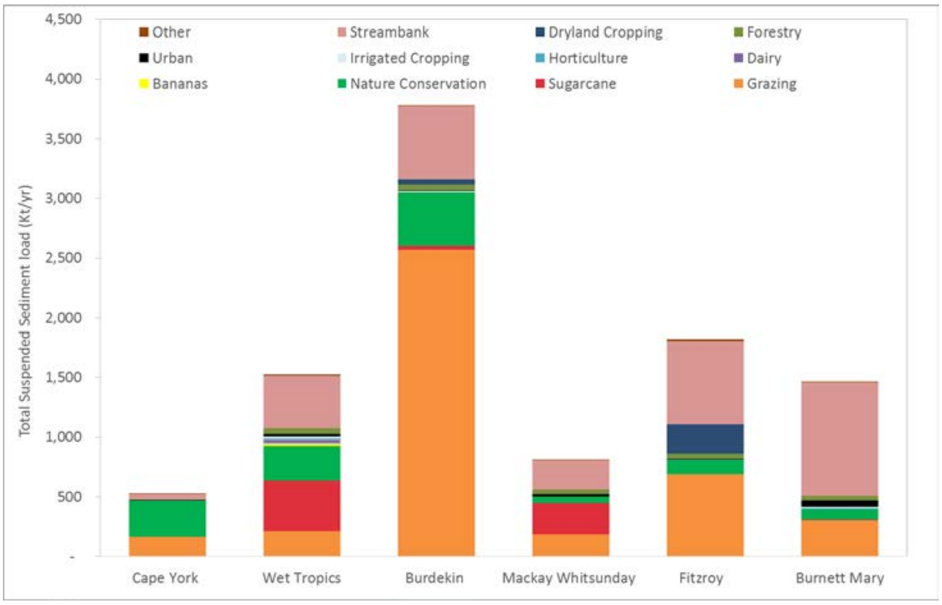


Figure 7: Contribution of land uses to the total suspended sediment (TSS) load for each region. 'Other' includes intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbor, military areas and open water bodies.

Table 8: *Modelled* end-of-basin total suspended sediment (TSS) load by land use as a proportion of the total delivered load (%) based on the 1986-2014 flow period and most recent Queensland Land Use Mapping Program data in each region.

Region	Nature conservation	Dryland cropping	Forestry	Grazing	Horticulture	Irrigated cropping	Sugarcane	Bananas	Dairy	Urban	Water	Other	Stream banks	Total
Cape York	58	0	1	31	0	0	0	0	0	0	0	0	10	100
Wet Tropics	19	0	3	14	1	1	28	1	2	2	0	1	29	100
Burdekin	12	1	1	68	0	0	1	0	0	0	0	0	16	100
Mackay Whitsunday	7	0	4	23	0	0	32	0	0	3	0	1	31	100
Fitzroy	7	13	2	38	0	0	0	0	0	0	0	0	38	100
Burnett Mary	6	0	3	21	1	0	0	0	0	4	0	0	65	100

2.2 Nutrients

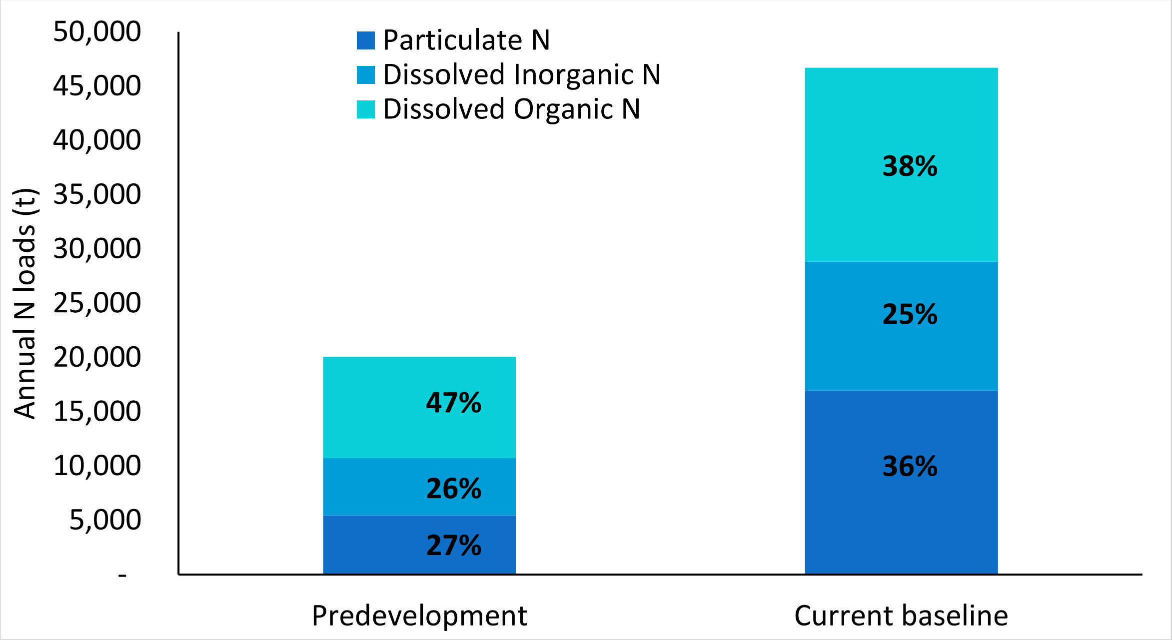
2.2.1 Where are the nutrients coming from?

This section focuses on the forms of nutrients for which there are Great Barrier Reef water quality targets, primarily DIN, PN and PP.

Nutrient forms

The contributions to total Great Barrier Reef nutrient loads vary markedly between nutrient species, regions and land use. As shown in Figure 8, this has changed over time with changing land use and landscape and hydrological modification. For example, modelled estimates of baseline loads suggest that anthropogenic activity has more than doubled TN loads (from 20,000 to 46,500 TN t/year), with the greatest proportional increase in PN (Figure 8). Pre-development estimates of TN composition indicated that DON comprised approximately half of the TN load, with approximately equal contributions from DIN (26%) and PN (27%). Current estimates indicate that these proportions have shifted, with reduced dominance of DON (38%) compared to DIN (25%) and PN (36%). DIN has remained relatively constant in terms of its proportional contribution (McCloskey et al., 2017a). However, as land use changed over the last 200 years, new land uses, especially those involving application of nitrogen fertiliser, led to large increases in the loads of DIN delivered to the end of catchments, with the source largely associated with fertiliser use (Lewis et al., 2014b; Thorburn et al., 2013; Waters et al., 2014). DIN event loads generally increase linearly with the area of fertilised land use upstream (e.g. Connolly et al., 2015; Mitchell et al., 2009).

Figure 8. The impact of changing land use (pre- and post-development) on estimated annual total and constituent nitrogen loads entering the Great Barrier Reef lagoon. Source: presented in Bell et al. (2016) using data from McCloskey et al. (2017a).



Current load estimates

A summary of all of the Great Barrier Reef nitrogen and phosphorus monitored load data is presented in the Appendix, and the data for DIN, PN and PP are presented in Table 9. Based on the monitoring data, the Burdekin River had the highest average DIN, PN and PP delivery to the Great Barrier Reef at ~1380 t/yr, 7450 t/yr and 3400 t/yr, respectively (Table 9). In terms of specific nutrient yields, Cattle Creek (in the Pioneer Basin) had the highest specific yields for PN and PP, closely followed by the North Johnstone and South Johnstone catchments for each of these pollutants. The Tully Basin had the highest specific yields for DIN (~0.5 t/km^2/yr). Based on the end-of-sub-catchment **monitored** specific loads (t/km^2/yr), the results shows that the top quartile of sites (n = 8) contribute 79% of the DIN load, 70% of the PN load and 68% of the PP load (Table 9).

Based on the most recent 2015 Source Catchments modelling, it is estimated that ~55 kt/yr of TN is delivered to the Great Barrier Reef (Table 10). The total amount of DIN delivered to the Great Barrier Reef lagoon is estimated to be ~12 kt/yr, which is a 1.2–6.0-fold increase from pre-development conditions (Table 12). The amount of PN delivered is ~25 kt/yr which is a 2–5-fold increase above estimated average pre-development loads (Table 13). On average, DIN contributes 22% of the TN load and PN contributes ~45% of the TN load (Table 10). On a regional basis the Wet Tropics has the highest loads of TN, DIN and PN (Table 10). The relative rankings of basin contributions for DIN, PN and PP loads delivered to the coast are shown in Figure 9, Figure 10 and Figure 11, respectively. The top five basins contributing to the DIN load are the Herbert, Burdekin, Johnstone, Haughton and Mulgrave-Russell. The top quartile of management units (i.e. 12 out of the 47 management units) contribute ~87% of the DIN based on the modelled area-specific nutrient yields (t/km^2/y). The top five basins contributing to the PN load are the Fitzroy, Mary, Burdekin, Johnstone and Herbert.

The modelling predicts that there is ~13 kt/yr of TP delivered to the Great Barrier Reef (Table 10 and Table 11) and ~10 kt/yr of PP, which is a 3–5-fold increase (Table 14). PP contributes 76% of TP (Table 11). The top basins contributing to the TP and PP load are the Fitzroy, Burdekin, Mary and Johnstone basins. The top quartile of management units (i.e. 12 out of the 47 management units) contribute 69% of the TP and 72% of PP based on the specific nutrient yields (t/km^2/yr) (Table 14).

Table 9: Average annual *monitored* dissolved inorganic nitrogen (DIN), particulate nitrogen (PN) and particulate phosphorus (PP) loads for each of the 32 sites in the Great Barrier Reef catchments. (Source: Garzon-Garcia et al., 2015; Joo et al., 2011; Turner et al., 2013; Turner et al., 2012; Wallace et al., 2016; Wallace et al., 2015; Wallace et al., 2014). The datasets were measured during events over three–nine years; sites with an * are based on two years only. Standard deviation (SD) in brackets.

NRM region	Catchment	Gauging station	River and site name	Monitored catchment area (km^2)	Years of data	Number of samples	DIN (t)	DIN (kg/km^2)	PN (t)	PN (kg/km^2)	PP (t)	PP (kg/km^2)
Cape York	Normanby	105107A	Normanby River at Kalpowar Crossing	15,030	9	264	75 (± 37)	5.0	300 (± 170)	20	93 (± 39)	6.2
Wet Tropics	Barron	110001D	Barron River at Myola	1,945	9	590	55 (± 27)	28	600 (± 420)	308	131 (± 103)	67
		110002A	Barron River at Mareeba	836	3	60	38 (± 13)	45	120 (± 110)	143	49 (± 39)	58
		110003A	Barron River at Picnic Crossing	228	3	371	36 (± 4)	157	30 (± 16)	131	15 (± 10)	65
	Johnstone	1120049	North Johnstone River at Tung Oil	959	9	306	283 (± 88)	295	830 (± 690)	865	293 (± 187)	305
		112101B	South Johnstone River at Upstream Central Mill	400	9	492	147 (± 72)	367	360 (± 230)	900	132 (± 87)	330
	Tully	113006A	Tully River at Euramo	1,450	9	1491	731 (± 258)	504	440 (± 230)	303	118 (± 73)	81
		113015A	Tully River at Tully Gorge National Park	482	5	311	129 (± 60)	267	160 (± 140)	332	34 (± 29)	70
	Herbert	116001F	Herbert River at Ingham	8,581	9	420	921 (± 615)	107	1,240 (± 1,350)	144	301 (± 333)	35
Burdekin	Haughton	119003A	Haughton River at Powerline*	1,773	2	37	28 (± 25)	15	30 (± 26)	16	9 (± 8)	5.1
		119101A	Barratta Creek at Northcote	753	6	649	82 (± 13)	108	90 (± 90)	119	24 (± 24)	31
	Burdekin	120001A	Burdekin River at Home Hill	129,939	9	436	1,382 (± 863)	10	7,450 (± 6,860)	57	3,426 (± 2,783)	26
		120002C	Burdekin River at Sellheim	36,290	9	171	298 ±(154)	8.2	5,250 (± 5,770)	144	2,334 (± 2,411)	64
		120302B	Cape River at Taemas	16,074	7	367	47 (± 44)	2.9	680 (± 480)	42	179 (± 136)	11
		120301B	Belyando River at Gregory Development Road	35,411	7	452	29 (± 21)	0.8	540 (± 560)	15	182 (± 171)	5.1
		120310A	Suttor River at Bowen Development Road	50,291	7	182	28 (± 15)	0.6	270 (± 190)	5.4	102 (± 59)	2.0

NRM region	Catchment	Gauging station	River and site name	Monitored catchment area (km^2)	Years of data	Number of samples	DIN (t)	DIN (kg/km^2)	PN (t)	PN (kg/km^2)	PP (t)	PP (kg/km^2)
		120205A	Bowen River at Myuna	7,104	3	112	85 (± 41)	12.0	1,160 (± 1,060)	163	734 (± 800)	103
Mackay Whitsunday	O'Connell	1240062	O'Connell River at Caravan Park	825	4	86	36 (± 21)	43	250 (± 190)	303	74 (± 58)	89
		124001B	O'Connell River at Stafford's Crossing	340	3	55	18 (± 8)	52	70 (± 20)	205	14 (± 5)	41
	Pioneer	125013A	Pioneer River at Dumbleton Pump Station	1,485	9	657	270 (± 170)	181	780 (± 750)	525	230 (± 220)	154
		125004B	Cattle Creek at Gargett	326	3	39	137 (± 11)	420	420 (± 250)	1288	117 (± 59)	358
	Plane	126001A	Sandy Creek at Homebush	325	6	262	51 (± 26)	156	120 (± 80)	369	40 (± 28)	123
Fitzroy	Fitzroy	1300000	Fitzroy River at Rockhampton	139,159	9	338	1,340 (± 1,100)	9.6	5,100 (± 5,200)	36	2,800 (± 2,700)	20
		130206A	Theresa Creek at Gregory Highway	15,846	6	75	66 (± 62)	7.8	450 (± 460)	52	208 (± 213)	24
		130504B	Comet River at Comet Weir	8,500	6	104	233 (± 238)	14	1,070 (± 920)	65	712 (± 513)	43
		130302A	Dawson River at Taroom	16,450	4	109	74 (± 80)	4.7	1,030 (± 1,580)	65	294 (± 430)	18
Burnett Mary	Burnett	136014A	Burnett River at Ben Anderson Barrage HW	32,891	9	457	239 (± 465)	7.3	2,060 (± 3,660)	62	680 (± 1,190)	20
		136002D	Burnett River at Mt Lawless	7,117	6	396	125 (± 208)	4.3	2,160 (± 4,310)	73	753 (± 1,521)	25
		136094A	Burnett River at Jones Weir Tail Water	21,700	6	297	140 (± 239)	6.5	1,050 (± 1,950)	48	368 (± 676)	17
		136106A	Burnett River at Eidsvold	29,395	5	220	63 (± 88)	8.9	280 (± 460)	39	99 (± 173)	13
	Mary	138014A	Mary River at Home Park*	6,845	2	176	294 (± 302)	43	420 (± 520)	61	155 (± 193)	22
		138008A	Tinana Creek at Barrage Head*	1,284	2	146	28 (± 15)	76	30 (± 3)	23	22 (± 16)	5.4

Table 10: Contribution of nutrient forms to *modelled* regional nitrogen budget based on the 2015 modelling (total load) estimates.

Region	DIN (t/yr)	DON (t/yr)	PN (t/yr)	TN (t/yr)
Cape York	420	4,540	1,900	6,850
Wet Tropics	5,500	4,390	6,700	16,580
Burdekin	2,570	2,560	3,660	8,790
Mackay Whitsunday	1,350	980	2,150	4,810
Fitzroy	1,140	3,410	6,360	10,910
Burnett Mary	1,040	2,110	3,990	7,150
Total	**12,030**	**18,300**	**24,750**	**55,080**

Table 11: Contribution of nutrient forms to *modelled* regional phosphorus budget based on the 2015 modelling (total load) estimates.

Region	DIP (t/yr)	DOP (t/yr)	PP (t/yr)	TP (t/yr)
Cape York	80	150	450	680
Wet Tropics	190	380	1,730	2,300
Burdekin	440	140	2,240	2,820
Mackay Whitsunday	250	70	990	1,310
Fitzroy	1,050	260	3,360	4,660
Burnett Mary	140	80	1,430	1,640
Total	**2,140**	**1,070**	**10,200**	**13,420**

Table 12: *Modelled* end-of-basin annual average dissolved inorganic nitrogen (DIN) loads for each of the 35 Great Barrier Reef basins plus additional 13 sub-catchments in the Burdekin and Fitzroy (in grey text). The modelling represents an annual average based on the 1986-2014 flow period. Note that ** highlights that the sub-catchment totals for the Fitzroy are within 1% of the basin loads. It was not suitable to present sub-catchment loads for the Burdekin due to modelling discrepancies. The data in this table are Queensland Government modelling outputs. The data were rounded to the nearest 10. Catchments highlighted in orange are in the top quartile (n = 12) for anthropogenic total load (t/yr) of DIN. Catchments highlighted in pink are in the top quartile (n = 12) for anthropogenic specific load of DIN (kg/km^2/yr).

Region	Basin #	Basin name	Basin area (km^2)	Total DIN load exported to the coast (t/yr)	Total specific DIN load exported to the coast (kg/km^2/yr)	Anthropogenic DIN export to the coast (t/yr)	Total specific Anthropogenic DIN export to the coast (kg/km^2/yr)
Cape York	101	Jacky Jacky	2,990	70	20	0	0
	102	Olive Pascoe	4,172	100	20	<5	0
	103	Lockhart	2,873	50	20	0	0
	104	Stewart	2,770	30	10	0	0
	105	Normanby	24,380	100	<5	10	0
	106	Jeannie	3,637	30	10	0	0
	107	Endeavour	2,186	40	20	<5	<5
		REGIONAL TOTAL	**43,008**	420		10	
Wet Tropics	108	Daintree	2,105	480	230	130	60
	109	Mossman	477	160	330	100	220
	110	Barron	2,188	150	70	90	40
	111	Mulgrave-Russell	1,975	930	470	420	210
	112	Johnstone	2,317	1,060	460	500	220
	113	Tully	1,668	780	470	380	230
	114	Murray	1,125	410	370	230	210
	116	Herbert	9,852	1,520	150	890	90
		REGIONAL TOTAL	**21,707**	5,500		2,750	
Burdekin		Upper Burdekin	40,413	450	10	0	0
		Cape Campaspe	20,255	70	<5	0	0
		Belyando	35,352	60	<5	0	0
		Suttor	18,577	90	0	0	0
		Bowen Bogie	11,718	170	10	0	0
		East Burdekin	3,299	90	30	20	10
		Sub-total (Burdekin)*	129,615	930			
	120	Burdekin	130,120	1,100	10	170	<5
	117	Black	1,057	100	90	20	20
	118	Ross	1,707	180	110	120	70
	119	Haughton (Lower Burdekin)	4,051	1,020	250	910	230
	121	Don	3,736	180	50	70	20

Region	Basin #	Basin name	Basin area (km^2)	Total DIN load exported to the coast (t/yr)	Total specific DIN load exported to the coast ($kg/km^2/yr$)	Anthropogenic DIN export to the coast (t/yr)	Total specific Anthropogenic DIN export to the coast ($kg/km^2/yr$)
		REGIONAL TOTAL	**140,671**	2,570		2,230	
Mackay Whits.	122	Proserpine	2,513	310	120	160	60
	124	O'Connell	2,305	320	140	190	80
	125	Pioneer	1,664	260	150	190	120
	126	Plane	2,547	460	180	370	140
		REGIONAL TOTAL	**9,029**	1,350	150	900	100
Fitzroy		Comet	17,290	40	<5	10	0
		Dawson	50,734	140	<5	20	0
		Isaac	22,226	240	10	20	<5
		Mackenzie	13,128	60	<5	10	<5
		Nogoa	19,196	20	<5	<5	0
		Theresa Creek	8,473	20	<5	<5	0
		Fitzroy River – lower	11,339	280	30	90	10
		Sub-total (Fitzroy)**	142,387	800		160	
	130	Fitzroy	142,144	800	10	160	<5
	127	Styx	2,997	90	30	10	<5
	128	Shoalwater	3,614	100	30	<5	<5
	129	Water Park	1,846	70	40	<5	<5
	132	Calliope	2,416	50	20	10	<5
	133	Boyne	2,498	40	10	<5	<5
		REGIONAL TOTAL	**155,515**	1,140		830	
Burnett Mary	134	Baffle	4,101	60	10	30	10
	135	Kolan	2,891	80	30	70	20
	136	Burnett	33,274	250	10	210	10
	137	Burrum	3,346	200	60	190	60
	138	Mary	9,420	460	50	360	40
		REGIONAL TOTAL	**53,031**	1,040		850	
		TOTAL Great Barrier Reef	***422,961***	12,030		7,570	

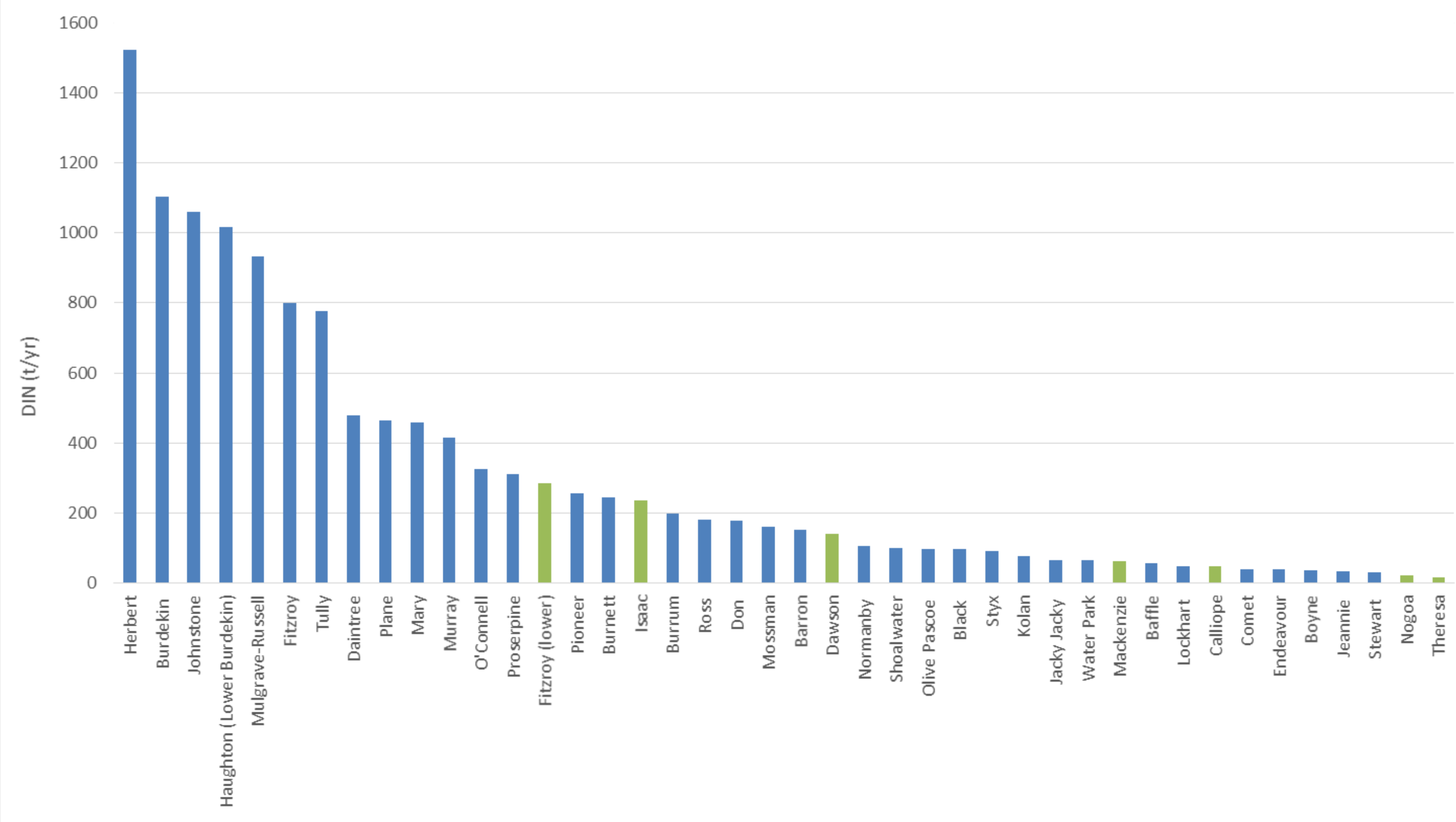


Figure 9: Ranking of the *modelled* end-of-catchment annual average total dissolved inorganic nitrogen (DIN) delivery (t/yr) for each of the 35 Great Barrier Reef basins (in blue) plus the additional internal sub-catchments in the Fitzroy (in green). The modelling represents an annual average based on the 1986-2014 flow period.

Table 13: *Modelled* end-of-basin annual average particulate nitrogen (PN) loads for each of the 35 Great Barrier Reef basins plus additional 13 sub-catchments in the Burdekin and Fitzroy (in grey text). The modelling represents an annual average based on the 1986-2014 flow period. Note that the * and ** highlight that the sub-catchment totals for the Burdekin and Fitzroy are within 3% and 1% of the basin loads. The data in this table are Queensland Government modelling outputs. The data were rounded to the nearest 10. Catchments highlighted in orange are in the top quartile (n = 12) for anthropogenic total load (t/yr) of PN. Catchments highlighted in pink are in the top quartile (n = 12) for anthropogenic specific load of PN (kg/km^2/yr).

Region	Basin #	Basin name	Basin area (km^2)	Total PN load exported to the coast (t/yr)	Total specific PN load exported to the coast (kg/km^2/yr)	Anthropogenic PN export to the coast (t/yr)	Total specific Anthropogenic PN export to the coast (kg/km^2/yr)
Cape York	101	Jacky Jacky	2,990	270	90	220	70
	102	Olive Pascoe	4,172	450	110	340	80
	103	Lockhart	2,873	320	110	260	90
	104	Stewart	2,770	150	60	120	40
	105	Normanby	24,380	250	10	150	10
	106	Jeannie	3,637	200	60	150	40
	107	Endeavour	2,186	250	110	110	50
		REGIONAL TOTAL	**43,008**	1,900		1,350	
Wet Tropics	108	Daintree	2,105	580	280	60	30
	109	Mossman	477	100	210	20	50
	110	Barron	2,188	200	90	90	40
	111	Mulgrave-Russell	1,975	1,230	620	530	270
	112	Johnstone	2,317	1,990	860	1,220	530
	113	Tully	1,668	870	520	340	200
	114	Murray	1,125	400	360	160	140
	116	Herbert	9,852	1,330	130	700	70
		REGIONAL TOTAL	**21,707**	6,700		3,110	
Burdekin		Upper Burdekin	40,413	510	10	450	10
		Cape Campaspe	20,255	30	<5	20	<5
		Belyando	35,352	70	<5	60	<5
		Suttor	18,577	70	0	60	0
		Bowen Bogie	11,718	1,900	160	1,550	130
		East Burdekin	3,299	170	50	140	40
		Sub-total (Burdekin)*	129,615	2750		2280	
	120	Burdekin	130,120	2,890	20	2,410	20
	117	Black	1,057	140	140	50	50
	118	Ross	1,707	100	60	80	50
	119	Haughton (Lower Burdekin)	4,051	220	60	190	50
	121	Don	3,736	310	80	250	70
		REGIONAL TOTAL	**140,671**	3,660		2,980	

Region	Basin #	Basin name	Basin area (km^2)	Total PN load exported to the coast (t/yr)	Total specific PN load exported to the coast (kg/km^2/yr)	Anthropogenic PN export to the coast (t/yr)	Total specific Anthropogenic PN export to the coast (kg/km^2/yr)
Mackay Whits.	122	Proserpine	2,513	390	150	230	90
	124	O'Connell	2,305	840	370	620	270
	125	Pioneer	1,664	450	270	300	180
	126	Plane	2,547	470	180	310	120
		REGIONAL TOTAL	**9,029**	2,150		1,460	
Fitzroy		Comet	17,290	70	<5	40	<5
		Dawson	50,734	540	10	350	10
		Isaac	22,226	580	30	370	20
		Mackenzie	13,128	230	20	160	10
		Nogoa	19,196	30	<5	20	<5
		Theresa Creek	8,473	40	<5	20	<5
		Fitzroy River – lower	11,339	1,600	140	1,210	110
		Sub-total (Fitzroy)**	142,387	3,090		2,160	
	130	Fitzroy	142,144	3,070	20	2,150	20
	127	Styx	2,997	830	280	700	240
	128	Shoalwater	3,614	650	180	550	150
	129	Water Park	1,846	1,270	690	1,120	610
	132	Calliope	2,416	440	180	360	150
	133	Boyne	2,498	110	50	20	10
		REGIONAL TOTAL	**155,515**	6,360		5,820	
Burnett Mary	134	Baffle	4,101	270	70	160	40
	135	Kolan	2,891	100	30	70	20
	136	Burnett	33,274	670	20	340	10
	137	Burrum	3,346	60	20	40	10
	138	Mary	9,420	2,900	310	2,350	250
		REGIONAL TOTAL	**53,031**	3,990		2,960	
		TOTAL Great Barrier Reef	***422,961***	24,750		17,680	

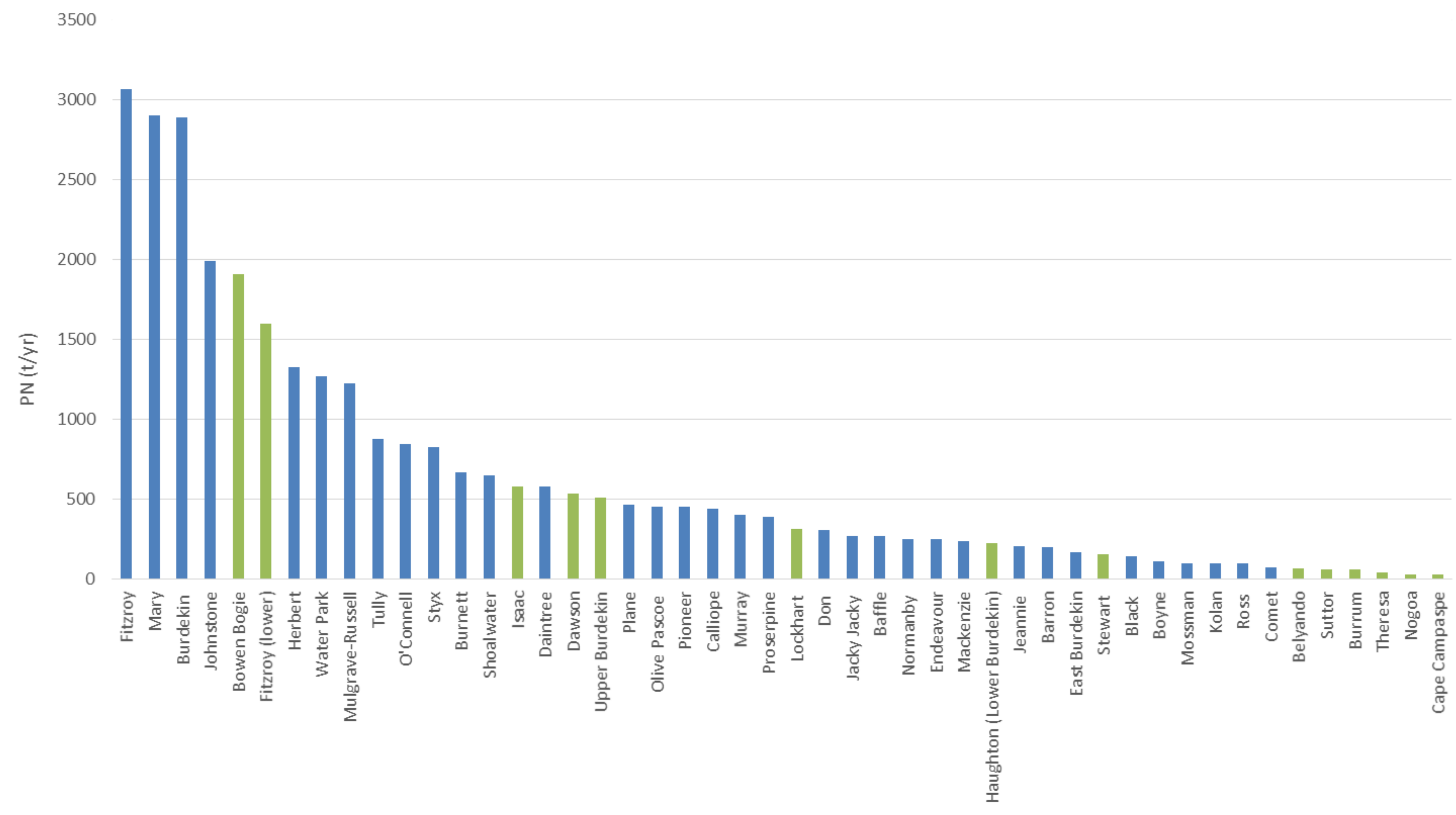


Figure 10: Ranking of the *modelled* end-of-basin annual average total particulate nitrogen (PN) delivery (t/yr) for each of the 35 Great Barrier Reef basins (in blue) plus the additional internal sub-catchments in the Burdekin and Fitzroy (in green). The modelling represents an annual average based on the 1986-2014 flow period.

Table 14: *Modelled* end-of-basin annual average particulate phosphorus (PP) loads for each of the 35 Great Barrier Reef basins plus additional 13 sub-catchments in the Burdekin and Fitzroy (in grey text). The modelling represents an annual average based on the 1986-2014 flow period. Note that the * and ** indicate that the sub-catchment totals for the Burdekin and Fitzroy are within 3% and 1% of the basin loads. The data in this table are Queensland Government modelling outputs. The data were rounded to the nearest 10. Catchments highlighted in orange are in the top quartile for anthropogenic specific yield delivery of PP. Catchments highlighted in pink are in the top quartile (n = 12) for anthropogenic specific load of PP (kg/km^2/yr).

Region	Basin number	Basin name	Basin area (km^2)	Total PP load exported to the coast (t/yr)	Total specific PP load exported to the coast (kg/km^2/yr)	Anthropogenic PP export to the coast (t/yr)	Total specific Anthropogenic PP export to the coast (kg/km^2/yr)
Cape York	101	Jacky Jacky	2,990	40	10	40	10
	102	Olive Pascoe	4,172	70	20	60	10
	103	Lockhart	2,873	100	30	80	30
	104	Stewart	2,770	50	20	40	10
	105	Normanby	24,380	80	<5	50	<5
	106	Jeannie	3,637	40	10	30	10
	107	Endeavour	2,186	80	40	30	10
		REGIONAL TOTAL	**43,008**	450		330	
Wet Tropics	108	Daintree	2,105	80	40	20	10
	109	Mossman	477	20	40	10	10
	110	Barron	2,188	50	20	30	10
	111	Mulgrave-Russell	1,975	280	140	190	90
	112	Johnstone	2,317	760	330	620	270
	113	Tully	1,668	180	110	120	70
	114	Murray	1,125	80	70	60	50
	116	Herbert	9,852	290	30	190	20
		REGIONAL TOTAL	**21,707**	1,730		1,220	
Burdekin		Upper Burdekin	40,413	410	10	360	10
		Cape Campaspe	20,255	20	<5	20	<5
		Belyando	35,352	40	<5	40	<5
		Suttor	18,577	50	0	50	0
		Bowen Bogie	11,718	1,090	90	860	70
		East Burdekin	3,299	110	30	90	30
		Sub-total (Burdekin)*	129,615	1,720		1,420	
	120	Burdekin	130,120	1,800	10	1,480	10
	117	Black	1,057	80	70	20	20
	118	Ross	1,707	50	30	40	20
	119	Haughton (Lower Burdekin)	4,051	140	30	120	30
	121	Don	3,736	170	50	140	40
		REGIONAL TOTAL	**140,671**	2,240		2,120	

Region	Basin number	Basin name	Basin area (km^2)	Total PP load exported to the coast (t/yr)	Total specific PP load exported to the coast (kg/km^2/yr)	Anthropogenic PP export to the coast (t/yr)	Total specific Anthropogenic PP export to the coast (kg/km^2/yr)
Mackay Whits.	122	Proserpine	2,513	160	70	90	40
	124	O'Connell	2,305	420	180	300	130
	125	Pioneer	1,664	180	110	120	70
	126	Plane	2,547	230	90	140	60
		REGIONAL TOTAL	**9,029**	990		650	
Fitzroy		Comet	17,290	50	<5	30	<5
		Dawson	50,734	330	10	210	<5
		Isaac	22,226	330	10	210	10
		Mackenzie	13,128	140	10	100	10
		Nogoa	19,196	10	<5	10	0
		Theresa Creek	8,473	20	<5	10	<5
		Fitzroy River – lower	11,339	950	80	700	60
		Sub-total (Fitzroy)**	142,387	1,830		1,270	
	130	Fitzroy	142,144	1,820	10	1,260	10
	127	Styx	2,997	430	140	360	120
	128	Shoalwater	3,614	310	90	260	70
	129	Water Park	1,846	520	280	460	250
	132	Calliope	2,416	220	90	180	70
	133	Boyne	2,498	60	20	10	0
		REGIONAL TOTAL	**155,515**	3,360		3,100	
Burnett Mary	134	Baffle	4,101	130	30	80	20
	135	Kolan	2,891	40	10	30	10
	136	Burnett	33,274	270	10	150	<5
	137	Burrum	3,346	20	10	20	<5
	138	Mary	9,420	970	100	790	80
		REGIONAL TOTAL	**53,031**	1,430		1,050	
		TOTAL Great Barrier Reef	***422,961***	10,200		8,470	

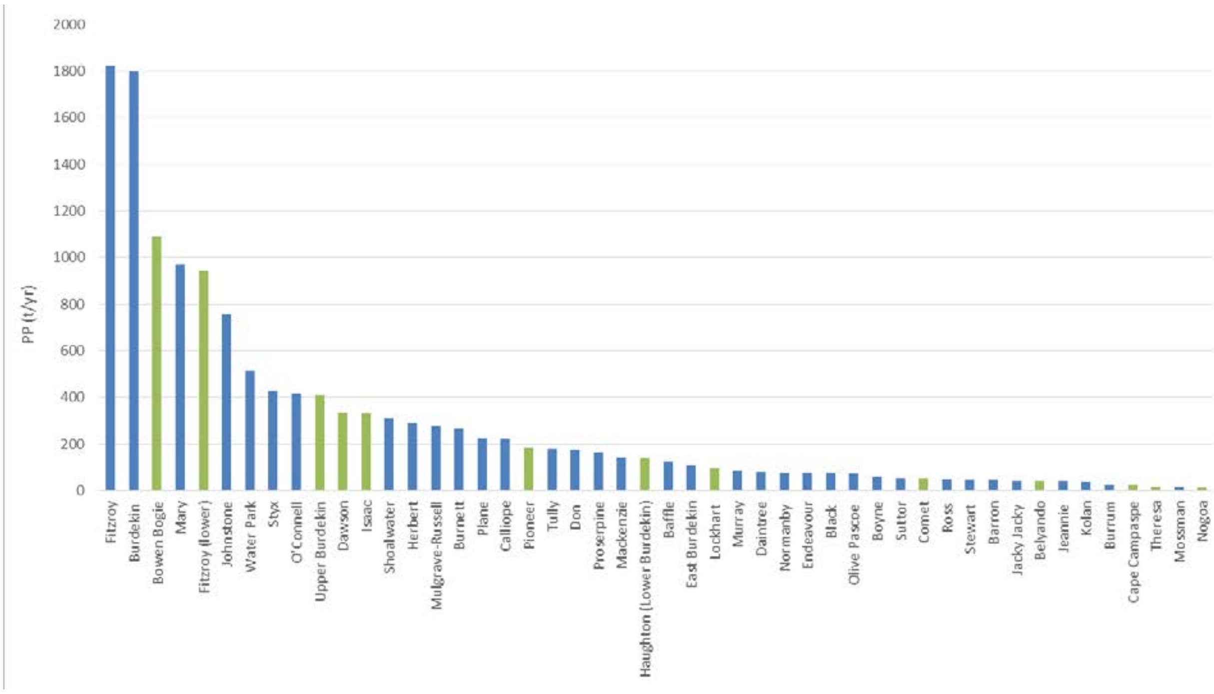


Figure 11: Ranking of the *modelled* end-of-basin annual average total particulate phosphorus (PP) delivery (t/yr) for each of the 35 Great Barrier Reef basins (in blue) plus the additional internal sub-catchments in the Burdekin and Fitzroy (in green). The modelling represents an annual average based on the 1986-2014 flow period.

In addition to the monitored and modelled load estimates, there are also some basin-specific assessments of end-of-catchment loads and changes over time. For example, in the combined Tully and Murray basins, Lewis et al. (2014b) used an independent modelling framework for the period 1800-1829 (30-year period) to estimate pre-development loads for DIN and dissolved inorganic phosphorus (DIP) (Figure 12). The reconstructed annual mean pre-development loads for the Tully-Murray Basin were DIN: 254 t; DIP: 463 t; PN: 63 t; PP: 40 t; and TSS: 58 kt. In comparison, the reconstructed average annual loads for the past 30 years (1982-2011) for the Tully-Murray Basin were DIN: 542 t (2.1-fold increase); DIP: 37 t (2.2-fold increase); PN: 781 t (1.7-fold increase); PP: 164 t (4.1-fold increase); and TSS: 122 kt (2.1-fold increase) (Figure 12). This illustrates another technique for estimating anthropogenic loads in the Great Barrier Reef catchments and another line of evidence for assessing changes over time. In the Source Catchments model, the pre-development loads were based on current hydrology (including dams and weirs) but pre-development land use and ground cover (McKergow et al., 2005a; McKergow et al., b) may contribute to variations in these analyses.

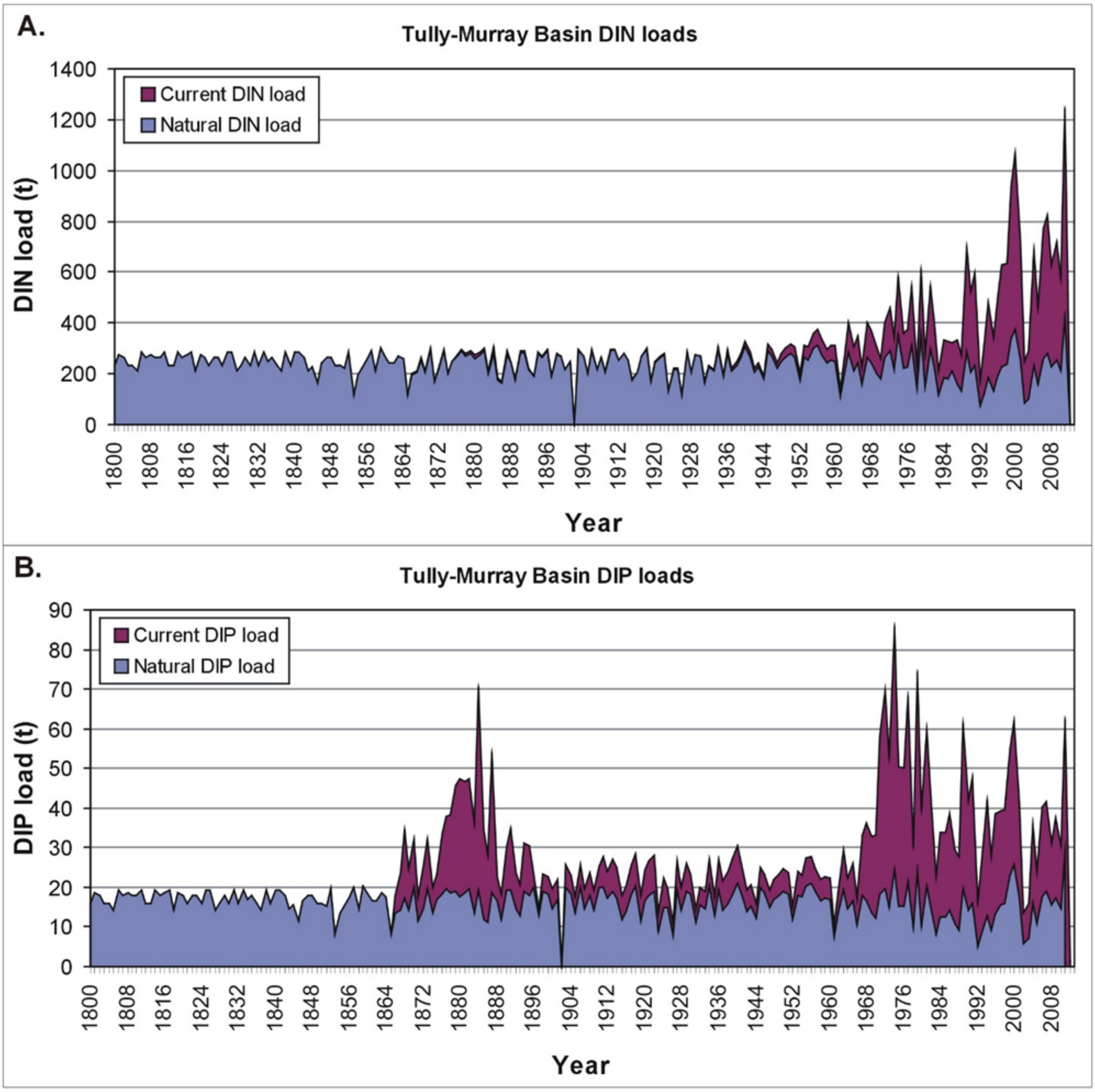


Figure 12: The modelled loads of (top) dissolved inorganic nitrogen (DIN) and (bottom) dissolved inorganic phosphorus (DIP) for the Tully-Murray Basin. Source: Reproduced from Lewis et al. (2014b)**.**

2.2.2 What are the drivers and land uses delivering the anthropogenic nutrient loss?

Isolating the effect of land use on pollutant loss in a catchment setting is a challenging task and can generally only be done at large scales by combining several datasets (e.g. Walton and Hunter, 2009). Land use (and land management) change is seen as the primary factor responsible for changes in nutrient loss from the landscape and hence delivery to water bodies downstream. DIN is sourced from all land uses, whether in 'natural' condition or modified by human activity. Undisturbed landscapes can export large quantities of DIN but generally at low concentrations (Brodie and Mitchell, 2005). Large datasets are available of run-off losses of DIN from different land uses, both in the Great Barrier Reef catchment (Brodie and Mitchell, 2005), Australia-wide (Bartley et al., 2012) and internationally (Kaushal et al., 2014).

For nitrogen, the Wet Tropics region is the main regional contributor of TN load (~32%), while Mackay Whitsunday and Burnett Mary regions (each 9%) are the lowest contributors (Bell et al., 2016). The most recent modelling estimates that sugarcane delivers the most DIN to the Great Barrier Reef from the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary regions (Figure 13). Grazing is the highest contributor of total DIN in the Fitzroy and also contributes >20% of the DIN load in all regions except the Wet Tropics (**Error! Reference source not found.**). In the Wet Tropics and Mackay Whitsunday regions, PN and PP delivery is dominated by sugarcane. Grazing dominates PN and PP delivery in all other regions except Cape York. Urban areas contribute less than 7% for DIN, PN and PP.

These data are also presented at a basin scale in the Appendix (Table 23), highlighting the contribution of sugarcane to DIN loads in many Great Barrier Reef basins. In basins with large areas of sugarcane, more than 40% of the total DIN load comes from sugarcane. Examples include Mulgrave-Russell (42%), Haughton (89%), Pioneer (73%) and Mary (45%). When considering anthropogenic sources, sugarcane contributes up to 80% of the total DIN load in some basins (Waters et al., 2014).

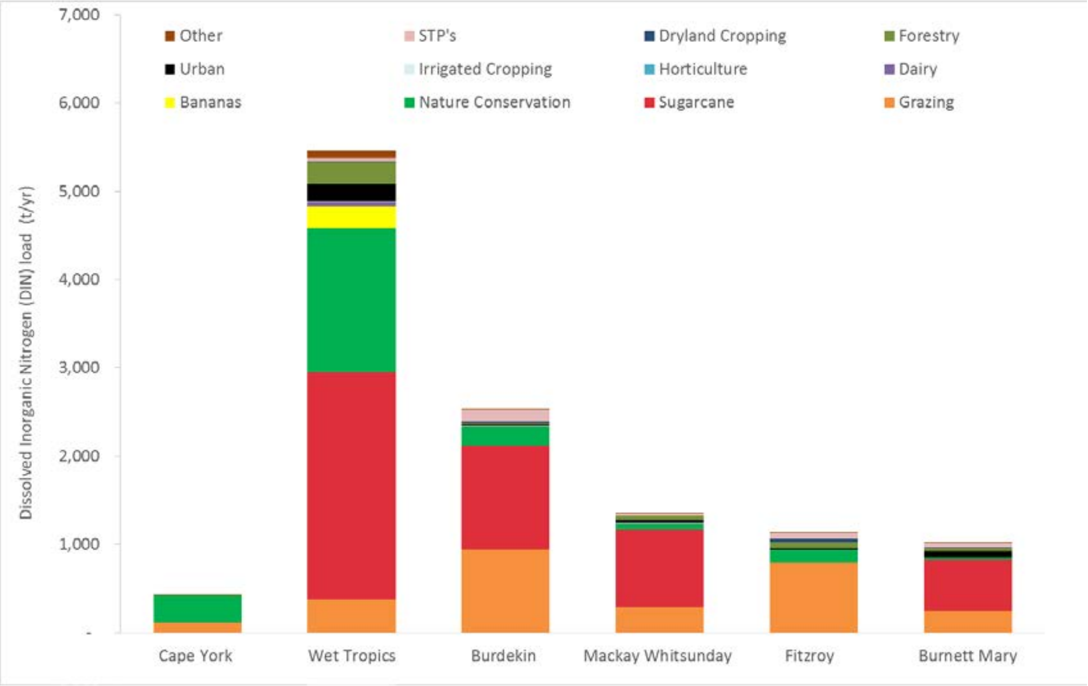


Figure 13: Contribution of main land uses to the dissolved inorganic nitrogen (DIN) load for each region. 'STP's' represent sewerage treatment plant. 'Other' includes intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbor, military areas and open water bodies.

Table 15: Source Catchment (2015 Report Card) end-of-basin pollutant loads (%).

Total dissolved inorganic nitrogen (DIN) load by land use (%).

Region	Nature conservation	Dryland cropping	Forestry	Grazing	Horticulture	Irrigated cropping	Sugarcane	Bananas	Dairy	Urban	Water	Other	Sewage Treatment Plants
Cape York	72	0	0	28	0	0	0	0	0	0	0	0	0
Wet Tropics	30	0	5	7	1	0	47	4	1	4	0	1	1
Burdekin	9	1	1	36	1	0	46	0	0	1	0	0	5
Mackay Whitsunday	5	0	3	21	0	0	65	0	0	3	0	1	2
Fitzroy	13	3	6	70	0	0	0	0	0	1	0	1	5
Burnett Mary	3	1	4	24	1	1	56	0	0	6	0	0	5

Total particulate nitrogen (PN) load by land use (%).

Region	Nature conservation	Dryland cropping	Forestry	Grazing	Horticulture	Irrigated cropping	Sugarcane	Bananas	Dairy	Urban	Water	Other	Stream-banks
Cape York	73	0	1	21	0	0	0	0	0	0	0	0	5
Wet Tropics	36	0	5	14	1	0	28	1	2	2	0	1	12
Burdekin	22	0	2	65	0	0	1	0	0	0	0	0	9
Mackay Whitsunday	8	0	10	29	0	0	40	0	0	4	0	1	8
Fitzroy	29	5	10	49	0	0	0	0	0	0	0	0	8
Burnett Mary	21	1	15	38	0	0	2	0	0	1	0	0	23

Total particulate phosphorus (PP) load by land use (%).

Region	Nature conservation	Dryland cropping	Forestry	Grazing	Horticulture	Irrigated cropping	Sugarcane	Bananas	Dairy	Urban	Water	Other	Stream-banks
Cape York	71	0	1	23	0	0	0	0	0	0	0	0	5
Wet Tropics	16	0	2	15	0	1	49	1	1	1	0	0	14
Burdekin	24	1	2	63	0	1	1	0	0	0	0	0	9
Mackay Whitsunday	8	0	5	34	0	0	43	0	0	3	0	1	6
Fitzroy	25	5	9	53	0	0	0	0	0	0	0	0	8
Burnett Mary	20	0	14	39	0	0	2	0	0	1	0	0	24

Total Suspended Sediment (TSS) load by land use (%).

Region	Nature conservation	Dryland cropping	Forestry	Grazing	Horticulture	Irrigated cropping	Sugarcane	Bananas	Dairy	Urban	Water	Other	Stream-banks
Cape York	58	0	0	31	0	0	0	0	0	0	0	0	10
Wet Tropics	19	0	3	14	1	1	28	1	2	2	0	1	29
Burdekin	12	1	1	68	0	0	1	0	0	0	0	0	16
Mackay Whitsunday	7	0	4	23	0	0	32	0	0	3	0	1	31
Fitzroy	7	13	2	38	0	0	0	0	0	0	0	0	38
Burnett Mary	6	0	3	21	1	0	0	0	0	4	0	0	65

Further analysis of nitrogen sourced from sugarcane shows that nitrogen surpluses and nitrogen fertiliser application rates are correlated with nitrogen losses (in both dissolved and particulate forms) from Great Barrier Reef catchments (Bell et al., 2016; Thorburn and Wilkinson, 2013; Thorburn et al., 2013) (Figure 14). The relationships in the Great Barrier Reef are similar to catchments in the northern hemisphere and the USA (Thorburn et al., 2013). Conversely, lowered nitrogen fertiliser usage leads to smaller losses of nitrogen as seen in fertiliser trials (Rohde et al., 2013; Webster et al., 2012).

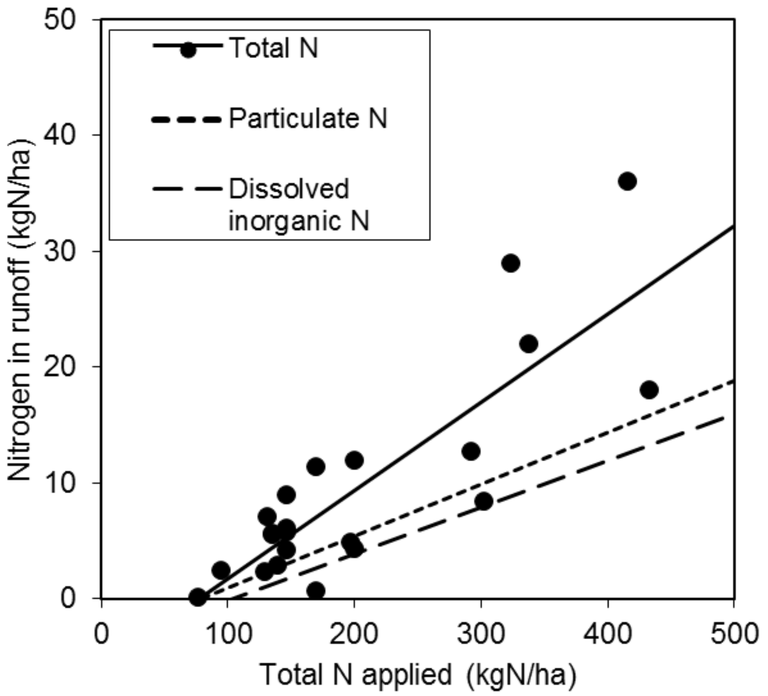


Figure 14. Relationship between total nitrogen input (fertiliser and legumes) and total wet season nitrogen in run-off (total nitrogen, particulate nitrogen and dissolved inorganic nitrogen) from >20 sugarcane sites in Great Barrier Reef catchments. Data points indicate TN losses, while fitted regressions are shown for PN and DIN from the same sites. Source: Reproduced from Bell et al. (2016).

2.2.3 How does the source of nutrients vary over time and space?

Dissolved inorganic nitrogen

Research into the sources of nutrients across large catchment scales (e.g. Bainbridge et al., 2009; Hunter and Walton, 2008) has not been as extensive as research into sediment sources. Most of the recent work on understanding the source of nutrients has focused on sugarcane growing areas.

A number of recent studies in the Mulgrave catchment have investigated the sources of nutrients in sugarcane areas and evaluated the influence of deep drainage, groundwater losses and riparian zones. A study of the lateral export of nutrients from groundwater to surface water was carried out by Rasiah et al. (2013) who determined that ~52% of the total nutrient loading in the local river systems was from groundwater. This research was conducted over a small plot scale, and the authors cautioned the use of these data to upscale to larger catchment areas (Rasiah et al., 2013). In the same catchment, Connolly et al. (2015) determined that NO_x (nitrate + nitrite) concentrations and loads were significantly lower in streams with greater riparian vegetation which may suggest some removal in this zone, although the dominant influence on the concentrations was likely the fertilised area above the sampling site. Connor et al. (2013) determined that due to highly variable groundwater table fluctuations, riparian zones in humid tropical lowlands are unlikely to be effective at removing nitrogen from groundwater. Therefore riparian zones have only a modest direct influence on NO_x, which is overwhelmed by the large input of nutrients from agriculture. Connolly et al. (2015) suggest that adequate reduction of inorganic nitrogen in Wet Tropics waterways can only be achieved by reduced fertiliser application. Other research identified a need for nitrogen fertiliser management practices that minimise nitrate leaching to groundwater (Rasiah et al., 2013). The increased nitrate loading also threatens groundwater-dependent ecosystems, which have been mapped in several areas (Glanville et al., 2016) and have also been shown to be at high risk from saltwater intrusion (Hunter, 2012; Lenahan and Bristow, 2010).

Particulate nitrogen and dissolved organic nitrogen

Particulate and dissolved organic nutrients comprise the majority of the end-of-basin loads to the Great Barrier Reef (Table 9, Table 21 and Table 24) but very little is known of their sources and losses/transformation as they are transported from terrestrial to marine systems (Brodie et al., 2015; Wooldridge et al., 2015). These nutrient fractions are most likely contributing to the end-of-catchment monitored DIN load through in-stream mineralisation processes, but their relative contribution and sourcing are not well understood or modelled at present (Figure 15). This highlights the potential for elevated DIN loads, depleted PN loads (mineralisation and/or denitrification) and loads (mineralisation) at the end of catchments as a result of in-stream processes. Thorburn and Wilkinson (2013) concluded that in-catchment nitrogen loss processes like denitrification may be minimal for surplus nitrogen lost from cropping systems due to short residence times and rapid flow rates in coastal river systems draining the main crop production centres. However, this may not be the case for nitrogen losses from the more distant inland grazing areas (Bell et al., 2016). For example, a study in the Fitzroy catchment using generalised additive modelling found that the Nogoa sub-catchment, which is dominated by grazing, is important for determining the DIN and DIP concentrations reaching the Fitzroy River mouth (Robson and Dourdet, 2015). This suggests that grazing, rather than cropping, is a major source of DIN in some catchments, although the exact source and mechanism generating the DIN within the grazed areas is not known. In areas such as the Nogoa sub-catchment, which is known for its severe gully erosion (Ciesiolka, 1987), gully erosion may be an indirect source of the DIN. Additionally, PN and are likely to be contributing DIN to the Great Barrier Reef lagoon through estuarine and marine mineralisation processes that are not well understood (Brodie et al., 2015).

The role and impact of nutrients on the Great Barrier Reef is dependent on their bioavailability (fraction of the TN and phosphorus pools that are immediately available plus those that have the potential to become available to phytoplankton over a specified period of time) (see also Chapter 3). In the past, the focus has been principally on dissolved forms (e.g. ammonium-N, nitrate-N, dissolved reactive phosphorus), assuming they are immediately or partially (e.g.) bioavailable when discharged from rivers into the Great Barrier Reef lagoon (Brodie et al., 2015). Understanding the sources, transport, transformation, fate and impact of bioavailable nutrients of terrestrial origin on the Great Barrier Reef remains a critical knowledge gap. This is crucial for determining the land management practices that will be effective at reducing nitrogen loads.

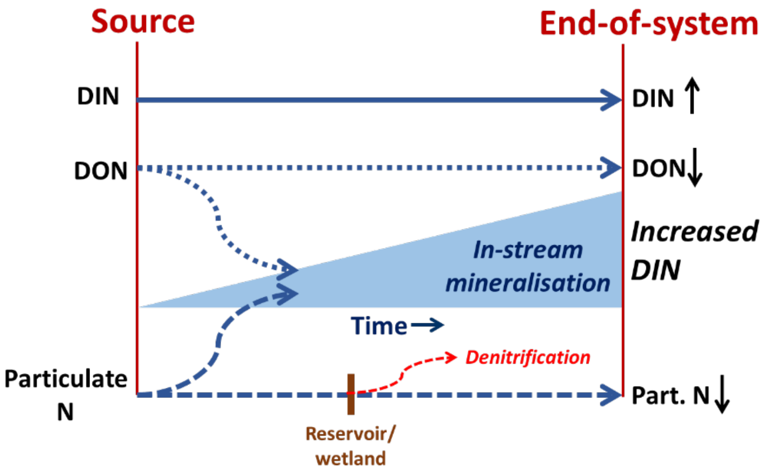


Figure 15: Conceptual model illustrating potential in-stream nitrogen transformations influencing end-of-catchment loads. Source: Bell et al. (2016).

Burton et al. (2015) carried out a pilot study to test the bioavailability of particulate nutrients on selected soil types from sugarcane, banana and grazing land uses and found that measurements of PN and PP are not good indicators of bioavailable nitrogen and phosphorus pools, and the bioavailable nitrogen, phosphorus and organic carbon contents in fine sediments (<10 µm) vary widely across soil types. Fine sediment (<10 µm) tends to be enriched in bioavailable nitrogen and phosphorus compared to its parent soil, and the quantity of nitrogen mineralised was not affected when conditions changed from freshwater to marine, hence sediment continues to be a bioavailable nitrogen and phosphorus source in the marine environment. The main sources of bioavailable nitrogen and phosphorus will depend on the relative contribution of surface and sub-surface sediments to end-of-system loads, with surface sediments having higher bioavailability status.

2.2.4 What processes are responsible for the excess nutrients?

Based on the most recent Source Catchments modelling (McCloskey et al., 2017b), the erosion process responsible for the delivery of PP largely follows the same pattern as for sediments (therefore data not shown). The erosion source responsible for delivering PN, however, is dominated by hillslope erosion in all regions except the Burdekin where channel sources (combined gully and streambank) represent ~52% of the PN erosion source (Table 15).

Current literature suggests that the dominant source of DIN is from fertilised crops such as sugarcane, and it is transported off the paddock as surface or sub-surface flow (Waters et al., 2014). The catchment models deliver DIN to the stream in sugarcane areas as surface run-off or by sub-surface pathways (McCloskey et al., 2017a; McCloskey et al., 2017b).

Garzon-Garcia et al. (2016) quantified various indicators of bioavailable nitrogen and phosphorus for different geomorphological units on a limited number of alluvial gullies in the Normanby catchment. The study determined that alluvial gullies in grazed catchments are likely to be important sources of bioavailable nitrogen and phosphorus to the aquatic environment. The <10 µm fraction is generally enriched in bioavailable nitrogen and phosphorus and organic carbon compared to the <63 µm fraction, and therefore the finer grained terrace soils are a more important source than bank sub-surfaces and gully floors. Importantly, the relative contributions at the landscape scale from surface and sub-surface soils have not been evaluated for PN nor bioavailable nutrients. This was done for alluvial gully complexes only (Garzon-Garcia et al., 2016). Recent research in gullied catchments of South East Queensland has shown that a relatively small variation in the proportion of sediment coming from surface and sub-surface sources between wet and dry years changes the main source of nitrogen (Garzon-Garcia et al., 2017). Hence, management of both surface and sub-surface erosion sources plays a role in the reduction of bioavailable nutrients delivered to the Great Barrier Reef.

Based on the modelling data (Table 16) the proportion of PN coming from gullies in the Burdekin Basin appears to reflect the initial findings from Garzon-Garcia et al. (2016); however, modelling of other rangeland areas where gullies are likely to be a major source of PN (e.g. Cape York and Fitzroy) indicates a disproportionate amount of PN from hillslope sources.

Table 15: *Modelled* particulate nitrogen (PN) loads by erosion process as a % for each region based on 2015 Source Catchment modelling.

Region	Gully	Streambank	Hillslope
Cape York*	6	2	92
Wet Tropics	2	10	88
Burdekin	43	9	48
Fitzroy	5	7	88
Mackay Whitsunday	1	8	91
Burnett Mary	2	7	81

* For the Normanby Basin gully density data layer was replaced with data derived from gully mapping. Gully PP for the Normanby Basin is 45%.

2.3 Pesticides and other pollutants

2.3.1 Where are the pesticides coming from?

Compared with sediment and nutrient data, there has generally been less research into the sources of pesticides and new pollutants delivered from the Great Barrier Reef catchments to the marine system. A detailed update of the source, transport and management of pesticides in the Great Barrier Reef catchments was provided by Devlin et al. (2015). Monitoring programs have detected up to 55 different pesticide residues (including metabolites) in waterways of the Great Barrier Reef catchments (Devlin et al., 2015). The highest concentrations of pesticides are generally detected in smaller catchments with a high proportion of sugarcane, for example Sandy Creek and Pioneer River in the Mackay Whitsunday and Barratta Creek in the Lower Burdekin (Devlin et al., 2015).

The monitored loads of five prevalent PSII herbicides (ametryn, atrazine, diuron, hexazinone and tebuthiuron) have been reported from up to 14 end-of-system water quality monitoring sites and five sub-catchment sites since 2009. Table 17 presents the annual average loads from 2010 to 2015 and the monitored loads of a much larger suite of pesticides, including herbicides and some insecticides and fungicides, that have been reported since 2012 (Garzon-Garcia et al., 2015; Wallace et al., 2015; Wallace et al., 2016). Two sites on the Mulgrave River at Deeral and the Russell River at East Russell have been monitored since 2014-2015; however, as there was only one year of loads data available for each of these rivers at the time of publication, an annual average could not be calculated, and the data were not included in the pesticide loads assessment.

For the five PSII herbicides, the monitoring results suggest that the highest loads of ametryn are coming from the Burnett Basin at ~27 kg/yr, atrazine from the Fitzroy at ~886 kg/yr, diuron from the Pioneer at ~292 kg/yr, hexazinone from the Tully at ~102 kg/yr and tebuthiuron from the Fitzroy at ~2484 kg/yr. However, the total load for each basin can be better expressed using the toxic load approach (Smith et al., 2016a; Smith et al., 2016b) which accounts for the type of pesticides in the load and their relative toxicities and reports them as a diuron-equivalent (d-eq.) mass. The highest annual average toxic load recorded for the end-of-system sites is discharged from the Pioneer River

(332 d-eq. kg), followed by Tully River (311.5 d-eq. kg), Sandy Creek (201 d-eq. kg), Herbert River (162.2 d-eq. kg), Fitzroy River (148.6 d-eq. kg), Barratta Creek (73 d-eq. kg), Burnett River (56.9 d-eq. kg), Comet River (52.4 d-eq. kg), Burdekin River (28 d-eq. kg), North Johnstone River (27.8 d-eq. kg), O'Connell River (15.5 d-eq. kg), Tinana Creek (10.5 d-eq. kg), Mary River (8.6 d-eq. kg) and Haughton River (1.5 d-eq. kg). Based on the loads estimated for 2014-2015 (Wallace et al., 2016), other pesticides with relatively high loads include metolachlor from the Fitzroy (440 kg), imidacloprid from Tully (120 kg), fluroxypyr from Fitzroy (110 kg) and 2,4-D from all basins (total monitored = 300 kg).

The exports of the prevalent PSII herbicides from the recent 2015 Source Catchments modelling (McCloskey et al., 2017b) for each of the 35 major basins are presented in Table 18. The total amount of each PSII herbicide estimated to be delivered to the Great Barrier Reef each year is ~860 kg/yr of ametryn, 2600 kg/yr of atrazine, 5700 kg/yr of diuron, 690 kg/yr of hexazinone and 1900 kg/yr of tebuthiuron. The modelling results suggest that these PSII herbicides are not a major concern on Cape York. In the Wet Tropics and Mackay Whitsunday regions atrazine, diuron and hexazinone are found in moderate to high loads. In the Burdekin and Burnett Mary region only atrazine and diuron are found, and in the Fitzroy only atrazine and tebuthiuron are present.

The highest concentrations of pesticides are also found closest to the source in sub-catchments, with concentrations decreasing towards the end of system (Devlin et al., 2015). The highest loads of pesticides are detected in larger catchments and those catchments with high discharge volumes, for example Fitzroy and Tully (Turner et al., 2013; Wallace et al., 2014; Garzon-Garcia et al., 2015; Wallace et al., 2015; Wallace et al., 2016). However, large discharge volumes also provide greater dilution potential, therefore these catchments often have low concentrations of pesticides. The highest concentrations are most often detected at the start of the wet season in the first flush events, with concentrations dissipating over time with sequential rain events (Davis et al., 2016; Devlin et al., 2015). In irrigation-based farming systems, high concentrations can be detected before the wet season if irrigation tail water is released into catchments, for example, at Barratta Creek in the Lower Burdekin (Devlin et al., 2015).

Table 16: Average annual measured PSII herbicide loads for each of the 14 sites in the GBR catchments (Garzon-Garcia et al., 2015; Turner et al., 2013; Turner et al., 2012; Wallace et al., 2015; Wallace et al., 2014)

Region	Catchment	Gauging station	River and site name	Years of sampling	Number of samples	Ametryn (kg/yr)	Total atrazine (kg/yr)	Total diuron (kg/yr)	Hexazinone (kg/yr)	Tebuthiuron (kg/yr)	Total toxic load (kg/yr)
Wet Tropics	Johnstone	1120049	North Johnstone River at old Bruce Highway Bridge (Goondi)	4	125	NC	15.8	26.0	8.0	0.3	27.8
	Tully	113006A	Tully River at Euramo	5	371	8.1	166.0	282.0	102.0	4.4	311.5
	Herbert	116001F	Herbert River at Ingham	5	274	9.5	71.0	146.0	47.0	NC	162.2
Burdekin	Haughton	119003A	Haughton River at Powerline	2	35	0.1	5	1.2	NC	0.1	1.5
	Barratta	119101A	Barratta Creek at Northcote	5	360	4.3	290.0	58.8	4.7	0.6	73.0
	Burdekin	120001A	Burdekin River at Home Hill	5	215	12.9	158.6	18.5	0.5	217.5	28.0
Mackay Whitsunday	O'Connell	1240062	O'Connell River at Caravan Park	2	59	0.02	6.3	13.0	8.6	6.8	15.5
	Pioneer	125013A	Pioneer River at Dumbleton Pump Station	5	537	23.7	316.0	292.0	63.0	0.9	332.0
	Plane	126001A	Sandy Creek at Homebush	5	234	10.3	147.2	179.6	44.6	0.2	201.0
Fitzroy	Fitzroy	1300000	Fitzroy River at Rockhampton	5	172	NC	885.6	67.4	16.5	2,484.0	148.6
		130302A	Comet River at Comet Weir	4	55	NC	420.3	35.9	16.9	404.0	52.4
Burnett Mary	Burnett	136014A	Burnett River at Ben Anderson Barrage	5	335	27.0	110.1	42.6	35.9	72.9	56.9
	Mary	138014A	Mary River at Home Park	2	174	NC	14.5	7.55	3.2	NC	8.6
		138008A	Tinana Creek at Barrage Head Water	2	134	NC	10.4	9.9	2.8	NC	10.5

Table 17: *Modelled* end-of-basin PSII herbicide loads for each of the 35 basins based on the 2015 Source Catchments modelling.

Region	Basin name	Toxic equivalent load (kg/yr)	PSII (kg/yr)	Ametryn (kg/yr)	Atrazine (kg/yr)	Diuron (kg/yr)	Hexazinone (kg/yr)	Tebuthiuron (kg/yr)
Cape York	Jacky Jacky Ck	0	0	0	0	0	0	0
	Olive Pascoe	0	0	0	0	0	0	0
	Lockhart River	0	0	0	0	0	0	0
	Stewart River	0	0	0	0	0	0	0
	Normanby River	0	10	0	10	0	0	0
	Jeannie River	0	0	0	0	0	0	0
	Endeavour River	0	<5	0	<5	0	0	0
	Total	**<1**	20	**0**	20	**0**	**0**	**0**
Wet Tropics	Daintree	100	120	0	10	90	20	0
	Mossman	70	80	0	<5	60	10	0
	Barron	40	120	1	80	30	10	0
	Mulgrave-Russell	620	750	0	50	600	90	0
	Johnstone	750	920	0	90	730	100	0
	Tully	410	490	0	30	400	60	0
	Murray	310	370	0	20	300	50	0
	Herbert	110	250	120	90	30	<5	0
	Total	2,420	3,090	**120**	380	**2,250**	**330**	**0**
Burdekin	Black	<5	<5	0	0	<5	0	0
	Ross	0	<5	0	<5	0	0	0
	Haughton	940	1,710	0	800	910	0	0
	Burdekin	260	500	0	260	250	0	0
	Don	90	180	0	90	90	0	0
	Total	1,280	2,390	**0**	1,150	**1,240**	**0**	**0**
Mackay Whitsunday	Proserpine	250	330	50	40	200	30	0
	O'Connell	700	970	180	140	560	90	0
	Pioneer	710	980	200	140	550	90	0
	Plane	1,270	1,760	330	250	1,010	170	0
	Total	2,920	4,040	**760**	570	**2,330**	**380**	**0**
Fitzroy	Styx River	<5	200	0	<5	0	0	200
	Shoalwater	<5	110	0	0	0	0	110
	Waterpark Ck	0	20	0	0	0	0	20
	Fitzroy River	40	1750	0	290	0	0	1,460
	Calliope River	<5	100	0	0	0	0	100
	Boyne River	<5	40	0	0	0	0	40
	Total	50	2,210	**0**	300	**0**	**0**	**1,910**
Burnett Mary	Baffle	<5	10	0	10	<5	0	0
	Kolan	30	70	0	40	30	0	0
	Burnett	20	120	0	100	20	0	0
	Burrum	20	80	0	70	10	0	0
	Mary	10	70	0	60	10	0	0
	Total	90	350	**0**	270	**80**	**0**	**0**

TOTAL		***6,760***	12,100	***880***	***2,690***	***5,900***	***710***	***1,910***

2.3.2 What are the drivers and land uses delivering the pesticide loss?

Pesticide data collected across a multitude of Great Barrier Reef land uses (grazing, urban, horticulture, forestry and intensive cropping) showed that diffuse load losses were highest from intensive agriculture, mainly sugarcane (Devlin et al., 2015) (Figure 16). Physico-chemical characteristics determine the likelihood of off-paddock transport of pesticides (Simpson et al., 2000; Wauchope et al., 2002). The persistence and transport of pesticides in tropical environments is not well understood, although it is assumed that herbicides will generally dissipate more quickly in tropical and subtropical environments than under temperate conditions because of the higher temperatures and wetter conditions (Racke et al., 1997; Sanchez-Bayo and Hyne, 2011). Recent research (Shaw et al., 2013) showed that half-lives of commonly applied sugarcane herbicides under local conditions were comparable or lower than published international values. In addition, herbicides on cane residues (without rainfall) degraded slower than has been previously reported (Shaw et al., 2013).

The greatest risk window for herbicide losses from paddocks in rain-fed farming systems is within 25 days of application, whereas within irrigated farming systems, where paddocks are typically irrigated 2-4 days after herbicide application, >80% of annual herbicide losses occur in the two irrigations following application. Pesticides are delivered predominantly from surface water run-off or in irrigation tail water; only a small proportion is delivered through other mechanisms, including groundwater and airborne drift. The majority of herbicide run-off from paddocks was found to be in the dissolved phase with the exception of pendimethalin, glyphosate, diuron and imazapic. Herbicides at the sub-catchment level were also predominately (>80%) transported in the dissolved phase (Devlin et al., 2015).

Many of the pesticides detected in Great Barrier Reef catchments are registered to a multitude of different crops and land uses (Devlin et al., 2015). Catchment monitoring programs (for a review see Devlin et al., 2015) have provided evidence of the association between various pesticides and specific land uses, including sugarcane, horticulture (e.g. mixed crops in Bowen and Atherton Tableland regions, bananas), broadacre cropping, cotton, grazing, forestry and urban (including sewage treatment plants). Non-agricultural sources have also been investigated with a total of 17 pesticide residues (not including metabolites) detected in sewage treatment plants in the Cairns region (O'Brien et al., 2014); however, the concentrations (and water volumes) were relatively low compared to run-off from diffuse cropping lands. According to the 2015 modelling results the dominant source of the pesticides is sugarcane for all regions except the Fitzroy which, while it is dominated by open grazing, has significant grain and cotton cropping areas. Cape York does not contribute any significant pesticide sources to the Great Barrier Reef lagoon (Table 19). Tebuthiuron is also used in grazing areas in the Fitzroy Basin; however, it is considered to be less toxic than the other PSII chemicals.

A study comparing pesticide risk indictors with measured pesticide data from fruit tree crops determined that simple risk indicators (e.g. Pesticide Impact Rating Index, Environmental Potential Risk Indicator for Pesticides) can be good predictors or a first-tier risk assessment of pesticide transport to neighbouring water bodies (Oliver et al., 2016). Oliver et al. (2014) also determined that the application of herbicides (such as diuron and atrazine) to raised beds only is a highly effective way of minimising migration of these herbicides in drainage water from furrow-irrigated sugarcane.

Table 18: *Modelled* end-of-basin pesticide (toxic equivalent) loading by land use for each natural resource management region (%).

Region	Nature conservation	Dryland cropping	Forestry	Grazing	Horticulture	Irrigated cropping	Sugarcane	Bananas	Dairy	Urban	Water	Other	Stream banks
Cape York	0	~0	0	0	0	~0	0	0	0	0	0	0	0
Wet Tropics	0	<1	0	0	0	<1	>99	0	0	0	0	0	0
Burdekin	0	<1	0	0	0	<1	>99	0	0	0	0	0	0
Mackay Whitsunday	0	0	0	0	0	0	100	0	0	0	0	0	0
Fitzroy	0	23	0	77	0	0	0	0	0	0	0	0	0
Burnett Mary	0	2	0	0	0	1	97	0	0	0	0	0	0

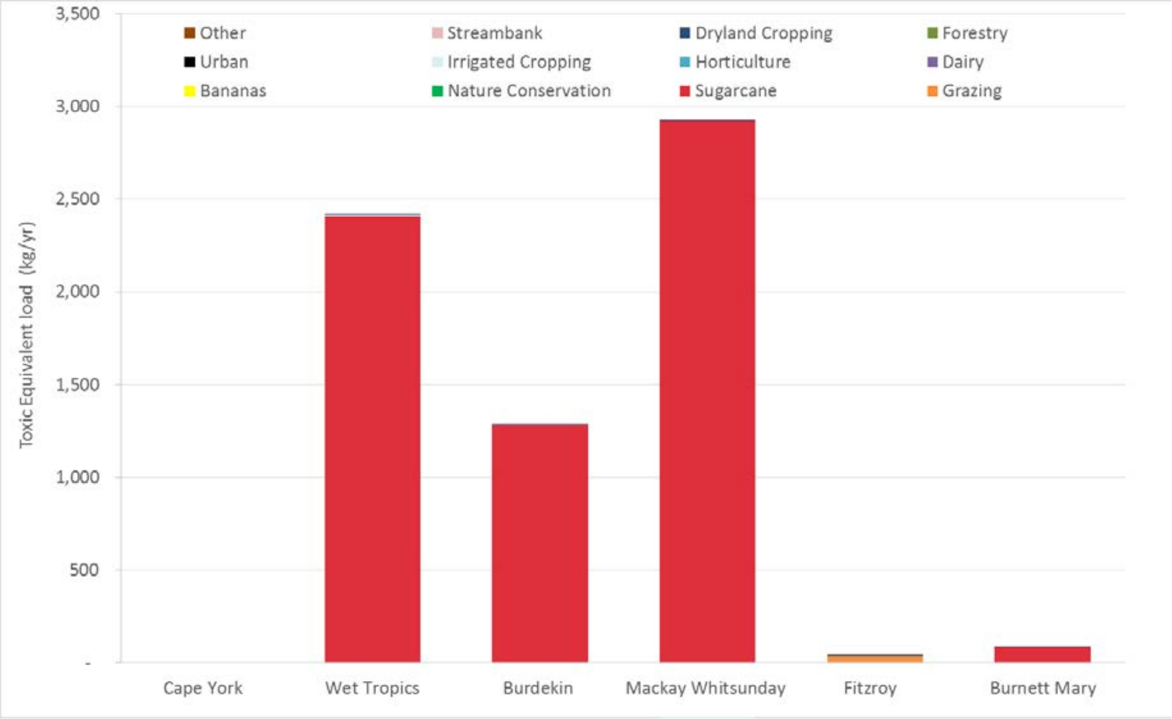


Figure 16: Contribution of main land uses to the Toxic Equivalent pesticide load for each region. 'Other' includes intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbor, military areas and open water bodies.

2.3.3 Other pollutants

Other pollutants are known to be present in the coastal and marine waters of the Great Barrier Reef (Kroon et al., 2015a). These include antifouling paints, coal particles, heavy and trace metals/metalloids, personal care products, petroleum hydrocarbons, pharmaceuticals and marine debris. In addition, pollutants such as nanomaterials, perfluorooctane sulfonate and perfluorooctanoic acid may be present but no monitoring information is available for the Great Barrier Reef lagoon. These pollutants are derived from a range of diffuse and point sources including agriculture (including intensive animal production), manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, coastal/marine tourism, military areas, and shipping (Kroon et al., 2015b). Aquaculture activities in north Queensland present possible sources of antifouling paints and pharmaceuticals. Increasing coastal development including agricultural, urban, industrial, aquaculture and defence land uses and ports, and associated projected increases in shipping traffic (Great Barrier Reef Marine Park Authority, 2014), are expected to increase the sources and diversity of pollutants being released into the Great Barrier Reef lagoon in the near future.

Monitoring information on pollutants other than sediments, nutrients and pesticides is not detailed enough, or does not exist, to provide information on the spatial and temporal variation of contaminant sources (Kroon et al., 2015b). For example, only two studies present limited monitoring data for Great Barrier Reef sewage treatment plants, confirming the presence of 26 pharmaceuticals and five personal care products in discharge effluent (O'Brien et al., 2014; Scott et al., 2014). Based on Australian (Birch et al., 2015; French et al., 2015) and overseas (Dai et al., 2016) studies, it is likely that the number of pharmaceutical personal care products in sewage treatment plant effluent and stormwater run-off is much higher. Urban stormwater and sewage treatment plants are also known sources of heavy metals (Gobeil et al., 2005), marine debris and microplastics such as fibres from clothing and microbeads from cosmetics (Browne et al., 2011; GESAMP, 2015), nanomaterials (in personal care products; Keller et al., 2014), petroleum hydrocarbons (Yunker et al., 2002) and perfluorooctane sulfonate and perfluorooctanoic acid (Xiao et al., 2012); however, no recent monitoring information is available for the Great Barrier Reef region. Similarly, limited available monitoring data demonstrates that Queensland industrial areas and ports are sources of antifouling paints (Advisian, 2015; Department of Environment and Heritage Protection, 2012; GHD Pty Ltd, 2005; Port of Townsville Limited et al., 2013; Ports North, 2015), coal dust (GHD Pty Ltd, 2012a), metals (GHD Pty Ltd, 2005; GHD Pty Ltd, 2012b; Port of Townsville Limited et al., 2013; Ports North, 2015; Taylor, 2015), and petroleum hydrocarbons (Department of the Environment, Water, Heritage and the Arts, 2009; Simpson et al., 2013) (for more detail, see Kroon et al., 2015b).

In the Great Barrier Reef catchment, other pollutants are mostly discharged from industrial, urban and sewage treatment plants but also from agricultural land uses, mines (existing and abandoned) and ports/marinas. Point sources of pollutants are generally regulated; however, (i) not all pollutants are monitored as part of these regulations (e.g. pharmaceuticals and personal care products in wastewater treatment plants), (ii) monitoring information is generally not readily available, and (iii) exceedances of ANZECC/ARMCANZ sediment and water quality guidelines (ANZECC and ARMCANZ, 2000) and the interim National Assessment Guidelines for Dredging (Department of the Environment, Water, Heritage and the Arts, 2009; Simpson et al., 2013 have been reported (Kroon et al., 2015). In addition, diffuse sources such as agricultural land uses also have the potential to contribute to the excess of other pollutants, such as metals, nanomaterials and plastic polymers, through fertiliser and pesticide applications (Berry et al., 2013; De et al., 2014; Verburg et al., 2014).

Agricultural land uses are a known source of metals (Mico et al., 2006), nanomaterials (De et al., 2014), pharmaceuticals such as antibiotics (Sarmah et al., 2006) and potentially also of microplastics, but no recent monitoring data are available for the Great Barrier Reef region. Heavy/trace metals and metalloids occur naturally in rocks and soils, but anthropogenic input of metals such as cadmium, copper, lead and zinc occurs through fertiliser applications (Mico et al., 2006). Elevated levels of arsenic, cadmium and mercury in sediments near Great Barrier Reef catchments influenced by agriculture were attributed, in part, to applications of phosphatic fertilisers and fungicides containing these elements (Haynes, 2001; Walker and Brunskill, 1996). Nanoparticles are increasingly being used for targeted delivery of pesticides in agricultural systems (De et al., 2014). Antibiotics are used to treat disease and protect animal health, including cattle, pigs and poultry (Sarmah et al., 2006). Coatings (partly) consisting of plastic polymers in slow-release fertilisers may contribute to microplastic contamination in receiving waters (Verburg et al., 2014).

Urban areas can also contribute to coastal pollution through wastewater treatment plants and urban storm water run-off (Gunn, 2014). The current population of northern Queensland exceeds 1.2 million people (Australian Bureau of Statistics, 2015), with the majority of this population in Townsville (189,000 people), Cairns (169,000), Mackay (122,000), Rockhampton (118,000), Maryborough (100,000) and Bundaberg (94,000). Over 50 wastewater treatment plants operational in north Queensland discharge into rivers that are connected to the Great Barrier Reef marine environment (Hill et al., 2012).

Industrial areas, including ports, can contribute to coastal pollution through point source releases into the air or water, as well as during transfer and transport of goods. The National Pollutant Inventory (Department of the Environment and Energy, 2016) records annual emissions and transfers of 93 pollutants from facilities around Australia, including in the Great Barrier Reef region, under the National Environment Protection Measures legislation. The inventory data do not, however, provide information on the fate of these pollutants in the environment.

Mines, both existing and abandoned, are potential sources of pollutants to adjacent coastal and marine environments. Queensland has >15,000 abandoned mines with many occurring in the Great Barrier Reef catchment (e.g. Mount Morgan gold mine) (Unger et al., 2012; Unger et al., 2015). For example, elevated mercury in a sediment core from Bowling Green Bay was thought to be a legacy of gold mining in the Charters Towers / Ravenswood area (Walker and Brunskill, 1996), although it can also be found in pesticides (Kealley, 2015). Discontinued mine sites continue to release pollutants into receiving waters (e.g. see Little, 2014), such as the tailings dam at Collingwood Bluestone tin mine near Cooktown into the Annan River (Howley, 2012). The Queensland Floods Commission also identified abandoned mine pits as a potential source of pollution to the Great Barrier Reef (Queensland Floods Commission of Inquiry, 2012).

Existing mines in the Great Barrier Reef catchment include coal, extraction of coal seam gas, underground coal gasification (which has now ceased), liquid natural gas, oil shale mining and refining and metalliferous ores. More than 50 operating coal mines currently export their product via ports in the Great Barrier Reef, and further large-scale thermal coal mines are proposed in the Surat and Galilee basins (Department of Employment, 2016). An emerging issue is the large volume of water requiring emergency releases from mines and refineries after high rainfall events (Great Barrier Reef Marine Park Authority, 2014).

Approximately 666,000 ha of acid sulphate soils occur along the Great Barrier Reef coast in close proximity to reef waters (McClurg et al., 2009a; McClurg et al., 2009b; Powell and Martens, 2005a; Ross, 2003; Ross, 2004; Ross, 2005; Ross, 2007; Ross, 2008). Drainage from acid sulphate soils occurs widely along the Queensland coast and is usually related to soil disturbances for agriculture, aquaculture and coastal developments (Baker, 2003; Cook et al., 2000). Oxidation of iron sulfide in acid sulphate soils causes acidification, metal contamination, deoxygenation and iron precipitation in receiving coastal waters (Cook et al., 2000; Powell and Martens, 2005b). Estuarine sediments impacted by acid sulphate soil drainage can be enriched with aluminium, cadmium, cobalt, copper, manganese, nickel and zinc; concentrations 5–100 times greater than background have been reported (Nordmyr et al., 2008).

Landfills, combined with rivers, lakes and wetlands used as illegal dump sites and riverine transport of waste from landfills and other inland sources, have been identified as a primary source of land-based marine debris around the world (United Nations Environment Programme, 2009). In the Great Barrier Reef lagoon, high concentrations of marine debris were recorded between Shoalwater Bay and Townsville in February 2013 (Harmel et al., 2014). These were associated with large flooding events due to ex-tropical cyclone Oswald (Bureau of Meteorology, 2014) and thus were most likely derived from land-based sources.

Military exercise and range areas are present in the Great Barrier Reef, including maritime defence practice areas, land training areas with a coastal component (e.g. Shoalwater Bay, Cowley Beach) and airspace allocated for military aviation activities (e.g. Halifax Bay range near Townsville) (PGM Environment and Eco Logical Australia, 2014). Recent monitoring detected perfluorooctane sulfonate and perfluorooctanoic acid in groundwater, surface water and sediment at the RAAF Base Townsville (GHD Pty Ltd, 2016). No other monitoring data are available concerning military exercise and range areas being potential sources of pollutants, such as antifouling paints, marine debris, metals, nanomaterials, pharmaceutical personal care products and petroleum hydrocarbons. In addition, legacy impacts associated with past defence activities include the presence of large amounts of unexploded ordnance and chemical warfare agents that were dumped at sea at the end of World War II (Great Barrier Reef Marine Park Authority, 2014). Limited information exists concerning sources other than shipping and domestic sewage.

2.4 New approaches to estimating catchment loads and water quality trends

A range of techniques have been used over the last 30 years to estimate end-of-catchment and basin pollutant loads to the Great Barrier Reef. These include simple empirical models (e.g. Belperio, 1979; Moss et al., 1993; Neil et al., 2002), catchment budget modelling (McKergow et al., 2005a; McKergow et al. 2005b), monitored loads (Furnas, 2003; Joo et al., 2012) and integrated modelling and monitoring data (Kroon et al., 2012; Kuhnert et al., 2012). The most recent modelling approach is outlined in Waters et al. (2014) and McCloskey et al. (2017a; 2017b).

2.4.1 Validating modelled load estimates

Several studies have compared the Source Catchments model outputs against monitored data (Wilkinson et al., 2014b), other empirically derived data (Hughes and Croke, 2011) and alternative modelling approaches (Alvarez-Romero et al., 2014). These studies determined that the Source Catchment model gave similar levels of error when compared to general rating curve approaches and other similar catchment models for predicting end-of-catchment sediment load data. They also agreed that the models could be improved considerably by using locally derived estimates of erosion, storage, transformation and delivery. This would reduce the overestimates of erosion and delivery that generally occur when generic input parameters are used.

2.4.2 Data assimilation and estimating confidence

The more recent general additive modelling approach for sediment and nutrient modelling (Kuhnert et al., 2012; Robson and Dourdet, 2015) also formed the basis for an investigation into whether trends in total sediment loads could be detected with any level of certainty (Darnell et al., 2012). This research showed that end-of-catchment monitoring programs will have low statistical power (<40% chance) of detecting improved water quality trends (towards achieving the Reef Water Quality Protection Plan target) of a 20% TSS load reduction at end of catchment by 2020 for both the Tully and Burdekin rivers.

More recently, efforts have focused on assimilating measurements with modelled output with the intent of providing confidence estimates for load predictions across an entire catchment. Pagendam et al. (2014) developed a Bayesian Hierarchical Modelling framework for assimilating (or blending) monitoring data for a 14 km^2 rangeland catchment in the Burdekin using modelled outputs from the Loads Regression Estimator statistical model (Kuhnert et al., 2012) and SymHyd (Chiew et al., 2002). This work was then extended to estimating loads at 411 spatial locations across a time frame of 21 years in the Upper Burdekin catchment, where Source Catchments modelled output was assimilated with measurements from 14 sites where flow and/or concentration was measured in the Upper Burdekin (Gladish et al., 2016). The assimilation approach combined Source Catchments modelled outputs of flow and concentration with measurements (if available) using (a weighted average of) Bayesian methods. The weights of each piece of information were influenced by uncertainties specified through priors. Where the uncertainty was high for a particular information source (measured or modelled), this information was down-weighted in the estimation of flow and concentration. In general, where measurements were available, the estimate of the concentration, flow and the subsequent load was quantified with a high level of certainty. New methods for visualising and communicating the outputs from the Bayesian Hierarchical Modelling, particularly the uncertainty and how this can be linked to better and more informed decision-making, is currently being explored (Kuhnert et al., in review).

3. Synthesis of key findings

Table 20 provides a summary of (i) the key findings from the previous Scientific Consensus Statement in 2013, (ii) the new insights and information gained over the last four years of research, and (iii) contentious, unresolved areas of further research. The implications and considerations for improved management are discussed in Chapter 5.

Table 19: Synthesis of established knowledge, new information and areas of further research relating to the sources of pollutants to the Great Barrier Reef

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	New information or insights	Contentious, unresolved or unknown areas (for further research)
Overarching	• The key findings from the 2013 Scientific Consensus Statement were based on modelled export loads for the six natural resource management regions. Monitoring data were discussed, but only PSII herbicide data were presented.	In this review, data are presented using: • measured pollutant loads data for 32 sites (with up to nine years of data) for sediments, nutrients and pesticides • updated modelling data (up to 2014-2015) have been presented at the management unit (or sub-catchment) scale for the 47 management units • a synthesis of individual research project findings focusing on the last four years (2013-2017).	• Explicit estimates of confidence are required to highlight where we have high/medium or low confidence in the various datasets. • A more robust framework for incorporating new knowledge into Source Catchment modelling and reporting would improve transparency and knowledge integration.
Sediments	• Mean-annual river loads to the Great Barrier Reef lagoon for total suspended solids have increased 3.2 to 5.5-fold compared to pre-European conditions.	• There is an estimated 9900 kt/yr of fine (silt and clay) sediment being delivered to the Great Barrier Reef. Approximately 7930 kt/yr of this sediment is estimated to be anthropogenic and due to changes in land use and management. Modelled estimates suggest that fine sediment has increased ~5-fold (between 3 and 8 times depending on the basin) from pre-development conditions. • The relative rankings of modelled load data for catchments with high per unit area sediment loads have been reasonably consistent over the last 10 years. • Anthropogenic load increases from pre-development conditions have been validated against long half-life nuclides in some catchments (Burdekin, Barron).	• Independent estimates (not modelled) of the relative ratio of pre-development erosion rates for different landscapes will help refine pre-development model estimates (e.g. long half-life nuclides or similar approach), but these are not yet widely available.
	• Comparing mean annual total suspended solids loads by individual basin showed good agreement between	• The Burdekin Basin contributes ~40% of the anthropogenic total suspended solids load to the Great Barrier Reef lagoon, with the Wet Tropics	• A systematic review is required of both the modelling and monitoring data, using all available water quality data (including the sub-

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	New information or insights	Contentious, unresolved or unknown areas (for further research)
Sediments cont'd.	estimates derived from monitoring and modelling.	(~15%), Fitzroy (~18%) and Burnett Mary (~15%) the other dominant regions. - Within these regions, the top five sediment-contributing basins are the Burdekin, Fitzroy, Mary, Burnett and Herbert basins. - Reporting pollutant loads at smaller basin scales has highlighted that there are hotspot areas (e.g. Bowen Bogie), particularly within the larger catchments. This is supported by more recent monitoring data.	catchment and pre-2006 data), across similar flow periods at a range of nested scales. - Many monitoring records remain short (< 5-10 years).
	- The main sources for the anthropogenic total suspended solids load to the Great Barrier Reef lagoon are (i) grazing lands (gully and hillslope erosion) (45%) and streambank erosion (39%), (ii) the Fitzroy and Burdekin basins (at least 70%), and (iii) a combination of gully and streambank erosion and subsoil erosion from hillslope rilling, rather than broadscale hillslope sheetwash erosion.	- Using the **monitored** specific sediment loads (t/km^2/yr), ~64% of the sediment load is coming from the top quartile (n = 8) of basins. - Using the anthropogenic **modelled** specific loads (t/km^2/yr), ~64% of the sediment load is coming from the top quartile (n = 12) of management units. - The dominant source of sediments according to land use has not changed significantly. Grazing dominates overall sediment delivery to the Great Barrier Reef, as well as in the Burdekin, Fitzroy and Burnett-Mary. In the Wet Tropics and Mackay Whitsundays, sugar cane is the largest source of total sediment. Sugar and bananas have high specific sediment yields. - Sediment source tracing in several catchments has identified that approximately 90% of fine sediment delivered to the Great Barrier Reef is from subsoil erosion (which could be derived from gully, bank, scald or deep rill erosion). Of the sediment coming	- The relative contribution of fine sediment from gullies in different soil types (alluvial vs hillslope) is currently not known for most of the Great Barrier Reef. - The influence of ground cover (amount, biomass, composition and distribution) on sub-catchment and catchment scale runoff and sediment delivery is not fully understood and is important for understanding the influence of hillslope hydrology on channel and gully erosion. - The contribution of erosion from un-sealed roads to end of catchment sediment yields is currently poorly understood, but is likely to be a significant point source in some areas. - Catchment modelling suggests that Cape York, as a region, is dominated by hillslope erosion sources (~64%). Tracing and dating studies in the Normanby catchment have now shown that gully erosion is the dominant erosion process

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	New information or insights	Contentious, unresolved or unknown areas (for further research)
Sediments cont'd.		from subsoil sources, ~50% is estimated to be from vertical surfaces (gullies and riverbanks) and 40% from horizontal surfaces of subsoil (hillslope scalds, rills and gully floors). • Sediments from urban land uses (particularly greenfield sites) can be important at local scales.	contributing to sediment loads. These data have been integrated into the Normanby modelling; however, further data are needed to refine the models for the remainder of Cape York.
	• Monitored total suspended solids in the Burdekin, Fitzroy, Plane, Burnett and Normanby catchments contain a high proportion of fine sediment (<10 µm) material, which is the fraction most likely to reach the Great Barrier Reef lagoon.	• It is the clay-rich <16 µm fine sediment that is travelling the furthest into the marine system. Larger particles are stored or trapped in the rivers or nearshore zone. • Large dams and weirs can trap considerable amounts (up to 70%) of fine sediment. This reduces the delivery of sediment to the coast from areas upstream of large dams. It is estimated that the Burdekin Falls Dam has reduced the total sediment load from the Burdekin River by 35% compared with pre-dam conditions. • Dating of in-channel sediment stores (benches) suggests that in-channel storage of both fine and coarse material can be significant in some areas. This reduces or delays the delivery of fine and coarse material to the marine system. This may also reduce the ability to evaluate remediation effectiveness if measurements are only taken at the end of the system.	• There needs to be better agreement regarding the particle size of the fine sediment fraction that is used in catchment and marine systems studies. • The range and dominant particle size of sediment is not well understood for many parts of the Great Barrier Reef catchments. Analysis and interpretation of previously collected particle size data should be a priority. • Further understanding of the variations in erosion, storage and delivery of fine sediment will improve targeting of areas for remediation.
	• Land-use change and intensification has been correlated with increased suspended sediment loads that are recorded within coral cores offshore of the Burdekin River mouth.	• New evidence from coral core (flow reconstruction) analysis suggests that there was a measured increase in river flow at the same time as human settlement of the Burdekin region. Any measured increase in pollutant yield after 1860 is	• The role of long-term natural climate fluctuation on end-of-catchment sediment fluxes is not well understood and is essential for developing achievable water quality targets.

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	New information or insights	Contentious, unresolved or unknown areas (for further research)
		therefore likely to be a combination of land use and climatic factors.	
Nutrients	- Mean annual river loads to the Great Barrier Reef lagoon have increased 2.0–5.7-fold for TN and 2.5–8.9 times for TP compared to pre-European conditions. - PN comprises by far the largest proportion of the mean annual anthropogenic TN loads, followed by DIN. - Most PN is lost or mineralised from fine sediment following delivery to the Great Barrier Reef lagoon and could be readily available for uptake in Great Barrier Reef ecosystems.	- The total modelled nutrient loads estimated to be delivered to the Great Barrier Reef are ~55 kt/yr for TN and 13.4 kt/yr for TP. Approximately 29 kt/yr and 8.8 kt/yr of this TN and TP is estimated to be anthropogenic and due to changes in land use and management, respectively. This is 2.1- and 2.9-fold increase for TN and TP, respectively. - The total modelled DIN estimated to be delivered to the GBR is ~12 kt/yr of which 6.0 kt/yr is estimated to be anthropogenic and due to changes in land use and management. For PN the total load is ~25 kt/yr, where ~17 kt/yr is anthropogenic, and for PP the total load is ~10 kt/yr, where ~7.5 kt/yr is anthropogenic. DIN increased by ~2-fold (range 1.2–6.0, or 38-fold in the case of Cape York) and for PN the increase has been ~1.5-fold (ranging between 1.2- and 2.2-fold). - Of these total loads, PN contributes ~45% of TN, and PP contributes 76% of TP. - DIN contributes 22% of TN at the GBR scale according to the models.	- There is relatively low confidence in the pre-European nutrient load estimates due to the scarcity of measured data to validate models. The lack of data makes the setting of water quality targets based on anthropogenic loads problematic. - Targeted monitoring of water quality data from less disturbed sites (e.g. rainforest) would provide important insights into pre-development conditions.
	- Comparing mean annual TN loads by individual basins showed reasonable agreement between estimates derived from modelling and monitoring.	- The available load monitoring data generally support the priority management units identified by modelling; however, absolute values can vary significantly for some forms of nutrients between data types.	- A systematic review of both the modelling and monitoring data for all pollutants at similar flow periods at a range of scales (not just at the end of system) is required.

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	New information or insights	Contentious, unresolved or unknown areas (for further research)
Nutrients cont'd.		• Lateral export of DIN to surface water is now included in the modelled estimates in sugarcane areas. The modelling of lateral movement supports studies which suggest this may be a potential pathway for DIN.	• The relative contribution of groundwater nitrogen to total loads exported to the stream needs further research.
	• The Fitzroy, Burdekin and Wet Tropics contribute over 75% to the anthropogenic TN load to the Great Barrier Reef lagoon. • The Fitzroy and Burdekin basins contribute approximately 55% of the anthropogenic TP load to the Great Barrier Reef lagoon.	• TN delivery to the GBR is dominated by the Wet Tropics (30%) and Fitzroy (20%) regions; DIN delivery is dominated by the Wet Tropics (46%) and Burdekin (21%); and PN delivery is dominated by the Wet Tropics (27%) and Fitzroy (20%) regions. PP delivery is dominated by the Fitzroy (33%) and Burdekin (22%) regions. • Within these regions, hotspot areas exist. The top five basins contributing to the DIN load are the Herbert, Burdekin, Johnstone, Haughton and Mulgrave-Russell. • The top five basins contributing to the PN 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 TN, ~87% of the DIN, 69% of the PN, 69% of the TP and 72% of PP based on the specific nutrient yields (t/km^2/y). • Using the monitored end-of-basin specific loads (t/km^2/yr), 68% of the PP, 70% of PN and 79% of the DIN load is coming from the top quartile of basins (n = 8). • Using the modelled data, the top quartile of management units (n = 12) deliver ~87% of the	• As above

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	New information or insights	Contentious, unresolved or unknown areas (for further research)
Nutrients cont'd.		DIN, 69% of PN, 67% of the TN, 72% of PP and 69% of the TP to the Great Barrier Reef.	
	• PN comprises by far the largest proportions of the mean annual anthropogenic TN loads, followed by DIN and . • PP comprises by far the largest proportions of the mean annual anthropogenic TP loads.	• The total modelled anthropogenic nitrogen load is made up of ~45% PN, ~33% and 22% DIN. • The total monitored nitrogen load is made up of ~49% PN, ~34% and 15% DIN. • Modelled PP comprises 76% of the mean annual anthropogenic TP load. This is the same per cent as for measured PP. • The total monitored phosphorus load is made up of ~76% PP, ~8% dissolved organic phosphorus and 16% DIP.	• The bioavailable status (the magnitude and timescales) and conversion processes of the various forms of nutrients, in both freshwater and marine settings, require further understanding. This will assist with targeting the main source of pollutants.
	• Most PN and PP is lost or mineralised from fine sediment following delivery to the Great Barrier Reef lagoon and could be readily available for uptake in Great Barrier Reef ecosystems.	• 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.	• There have been no investigations into the contribution of particulate nutrients from streambank erosion. • The contribution of bioavailable nitrogen from natural sources is not well understood and needs to be considered for evaluating anthropogenic loadings and future effectiveness of management actions. • There have been no published nutrient isotope studies at the sub-catchment or catchment scale.
	• Sediment erosion processes, particularly in grazing lands are sources of PN and PP; sugarcane and grazing are sources of DIN; and land-use changes in filter and buffer capacity are the main sources of .	• Grazing dominates the source of PN river loads, and sugar dominates DIN river loads. • The measured concentrations of DIN from natural (rainforest) settings are potentially higher than have been modelled.	• As above

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	New information or insights	Contentious, unresolved or unknown areas (for further research)
		• Although the spatial location of bioavailable PN sources may differ from TSS, the management strategies for mitigating export of PN and TSS are similar. • Dissolved and particulate nutrient loads from urban land uses, particularly wastewater discharges, can be important at local scales, but generally represent <7% overall.	
Pesticides	• The total mean annual load of PSII-inhibiting pesticides is estimated to range between 16,000 and 17,000 kg per year. • The total pesticide load to the Great Barrier Reef lagoon is likely to be considerably larger, given that at least 28 pesticides have been detected in the Great Barrier Reef catchments. • Comparing mean annual PSII inhibiting pesticide loads by individual basins showed large variability between estimates derived from modelling and monitoring.	• The 2015 modelled total mean annual load of PSII-inhibiting pesticides is ~12,100 kg per year. • Since the last Scientific Consensus Statement there is more monitored pesticide load data across a greater range of sites; however, detailed comparison of the measured and modelled data has not been explicitly undertaken for this review. Results from the measured end-of-system water quality monitoring sites suggest that the measured pesticide loads are generally lower than modelled estimates. • The measured pesticide data suggest that most pesticides are found in all regions, even though some are in very small quantities and may not be registered for use in those areas.	• Lack of on-farm application rates and pesticide usage data is a major limitation to understanding the source of pesticides. • There have been several laboratory-based studies; however, more field-based assessments would improve our understanding of (i) the fate and source of pesticides in various environmental conditions (groundwater, surface freshwater and marine conditions), (ii) pesticide half-lives in freshwater, and (iii) pesticides transported in the bound and dissolved phases. • A detailed comparison of pesticide concentrations obtained from monitoring and modelling is required.
	• The main sources for the PSII inhibiting pesticides load to the Great Barrier Reef lagoon are (i) sugarcane (94%), (ii) the Wet Tropics, Burdekin and Mackay Whitsunday basins (more than 85%).	• The toxic equivalent loads for pesticides are highest from sugarcane for all regions, except the Fitzroy, where grazing dominates. • Total toxic equivalent loads are dominated by the Wet Tropics, Mackay Whitsunday and Burdekin sugarcane areas.	• As above • A broader range of toxic pesticides should be reported (the current five should be expanded in annual reporting).

	Established knowledge and understanding (based on previous Scientific Consensus Statement findings)	**New information or insights**	**Contentious, unresolved or unknown areas (for further research)**
Other pollutants	• Other sources of pollutants to the Great Barrier Reef lagoon include point sources such as intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, and shipping. Compared to diffuse sources, most contributions of such point sources are relatively small but could be locally and over short time periods highly significant. Point sources are generally regulated activities; however, monitoring and permit information is not always available.	• Compared with sediment and nutrient data, there has generally been less research into the sources of pesticides and new pollutants delivered from the Great Barrier Reef catchments to the marine system. • Other pollutants are mostly discharged from industrial, urban and sewage treatment plant sources but also from agricultural land uses, mines (existing and abandoned) and ports/marinas.	• Monitoring information on pollutants other than sediments, nutrients and pesticides is not detailed enough or does not exist. • There is a need to increase our understanding of the types, concentrations and sources of a range of pollutants.

4. Research gaps and areas of further research

The key knowledge gaps related to each of the pollutant sources were summarised in Table 20. This section provides some more context on the key opportunities, research gaps and priority needs.

Limitations and associated opportunities

- There are good (up to nine-year) records of measured pollutant data at up to 32 sites across the Great Barrier Reef. It would be timely to undertake a focused analysis and comparison of the measured and modelled data at multiple sites within each catchment. This would provide (i) an understanding of where the models and measurements are working well and where they could be improved (e.g. Alvarez-Romero et al., 2014; Newham et al., 2003; Wilkinson et al., 2014b), (ii) an insight into how the models and measurements vary at different scales (sub-catchment vs. end of system) (e.g. Wilkinson, 2008), (iii) evaluate if there are differences between modelled and measured datasets for different pollutants or erosion processes (e.g. Bartley et al., 2007; Hughes and Croke, 2011), (iv) an evaluation of the potential influence of climate change.
- There is relatively low confidence in the pre-development load estimates for sediments and particulate nutrients due to the scarcity of measured data to validate models. The lack of data makes the setting of water quality targets based on anthropogenic loads problematic. Various techniques (e.g. isotopes and dating) are now available that would provide important insights into pre-development conditions that should be applied more broadly.
- Given our improved understanding of the importance of particle size and the nutrient status of sediments in terms of delivery and ecological risk to the Great Barrier Reef, an increased effort should be given to measuring and reporting on particle size and other chemical metrics within the loads monitoring program.

Research gaps

- Processes such as the 'Birch effect' (Jarvis et al., 2007; Xiang et al., 2008), which relates soil nutrient release to soil wetting and drying cycles, should be investigated.
- A more thorough consideration of the impact of roads and fences on sediment delivery should be undertaken.
- There is a need to initiate (i) targeted sampling programs, and (ii) open source data management for existing data on priority emerging pollutants.

Priority needs

- There is an urgent need to explicitly quantify certainty and confidence in the load modelling and monitoring data. Error or confidence is currently accounted for in the flow modelling but not the load modelling. Techniques are available for evaluating models (e.g. Daggupati et al., 2015; Moriasi et al., 2015; Saraswat et al., 2015) as well as for quantifying uncertainty by blending modelling and monitoring data (as discussed in Section 2.4.2).
- We now have considerable data to identify that sub-surface erosion is a dominant source of fine sediment and particulate nutrients; however, further work is needed to determine which type of sub-surface erosion dominates erosion sources in key areas (e.g. alluvial gully walls, hillslope gully walls, scalds, rills, cane drains or streambank erosion).
- The influence of ground cover (amount, biomass, composition and distribution) on sub-catchment- and catchment-scale run-off, sediment and nutrient delivery is not fully understood

and is important for understanding the influence of hillslope hydrology on riverbank and gully erosion. Continued work using the most recent, higher resolution, remotely sensed ground cover should be a priority.

- A key gap in our understanding is knowledge of the best place for returning riparian vegetation in the landscape and the associated cost effectiveness of such approaches.
- Recent research has highlighted the need for a better understanding of the role of land use, soil type and erosion processes (including gully erosion dynamics) in controlling the delivery and bioavailability of nutrients (nitrogen and phosphorus). Given this new knowledge, there is an urgent need to develop whole-of-catchment/basin nutrient budgets (using measured field data) that compare all bioavailable nutrient sources and include areas such as estuaries, mud flats, freshwater lagoons and a range of land uses (e.g. cropping AND grazing). Investigating the bioavailability of nutrients from individual processes or land units (e.g. alluvial gullies) is useful, but this needs to be put into a broader context, and all sources need to be evaluated at the landscape scale.
- The role of long-term natural climate fluctuation on end-of-catchment sediment and nutrient fluxes is not well understood; this knowledge is essential for developing achievable water quality targets.
- The availability of industry-specific pesticide/herbicide and chemical usage data is urgently needed. This would inform monitoring programs and improve modelling outputs. A greater linkage with relevant industries is required to facilitate communication between researchers, managers, regulators and end users so these data may become more accessible.

5. Reference list

Abernethy, B., Rutherfurd, I.D., 1998. Where along a river's length will vegetation most effectively stabilise stream banks? Geomorphology, 23, 55-75.

Advisian, 2015. Abbot Point Growth Gateway Project Environmental Impact Statement. Advisian, Brisbane, Australia, 591 pp.

Alvarez-Romero, J.G., Wilkinson, S.N., Pressey, R.L., Ban, N.C., Kool, J., Brodie, J., 2014. Modeling catchment nutrients and sediment loads to inform regional management of water quality in coastal-marine ecosystems: A comparison of two approaches. Journal of Environmental Management, 146, 164-178.

Amos, K.J., Alexander, J., Horn, T., Pocock, G.D., Fielding, C.R., 2004. Supply limited sediment transport in a high-discharge event of the tropical Burdekin River, North Queensland, Australia. Sedimentology, 51, 145-162.

Amos, K.J., Croke, J.C., Hughes, A.O., Chapman, J., Takken, I., Lymburner, L., 2008. A catchment-scale assessment of anabranching in the 143 000 km^2 Fitzroy River catchment, north-eastern Australia. Earth Surface Processes and Landforms, 33, 1222-1241.

ANZECC, ARMCANZ, 2000. The Australian and New Zealand Guidelines for Fresh and Marine Water Quality, National Water Quality Management Strategy, Paper No. 4. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand www.mincos.gov.au/publications/australian_and_new_zealand_guidelines_for_fresh_and_marine_water_quality.

Australian Bureau of Statistics, 2015. Data by Region. http://stat.abs.gov.au/itt/r.jsp?databyregion

Bainbridge, Z., 2004. Bank erosion in the Upper Burdekin River, North Queensland: an evaluation of a predictive bank erosion model, Tropical Environmental Studies and Geography. Honours Thesis, James Cook University, Townsville, 75 pp.

Bainbridge, Z.T., Brodie, J.E., Faithful, J.W., Sydes, D.A., Lewis, S.E., 2009. Identifying the land-based sources of suspended sediments, nutrients and pesticides discharged to the Great Barrier Reef from the Tully–Murray Basin, Queensland, Australia. Marine and Freshwater Research 60, 1081-1090.

Bainbridge, Z.T.., Wolanski, E.C., Alvarez-Romero, J., Lewis, S., Brodie, J., 2012. Fine sediment and nutrient dynamics related to particle size and floc formation in a Burdekin River discharge event, Australia. Marine Pollution Bulletin, 65(4–9), 236-248.

Bainbridge, Z.T., Lewis, S.E., Smithers, S.G., Kuhnert, P.M., Henderson, B.L., Brodie, J.E., 2014. Fine suspended sediment and water budgets for a large, seasonally dry tropical catchment: Burdekin River catchment, Queensland, Australia. Water Resources Research, 50, 9067-9087.

Bainbridge, Z., Lewis, S., Smithers, S., Wilkinson, S., Douglas, G., Hillier, S., Brodie, J., 2016. Clay mineral source tracing and characterisation of Burdekin River (NE Australia) and flood plume fine sediment. Journal of Soils and Sediments, 16, 687-706.

Baker, J.E., 2003. A report on the study of land-sources pollutants and their impacts on water quality in and adjacent to the Great Barrier Reef. Department of Primary Industries, Queensland Government, Brisbane, Australia, 187 pp.

Bartley, R., Olley, J., Henderson, A., 2004. A sediment budget for the Herbert River catchment, North Queensland, Australia. *In:* V. Golosov, V. Belyaev, and D.E. Walling (eds.). *Sediment Transfer through the Fluvial System*. IAHS Publ. No. 288, Moscow, pp. 147-153.

Bartley, R., Roth, C.H., Ludwig, J., McJannet, D., Liedloff, A., Corfield, J., Hawdon, A., Abbott, B., 2006. Runoff and erosion from Australia's tropical semi-arid rangelands: influence of ground cover for differing space and time scales. Hydrological Processes, 20, 3317-3333.

Bartley, R., Keen, R.J., Hawdon, A.A., Hairsine, P.B., Disher, M.G., Kinsey-Henderson, A.E., 2008. Bank erosion and channel width change in a tropical catchment. Earth Surface Processes and Landforms, 33, 2174-2200.

Bartley, R., Post, D.A., Kinsey-Henderson, A., Hawdon, A., 2007. Estimating sediment loads in Great Barrier Reef catchments: balance between modelling and monitoring. *In:* A.L. Wilson, R.L. Dehaan, R.J. Watts, K.J. Page, K.H. Bowmer, and A. Curtis (eds.). *5th Australian Stream Management Conference*. Charles Sturt University, Albury, May 2007, pp. 13-18.

Bartley, R., Corfield, J.P., Abbott, B.N., Hawdon, A.A., Wilkinson, S.N., Nelson, B., 2010. Impacts of improved grazing land management on sediment yields, Part I: hillslope processes. Journal of Hydrology, 389, 237-248.

Bartley, R., Speirs, W.J., Ellis, T.W., Waters, D.K., 2012. A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. Marine Pollution Bulletin, 65, 101-116.

Bartley, R., Bainbridge, Z.T., Lewis, S.E., Kroon, F.J., Wilkinson, S.N., Brodie, J.E., Silburn, D.M., 2014a. Relating sediment impacts on coral reefs to watershed sources, processes and management: A review. Science of the Total Environment, 468–469C, 1138-1153.

Bartley, R., Corfield, J.P., Hawdon, A.A., Kinsey-Henderson, A.E., Abbott, B.N., Wilkinson, S.N., Keen, R.J., 2014b. Can changes to pasture management reduce runoff and sediment loss to the Great Barrier Reef? The results of a 10-year study in the Burdekin catchment, Australia. The Rangeland Journal, 36, 67-84.

Bartley, R., Croke, J., Bainbridge, Z.T., Austin, J.M., Kuhnert, P.M., 2015a. Combining contemporary and long-term erosion rates to target erosion hot-spots in the Great Barrier Reef, Australia. Anthropocene, 10.

Bartley, R., Kinsey-Henderson, A., Wilkinson, S., Whitten, S., Rutherfurd, I., 2015b. Stream bank management in the Great Barrier Reef catchments: a handbook. CSIRO, Report to the Department of the Environment (Reef Program).

Bartley, R., Goodwin, N., Henderson, A.E., Hawdon, A., Tindall, D., Wilkinson, S.N., Baker, B., 2016a. A comparison of tools for monitoring and evaluating channel change. Report to NESP, Project 1.2b.

Bartley, R., Philip, S., Henderson, A.E., Tindall, D., 2016b. Investing in riparian zone management to reduce erosion from stream channels: how do we evaluate success? Report to NESP, Project 1.2a.

Beeson, C.E., Doyle, P.F., 1995. Comparison of bank erosion at vegetated and non-vegetated channel bends. American Water Resources Bulletin, 31, 983-990.

Bell, M., Schaffelke, B., Moody, P., Waters, D., Silburn, M., 2016. Tracking nitrogen from the paddock to the reef—a case study from the Great Barrier Reef. Proceedings of the 2016 International Nitrogen Initiative conference *Solutions to improve nitrogen use efficiency for the world*, Melbourne 4-8 December 2016, www.ini2016.com/pdf-papers/INI2016_Bell_Michael.pdf.

Belperio, A.P., 1979. The combined use of wash load and bed material load rating curves for the calculation of total load: An example from the Burdekin River, Australia. Catena, 6, 317-329.

Berry, K.L.E., O'Brien, D., Burns, K.A., Brodie, J., 2013. Unrecognized pollutant risk to the Great Barrier Reef. Great Barrier Reef Marine Park Authority, Townsville. 30 pp.

Birch, G.F., Drage, D.S., Thompson, K., Eaglesham, G., Mueller, J.F., 2015. Emerging contaminants (pharmaceuticals, personal care products, a food additive and pesticides) in waters of Sydney estuary, Australia. Marine Pollution Bulletin, 97, 56-66.

Bosomworth, B., Cowie, B., 2016. Response to the independent reviews of DNRM activities under Action 8 & 9 of Reef Plan 2013. Department of Natural Resources and Mines, Queensland Government,

Brodie, J.E., Mitchell, A.W., 2005. Nutrients in Australian tropical rivers: changes with agricultural development and implications for receiving environments. Marine and Freshwater Research, 56, 279-302.

Brodie, J., Burford, M., Davis, A., da Silva, E., Devlin, M., Furnas, M., Kroon, F., Lewis, S., Lonborg, C., O'Brien, D., Schaffelke, B., Bainbridge, Z., 2015. The relative risks to water quality from particulate nitrogen discharged from rivers to the Great Barrier Reef in comparison to other forms of nitrogen. Centre for Tropical Water & Aquatic Ecosystem Research, James Cook University, Townsville. 98 pp.

Brooke, B., Bostock, H., Smith, J., Ryan, D., 2006. Geomorphology and Sediments of the Fitzroy River coastal sedimentary system – Summary and overview. Cooperative Research Centre for Coastal Zone Estuary and Waterway Management Technical Report No. 47, Coastal CRC, Queensland.

Brooks, A., Spencer, J., Olley, J., Pietsch, T., Borombovits, D., Curwen, G., Shellberg, J., Howley, C., Gleeson, A., Simon, A., Bankhead, N., Klimetz, D., Eslami-Endargoli, L., Bourgeault, A., 2013. An empirically-based sediment budget for the Normanby Basin: Sediment sources, sinks and drivers on the Cape York Savannah. Griffith University, Brisbane. 506 pp.

Brooks, A., Borombovits, D., Spencer, J., Pietsch, T., Olley, J., 2014a. Measured hillslope erosion rates in the wet-dry tropics of Cape York, northern Australia Part 1: A low cost sediment trap for measuring hillslope erosion in remote areas—Trap design and evaluation. Catena, 122, 42-53.

Brooks, A., Spencer, J., Borombovits, D., Pietsch, T., Olley, J., 2014b. Measured hillslope erosion rates in the wet-dry tropics of Cape York, northern Australia: Part 2, RUSLE-based modeling significantly over-predicts hillslope sediment production. Catena, 122, 1-17.

Brooks, A., Olley, J., Iwashita, F., Spencer, J., McMahon, J., Curwen, G., Saxton, N.E., Gibson, S., 2014c. Reducing sediment pollution in Queensland Rivers: towards the development of a method to quantify and prioritise bank erosion in Queensland Rivers based on field evidence from the Upper Brisbane, O'Connell and Normanby Rivers, Final report to Queensland State Government, Department of Science Information Technology Innovation and the Arts.

Brooks, A., Curwen, G., Spencer, J., Shellberg, J., Garzon-Garcia, A., Burton, J., Iwashita, F., 2016. Reducing sediment sources to the Reef: managing alluvial gully erosion. Report to the National Environmental Science Programme (Project 1.7). Reef and Rainforest Research Centre Limited, Cairns.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of Microplastic on Shorelines Woldwide: Sources and Sinks. Environmental Science & Technology, 45, 9175-9179.

Browne, N.K., Smithers, S.G., Perry, C.T., 2012. Coral reefs of the turbid inner-shelf of the Great Barrier Reef, Australia: An environmental and geomorphic perspective on their occurrence, composition and growth. Earth-Science Reviews, 115, 1-20.

Bureau of Meteorology, 2014. Ex-TC Oswald Floods. January and February 2013. Bureau of Meteorology, Canberra. 73 pp.

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/.

Burton, J., Moody, P., DeHayr, R., Chen, C., Lewis, S., Olley, J., 2015. Sources of bioavailable particulate nutrients: Phase 1 (RP128G). Department of Science, Information Technology and Innovation 34 pp.

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..

Chiew, F.H.S., McMahon, T.A., 1993. Detection of trend or change in annual flow of Australian rivers. International Journal of Climatology, 13, 643-653.

Chiew, F., Peel, M., Western, A., 2002. Application and testing of the simple rainfall-runoff model SIMHYD. *In:* V. Singh and D. Frevert (eds.). *Mathematical Models of Small Watershed Hydrology and Applications*. Water Resources Publications, Littleton, Colorado, USA. pp. 335–367.

Ciesiolka, C., 1987. Catchment Management in the Nogoa Watershed. Australian Water Resources Council, Canberra.

Connolly, N.M., Pearson, R.G., Loong, D., Maughan, M., Brodie, J., 2015. Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. Agriculture, Ecosystems & Environment, 213, 11-20.

Connolly, R.D., Ciesiolka, C.A.A., Silburn, D.M. and Carroll, C., 1997. Distributed parameter hydrology model (Answers) applied to a range of catchment scales using rainfall simulator data. IV Evaluating pasture catchment hydrology. Journal of Hydrology, 201(1-4): 311-328.

Connor, S., Nelson, P.N., Armour, J.D., Henault, C., 2013. Hydrology of a forested riparian zone in an agricultural landscape of the humid tropics. Agriculture, Ecosystems & Environment, 180, 111-122.

Cook, F.J., Hicks, W., Gardner, E.A., Carlin, G.D., Froggatt, D.W., 2000. Export of acidity in drainage water from acid sulfate soils. Marine Pollution Bulletin, 41, 319-326.

Cooper, M., Lewis, S.E., Smithers, S.G., 2016. Spatial and temporal dynamics of suspended sediment causing persistent turbidity in a large reservoir: Lake Dalrymple, Queensland, Australia. Marine and Freshwater Research, 68(7). doi:/10.1071/MF16316.

Cowie, B.A., Thornton, C.M., Radford, B.J., 2007. The Brigalow Catchment Study: I. Overview of a 40-year study of the effects of land clearing in the brigalow bioregion of Australia. Australian Journal of Soil Research, 45, 479-495.

Croke, J., Bartley, R., Chappell, J., Austin, J.M., Fifield, K., Tims, S.G., Thompson, C.J., Furuichi, T., 2015. 10Be-derived denudation rates from the Burdekin catchment: The largest contributor of sediment to the Great Barrier Reef. Geomorphology, 241, 122-134.

Curran, J.C., Hession, W.C., 2013. Vegetative impacts on hydraulics and sediment processes across the fluvial system. Journal of Hydrology, 505, 364-376.

Daggupati, P., Pai, N., Ale, S., Doulgas-Mankin, K.R., Zeckoski, R., Jeong, J., Parajuli, P., Saraswat, D., Youssef, M., 2015. A recommended calibration and validation strategies for hydrological and water quality models. Transactions of ASABE, 58(6). doi:10.13031/trans.58.10712.

Dai, G., Wang, B., Fu, C., Dong, R., Huang, J., Deng, S., Wang, Y., Yu, G., 2016. Pharmaceuticals and personal care products (PPCPs) in urban and suburban rivers of Beijing, China: occurrence, source apportionment and potential ecological risk. Environmental Science-Processes & Impacts, 18, 445-455.

Darnell, R., Henderson, B., Kroon, F.J., Kuhnert, P., 2012. Statistical power of detecting trends in total suspended sediment loads to the Great Barrier Reef. Marine Pollution Bulletin, 65, 203-209.

Davis, A.M., Pearson, R.G., Brodie, J.E., Butler, B., 2016. Review and conceptual models of agricultural impacts and water quality in waterways of the Great Barrier Reef catchment area. Marine and Freshwater Research, 68, 1-19.

De, A., Bose, R., Kumar, A., Mozumdar, S., 2014. Targeted Delivery of Pesticides Using Biodegradable Polymeric Nanoparticles. Springer, New York, USA.

De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M., 2012. The 27–year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences, 109, 17995-17999.

Delandmeter, P., Lewis, S.E., Lambrechts, J., Deleersnijder, E., Legat, V., Wolanski, E., 2015. The transport and fate of riverine fine sediment exported to a semi-open system. Estuarine, Coastal and Shelf Science, 167, Part B, 336-346.

Department 2016. Queensland's coal: mines and advanced projects. Queensland Government, https://www.dnrm.qld.gov.au/__data/assets/pdf_file/0011/238079/coal-mines-advanced-projects.pdf Brisbane. 8 pp.

Department of Environment and Heritage Protection, 2012. Update on the Quality of Sediment from Port Curtis and Tributaries. Deparment of Environment and Heritage Protection, Brisbane. 31 pp.

Department of the Environment and Energy, 2016. National Pollutant Inventory. Australian Government, Canberra. www.npi.gov.au/.

Department of the Environment, Water, Heritage and the Arts, 2009. National Assessment Guidelines for Dredging. Department of the Environment, Water, Heritage and the Arts, Canberra. 92 pp.

Devlin, M., Lewis, S., Davis, A., Smith, R., Negri, A., Thompson, M., Poggio, M., 2015. Advancing our understanding of the source, management, transport and impacts of pesticides on the Great Barrier Reef 2011-2015: A report for the Queensland Department of Environment and Heritage Protection. Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication, James Cook University, Cairns. 134 pp.

Dougall, C., McCloskey, G.L., Ellis, R., Shaw, M., Waters, D., Carroll, C., 2014. Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments - Fitzroy NRM region. Queensland Department of Natural Resources and Mines, Rockhampton, Queensland.

Douglas, G.B., Ford, P.W., Palmer, M., Noble, R.M., Packett, R., 2006a. Fitzroy River, Queensland, Australia. II. Identification of Sources of Estuary Bottom Sediments. Environmental Chemistry, 3, 377-385.

Douglas, G.B., Ford, P.W., Palmer, M., Noble, R.M., Packett, R., 2006b. Fitzroy River Basin, Queensland, Australia. I. Identification of Sediment Sources in Impoundments and Flood Events. Environmental Chemistry, 3, 364-376.

Douglas, G.B., Ford, P.W., Palmer, M.R., Noble, R.M., Packett, R.J., Krull, E.S., 2008. Fitzroy River Basin, Queensland, Australia. IV. Identification of flood sediment sources in the Fitzroy River. Environmental Chemistry, 5, 243-257.

Elledge, A., Thornton, C., 2017. Effect of changing land use from virgin brigalow (*Acacia harpophylla*) woodland to a crop or pasture system on sediment, nitrogen and phosphorus in runoff over 25 years in subtropical Australia. Agriculture, Ecosystems & Environment, 239, 119-131.

Fitzroy Basin Association Inc., 2015. Fitzroy Water Quality Improvement Plan. 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. http://reefcatchments.com.au/files/2015/06/WATER-QUALITY-IMPROVEMENT-PLAN-MACKAY-WHITSUNDAY-ISAAC-2014-2021_DRAFT.pdf.

French, V.A., King, S.C., Kumar, A., Northcott, G., McGuinness, K., Parry, D., 2015. Characterisation of microcontaminants in Darwin Harbour, a tropical estuary of northern Australia undergoing rapid development. Science of the Total Environment, 536, 639-647.

Furnas, M., 2003. Catchment and Corals: Terrestrial Runoff to the Great Barrier Reef. Australian Institute of Marine Science, Townsville.

Furuichi, T., Olley, J., Wilkinson, S., Lewis, S., Bainbridge, Z., Burton, J., 2016. Paired geochemical tracing and load monitoring analysis for identifying sediment sources in a large catchment draining into the Great Barrier Reef Lagoon. Geomorphology, 266, 41-52.

Garzon-Garcia, A., Burton, J., Brooks, A., 2016. Bioavailable nutrients and organics in alluvial gully sediment. Department of Science, Information Technology and Innovation, Brisbane. 59 pp.

Garzon-Garcia, A., Wallace, R., Huggins, R., Turner, R.D.R., Smith, R.A., Orr, D., Ferguson, B., Gardiner, R., Thomson, B., J., Warne M. St. J., 2015. Total suspended solids, nutrient and pesticide loads (2013–2014) for rivers that discharge to the Great Barrier Reef Great Barrier Reef Catchment Loads Monitoring Program. Water Quality and Investigations, Environmental Monitoring and Assessment Science, Science Division, Department of Science, Information Technology and Innovation.

Garzon-Garcia, A., Laceby, J.P., Olley, J.M., Bunn, S.E., 2017. Differentiating the sources of fine sediment, organic matter and nitrogen in a subtropical Australian catchment. Science of the Total Environment, 575, 1384-1394.

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. ISBN 82-7701-011-7Goatley, C. H., & Bellwood, D. R. 2012. Sediment suppresses herbivory across a coral reef depth gradient. Biology letters, 8(6), 1016-1018.

GESAMP, 2015. Sources, fate and effects of microplastics in the marine environment: a global assessment. *In:* P.J. Kershaw (ed.). IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, London, UK. 96 pp.

GHD Pty Ltd, 2005. Port of Hay Point Apron Area and Departure Path Capital Dredging. Draft Environmental Impact Statement. GHD, Brisbane. 303 pp.

GHD Pty Ltd, 2012a. Abbott Point Cumulative Impact Assessment. Technical Report Marine Water Quality. Final. GHD Pty Ltd, Brisbane. 399 pp.

GHD Pty Ltd, 2012b. Abbot Point, Terminal 0, Terminal 2 and Terminal 3 Capital Dredging Public Environment Report (EPBC 2011/6213/GBRMPA G34897.1). GHD Pty Ltd, Brisbane. 35 pp.

GHD Pty Ltd, 2016. Defence per- and poly-fluoroalkyl Substances (PFAS) Environmental Management Preliminary Sampling Program, Final Report. GHD Pty Ltd, Brisbane. 47 pp.

Gladish, D.W., Kuhnert, P.M., Pagendam, D.E., Wilke, C.K., Bartley, R., Searle, R.D., Ellis, R.J., Dougall, C., Turner, R.D.R., Lewis, S.E., Bainbridge, Z.T., Brodie, J.E., 2016. Spatio-temporal assimilation of modelled catchment loads with monitoring data in the Great Barrier Reef. Annals of Applied Statistics, 10, 1590-1618.

Glanville, K., Ryan, T., Tomlinson, M., Muriuki, G., Ronan, M., Pollett, A., 2016. A Method for Catchment Scale Mapping of Groundwater-Dependent Ecosystems to Support Natural Resource Management (Queensland, Australia). Environmental Management, 57, 432-449.

Gleeson, A., 2012. Cape York's unsealed road network and its impact on the surrounding aquatic ecosystem. Griffith University, Unpublished Honours Thesis.

Gobeil, C., Rondeau, B., Beaudin, L., 2005. Contribution of municipal effluents to metal fluxes in the St. Lawrence river. Environvironmental Science & Technology, 39, 456-464.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., 1992. Stream Hydrology (An Introduction for Ecologists). John Wiley and Sons, England.

Gowen, R., Bray, S.G., 2016. Bioeconomic modelling of woody regrowth carbon offset options in productive grazing systems. The Rangeland Journal, 38, 307-317.

Great Barrier Reef Marine Park Authority, 2014. Great Barrier Reef Outlook Report 2014. Great Barrier Reef Marine Park Authority, Townsville. 328 pp.

Gunn, J., 2014. Urban Land Use in Great Barrier Reef Water Quality Improvement Plans: Background Report and Considered Guidance.

Hancock, G.J., Wilkinson, S.N., Hawdon, A.A., Keen, R.J., 2014. Use of fallout tracers 7Be, 210Pb and 137Cs to distinguish the form of sub-surface soil erosion delivering sediment to rivers in large catchments. Hydrological Processes, 28, 3855-3874.

Hardesty, B.D., Wilcox, C., Lawson, T.J., Lansdell, M., van der Velde, T., 2014. Understanding the effects of marine debris on wildlife. Final report to Earthwatch Australia.365 pp.

Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L., Arnold, J.G., 2006. Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Transactions of the ASABE, 49, 689-701.

Harmel, R.D., Smith, P.K., Migliaccio, K.W., Chaubey, I., Douglas-Mankin, K.R., Benham, B., Shukla, S., Munoz-Carpena, R. and Robson, B.J., 2014. Evaluating, interpreting, and communicating performance of hydrologic/water quality models considering intended use: A review and recommendations. Environmental Modelling & Software, 57, 40-51, doi:10.1016/j.envsoft.2014.02.013.

Haynes, D., 2001. Great Barrier Reef water quality: Current issues. Great Barrier Reef Marine Park Authority, Townsville. 97 pp.

Hewawasam, T., von Blanckenburg, F., Schaller, M., Kubik, P., 2003. Increase of human over natural erosion rates in tropical highlands constrained by cosmogenic nuclides. Geology, 31, 597-600.

Hill, R., Carter, L., Kay, R., 2012. National Wastewater Treatment Plants Database. 1st ed. Geosciences Australia, Canberra.

Hillier, S., 1995. Erosion, sedimentation and sedimentary origin of clays. *In:* B. Velde (ed.). *Origin and mineralogy of clays: Clays and the environment*. Springer, Berlin Heidelberg. pp. 162-219.

Hooke, J.M., 1980. Magnitude and distribution of rates of river bank erosion. Earth Surface Processes and Landforms, 5, 143-157.

Howley, C., 2012. Annan and Endeavour River Freshwater and Estuarine Water Quality Report: An assessment of ambient water quality and effects of land use 2002-2009. CYMAG Environmental Inc., Cooktown, Qld. 115 pp.

Hughes, A., Prosser, P., Stevenson, J., Scott, A., Lu, H., Gallant, J. and Moran, C., 2001. Gully erosion mapping for the National Land and Water Audit. Technical Report 26/01, CSIRO Land and Water, Canberra.

Hughes, A.O., Croke, J.C., 2011. Validation of a spatially distributed erosion and sediment yield model (SedNet) with empirically derived data from a catchment adjacent to the Great Barrier Reef Lagoon. Marine and Freshwater Research, 62, 962-973.

Hughes, A., Prosser, P., Stevenson, J., Scott, A., Lu, H., Gallant, J. and Moran, C., 2001. Gully erosion mapping for the National Land and Water Audit. Technical Report 26/01, CSIRO Land and Water, Canberra.

Hughes, A.O., Croke, J.C., Pietsch, T.J., Olley, J.M., 2009a. Changes in the rates of floodplain and in-channel bench accretion in response to catchment disturbance, central Queensland, Australia. Geomorphology, 114, 338-347.

Hughes, A.O., Olley, J.M., Croke, J.C., McKergow, L.A., 2009b. Sediment source changes over the last 250 years in a dry-tropical catchment, central Queensland, Australia. Geomorphology, 104, 262-275.

Hughes, A.O., Olley, J.M., Croke, J.C., Webster, I.T., 2009c. Determining floodplain sedimentation rates using 137Cs in a low fallout environment dominated by channel- and cultivation-derived sediment inputs, central Queensland, Australia. Journal of Environmental Radioactivity, 100, 858-865.

Hughes, K., Croke, J., Bartley, R., Thompson, C., Sharma, A., 2015. Alluvial terrace preservation in the Wet Tropics, northeast Queensland, Australia. Geomorphology, 248, 311-326.

Hunter, H.M., 2012. Nutrients and herbicides in groundwater flows to the Great Barrier Reef lagoon. Report to the Reef Policy Unit, Queensland Government. 86 pp.

Hunter, H.M., Walton, R.S., 2008. Land-use effects on fluxes of suspended sediment, nitrogen and phosphorus from a river catchment of the Great Barrier Reef, Australia. Journal of Hydrology, 356, 131-146.

Jackson, J., Ash, A.J., 1998. Tree-grass relationships in open eucalypt woodlands of northeastern Australia: influence of trees on pasture productivity, forage quality and species distribution. Agroforestry Systems, 40, 159-176.

Jackson, J., Ash, A.J., 2001. The role of trees in enhancing soil nutrient availability for native perennial grasses in open eucalypt woodlands of north-east Queensland. Australian Journal of Agricultural Research, 52, 377-386.

Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., Banza, J., David, J., Miglietta, F., Borghetti, M., Manca, G., Valentini, R., 2007. Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emission: the ‘Birch effect’. Tree Physiology, 27, 929-940.

Joo, M., Raymond, M.M., Huggins, R., Turner, R.D.R., Vardy, S., 2011. Sediment and Nutrient Loads Ten Priority Great Barrier Reef Catchments 2006–2009. Queensland Government Department of Environment and Resource Management, Brisbane.

Joo, M., Raymond, M.A.A., McNeil, V.H., Huggins, R., Turner, R.D.R., Choy, S., 2012. Estimates of sediment and nutrient loads in 10 major catchments draining to the Great Barrier Reef during 2006–2009. Marine Pollution Bulletin, 65, 150-166.

Karfs, R.A., Abbott, B.N., Scarth, P.F., Wallace, J.F., 2009. Land condition monitoring information for reef catchments: a new era. The Rangeland Journal, 31, 69-86.

Kaushal, S.S., Mayer, P.M., Vidon, P.G., Smith, R.M., Pennino, M.J., Newcomer, T.A., Duan, S., Welty, C., Belt, K.T., 2014. Land Use and Climate Variability Amplify Carbon, Nutrient, and Contaminant Pulses: A Review with Management Implications. JAWRA Journal of the American Water Resources Association, 50, 585-614.

Kealley, M., 2015. 'Shirtan—is its future limited?' Australian Canegrower, 30 Mar 2015, 11. www.canegrowers.com.au/icms_docs/225613_australian_canegrower_2015-03-30.pdf.

Keller, A.A., Vosti, W., Wang, H., Lazareva, A., 2014. Release of engineered nanomaterials from personal care products throughout their life cycle. Journal of Nanoparticle Research, 16, 24898. doi:10.1007/s11051-014-2489-9.

Kroon, F.J., Kuhnert, P.M., Henderson, B.L., Wilkinson, S.N., Kinsey-Henderson, A., Abbott, B., Brodie, J.E., Turner, R.D.R., 2012. River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoon. Marine Pollution Bulletin, 65, 167-181.

Kroon, F., Turner, R., Smith, R., Warne, M., Hunter, H.M., Bartley, R., Wilkinson, S., Lewis, S., Waters, D., Carroll, C., 2013. Chapter 4: Sources of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment. *In:* J. Brodie, J. Waterhouse, B. Schaffelke, F. Kroon, P.J. Thorburn, J. Rolfe, J. Johnson, K. Fabricius, S. Lewis, M. Devlin, M. Warne, L. McKenzie, L. (eds.). *2013 Scientific Consensus Statement*. Reef Water Quality Protection Plan Secretariat.

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., 2015a. 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. 149 pp.

Kroon, F., Berry, K., Brinkman, D., Davis, A., King, O., Kookana, R., Lewis, S., Leusch, F., Makarynskyy, O., Melvin, S., Mueller, J., Neale, P., Negri, A., O'Brien, D., Puotinen, M., Smith, R., Tsang, J., van de Merwe, J., Warne, M., Williams, M., 2015b. Identification, impacts and prioritsiation of emerging contaminants present in the GBR and Torres Strait marine environments, Final Report Project 1.10. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns. 138 pp.

Krumins, J.A., van Oevelen, D., Bezemer, T.M., De Deyn, G.B., Hol, W.H.G., van Donk, E., de Boer, W., de Ruiter, P.C., Middelburg, J.J., Monroy, F., Soetaert, K., Thebault, E., de Koppel, J.V., van Veen, J.A., Viketoft, M., van der Putten, W.H., 2013. Soil and Freshwater and Marine Sediment Food Webs: Their Structure and Function. Bioscience, 63, 35-42.

Kuhnert, P., Kinsey-Henderson, A., Herr, A., 2007. Incorporating uncertainty in gully erosion mapping using the random forests modelling approach. CSIRO Mathematical and Information Sciences, Brisbane. 38 pp.

Kuhnert, P., Henderson, B., Lewis, S.E., Bainbridge, Z.T., Wilkinson, S.N., Brodie, J.E., 2012. Quantifying total suspended sediment export from the Burdekin River catchment using the Loads Regression Estimator tool. Water Resources Research, 48, W04533. doi:10.1029/2011WR011080.

Kuhnert, P.M., Pagendam, D.E., Bartley, R., Gladish, D.W., Lewis, S.E., Bainbridge, Z.T., Searle, R.D., in review. Prioritising sites contributing high sources of sediment in the face of uncertainty: a case study using the Upper Burdekin catchment in the Great Barrier Reef. Marine and Freshwater Research.

Larcombe, P., Ridd, P.V., Prytz, A., Wilson, B., 1995. Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. Coral Reefs, 14, 163-171.

Leeder, M.R., 1982. Sedimentology: process and product. Chapman and Hall, London. 354 pp.

Lenahan, M.J., Bristow, K.L., 2010. Understanding sub-surface solute distributions and salinization mechanisms in a tropical coastal floodplain groundwater system. Journal of Hydrology, 390, 131-142.

Leonard, S., Nott, J., 2015a. Rapid Cycles of Episodic Adjustment: Understanding the Holocene fluvial archive of the Daintree River of Northeastern Australia. The Holocene, 25, 1208-1219.

Leonard, S., Nott, J., 2015b. Integrating Geomorphological Assessments and Oral Histories in Catchment Management: Implications for the Mulgrave River, Northeastern Australia. Geographical Research, 53, 160-174.

Lewis, S.E., Bainbridge, Z.T., Sherman, B.S., Brodie, J.E., Cooper, M., 2009. The trapping efficiency of the Burdekin Falls Dam: Estimates from a three-year monitoring program. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns, and Australian Centre for Tropical Freshwater Research, Townsville. 31 pp.

Lewis, S.E., Bainbridge, Z.T., Kuhnert, P.M., Sherman, B.S., Henderson, B., Dougall, C., Cooper, M., Brodie, J.E., 2013. Calculating sediment trapping efficiencies for reservoirs in tropical settings: A case study from the Burdekin Falls Dam, NE Australia. Water Resources Research, 49, 1017-1029.

Lewis, S., Brodie, J., Endo, G., Lough, J., Furnas, M., Bainbridge, Z., 2014a. Synthesizing Historical Land Use Change, Fertiliser and Pesticide Usage and Pollutant Load Data in the Regulated Catchments to Quantify Baseline and Changing Loads Exported to the Great Barrier Reef. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville. 105 pp.

Lewis, S.E., Olley, J., Furuichi, T., Sharma, A., Burton, J., 2014b. Complex sediment deposition history on a wide continental shelf: Implications for the calculation of accumulation rates on the Great Barrier Reef. Earth and Planetary Science Letters, 393, 146-158.

Lewis S., Bartley R., Bainbridge Z., Wilkinson, S., Burton J., Bui, E. 2015a. Burdekin sediment story. Report No. 15/50 for the NQ Dry Tropics NRM, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication, James Cook University, Townsville. 42 pp.

Lewis, S., Packett, B., Dougall, C., Brodie, J., Bartley, R., Silburn, M., 2015b. Fitzroy Sediment Story. Synthesis report to the Fitzroy Basin Association as part of the Water Quality Improvement Plan process. Fitzroy Basin Association, Rockhampton. 38 pp.

Lewis, S.E., Lough, J.M., Cantin, N.E., Matson, E.G., Kinsley, L., Bainbridge, Z.T., Brodie, J.E., in review. A critical evaluation of coral Ba/Ca, Mn/Ca and Y/Ca ratios as indicators of terrestrial input: new data from the Great Barrier Reef, Australia. Geochimica et Cosmochimica Acta.

Little, I., 2014. Upper Herbert River Catchment Sediment Sources and Rehabilitation Opportunities, Report to Terrain NRM.Ian Little Environmental Consultant Mining & Agriculture,Queensland . 52 pp.

Lough, J.M., Lewis, S.E., Cantin, N.E., 2015. Freshwater impacts in the central Great Barrier Reef: 1648–2011. Coral Reefs, 34, 739-751.

Ludwig, J.A., Tongway, D.J., 2002. Clearing savannas for use as rangelands in Queensland: altered landscapes and water-erosion processes. The Rangeland Journal, 24, 83-95.

Ludwig, J.A., Bartley, R., Hawdon, A., Abbott, B., McJannet, D., 2007. Patch configuration non-linearly affects sediment loss across scales in a grazed catchment in north-east Australia. Ecosystems, 10, 839-845.

Martin, T.G., McIntye, S., 2007. Impacts of livestock grazing and tree clearing on birds of woodland and riparian habitats. Conservation Biology, 21, 504-514.

McCloskey, G., 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. 220 pp.

McCloskey, G., 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. 185 pp.

McClurg, J.I., Powell, B., Morrison, D., Hampson, R.J., 2009a. Acid sulfate soil water quality improvement plan: Far North Queensland. Department of Natural Resources and Water, Brisbane. 95 pp.

McClurg, J.I., Powell, B., Norman, P., Hampson, R.J., 2009b. Acid Sulfate Soils Water Quality Improvement Plan Mackay - Whitsunday. Department of Environment and Resource Management, Coorparoo, Qld. 144 pp.

McCulloch, M., Fallon, S., Wyndham, T., Hendy, E., Lough, J., Barnes, D., 2003a. Coral record of increased sediment flux to the inner Great Barrier Reef since European Settlement. Nature, 421, 727-730.

McCulloch, M., Pailles, C., Moody, P., Martin, C.E., 2003b. Tracing the source of sediment and phosphorus into the Great Barrier Reef Lagoon. Earth and Planetary Science Letters, 210, 249-258.

McIvor, J.G., 2001. Pasture management in semi-arid tropical woodlands: regeneration of degraded pastures protected from grazing. Australian Journal of Experimental Agriculture, 41, 487-496.

McIvor, J.G., Williams, J., Gardener, C.J., 1995a. Pasture management influences runoff and soil movement in the semi-arid tropics. Australian Journal of Experimental Agriculture, 35, 55-65.

McIvor, J.G., Ash, A.J., Cook, G.D., 1995b. Land condition in the tropical tallgrass pasture lands 1. Effect of herbage production. The Rangelands Journal, 177(1), 69-85.

McKergow, L.A., Prosser, I.P., Hughes, A.O., Brodie, J., 2005a. Regional scale nutrient modelling: exports to the Great Barrier Reef World Heritage Area. Marine Pollution Bulletin, 51, 186-199.

McKergow, L.A., Prosser, I.P., Hughes, A.O., Brodie, J., 2005b. Sources of sediment to the Great Barrier Reef World Heritage Area. Marine Pollution Bulletin, 51, 200-211.

Micheli, E.R., Kirchner, J.W., Larsen, E.W., 2004. Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, central Sacramento River, California, USA. River Research and Applications, 20, 537-548.

Mico, C., Recatala, L., Peris, A., Sanchez, J., 2006. Assessing heavy metal sources in agricultural soils of an European Mediterranean area by multivariate analysis. Chemosphere, 65, 863-872.

Mitchell, A., Reghenzani, J., Faithful, J., Furnas, M., Brodie, J., 2009. Relationships between land use and nutrient concentrations in streams draining a ‘wet-tropics’ catchment in northern Australia. Marine and Freshwater Research, 60, 1097-1108.

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. Transactions of the ASABE, 58(6), 1763-1785.

Moss, A.J., Rayment, G.E., Reilly, N., Best, E.K., 1993. A preliminary assessment of sediment and nutrient exports from Queensland coastal catchments. Queensland Department of Environment and Heritage, Brisbane.

Neil, D.T., Orpin, A.R., Ridd, P.V., Yu, B., 2002. Sediment yield and impacts from river catchments to the Great Barrier Reef Lagoon. Marine and Freshwater Research, 53, 733-752.

Newham, L.T.H., Norton, J.P., Prosser, I.P., Croke, B.F.W., Jakeman, A.J., 2003. Sensitivity analysis for assessing the behaviour of a landscape-based sediment source and transport model. Environmental Modelling and Software, 18, 741-751.

Nichols, K.K., Bierman, P.R., Rood, D.H., 2014. 10Be constrains the sediment sources and sediment yields to the Great Barrier Reef from the tropical Barron River catchment, Queensland, Australia. Geomorphology, 224, 102-110.

Nordmyr, L., Åström, M., Peltola, P., 2008. Metal pollution of estuarine sediments caused by leaching of acid sulphate soils. Estuarine, Coastal and Shelf Science, 76, 141-152.

NQ Dry Tropics, 2016. Burdekin Region Water Quality Improvement Plan 2016. Better Water for the Burdekin. NQ Dry Tropics, Townsville. 236 pp.

O'Brien, D., Lewis, S., Gallen, C., O'Brien, J., Thompson, K., Eaglesham, G., Mueller, J., 2014. Barron River pesticide monitoring and Cairns WWTP WQ assessment. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication, James Cook University, Cairns. 49 pp.

Oliver, D.P., Anderson, J.S., Davis, A., Lewis, S., Brodie, J., Kookana, R., 2014. Banded applications are highly effective in minimising herbicide migration from furrow-irrigated sugar cane. Science of the Total Environment, 466–467, 841-848.

Oliver, D.P., Kookana, R.S., Anderson, J.S., Umali, B., 2016. Field evaluation of two risk indicators for predicting likelihood of pesticide transport to surface water from two orchards. Science of the Total Environment, 571, 819-825.

Olley, J., Brooks, A., Spencer, J., Pietsch, T., Borombovits, D., 2013. Subsoil erosion dominates the supply of fine sediment to rivers draining into Princess Charlotte Bay, Australia. Journal of Environmental Radioactivity, 124, 121-129.

Olley, J., Burton, J., Hermoso, V., Smolders, K., McMahon, J., Thomson, B., Watkinson, A., 2015. Remnant riparian vegetation, sediment and nutrient loads, and river rehabilitation in subtropical Australia. Hydrological Processes, 29, 2290-2300.

Packett, R., Dougall, C., Rohde, K., Noble, R., 2009. Agricultural lands are hot-spots for annual runoff polluting the southern Great Barrier Reef Lagoon. Marine Pollution Bulletin, 58, 976-986.

Pagendam, D.E., Kuhnert, P., Leeds, W.B., Wikle, C., Bartley, R. and Peterson, E., 2014. Assimilating catchment processes with monitoring data to estimate sediment loads to the Great Barrier Reef. Environmetrics, DOI: 10.1002/env.2255, DOI: 10.1002/env.2255. Peña-Arancibia, J.L., van Dijk, A.I.J.M., Guerschman, J.P., Mulligan, M., Bruijnzeel, L.A., McVicar, T.R., 2012. Detecting changes in streamflow after partial woodland clearing in two large catchments in the seasonal tropics. Journal of Hydrology, 416-417, 60-71.

PGM Environment and Eco Logical Australia, 2014. Strategic Environmental Assessment of Defence Activities in the Great Barrier Reef World Heritage Area, 2014: Update Report. Prepared for the Department of Defence. Eco Logical Australia Pty Ltd and Polglaze Griffin Miller & Associates Pty Ltd, Perth, Australia, 51pp.

Pietsch, T.J., Brooks, A.P., Spencer, J., Olley, J.M., Borombovits, D., 2015. Age, distribution, and significance within a sediment budget, of in-channel depositional surfaces in the Normanby River, Queensland, Australia. Geomorphology, 239, 17-40.

Port of Townsville Limited, AECOM Australia, BMT WBM Pty Ltd., 2013. Port expansion project : environmental impact statement. Port of Townsville Limited, Townsville, Australia, 1311p.

Ports North, 2015. Cairns Shipping Development Project. Draft : Environmental Impact Statement. Ports North, Cairns, Australia.

Powell, B., Martens, M., 2005a. A review of acid sulfate soil impacts, actions and policies that impact on water quality in Great Barrier Reef catchments, including a case study on remediation at East Trinity. Marine Pollution Bulletin, 51, 149-164.

Powell, B., Martens, M., 2005b. A review of acid sulfate soil impacts, actions and policies that impact on water quality in Great Barrier Reef catchments, including a case study on remediation at East Trinity. Marine Pollution Bulletin, 51, 149-164.

Pressland, A.J., Scanlan, J.C., Myles, D.J., Anderson, E.R., 1991. Ground flora composition influences rainfall-runoff and soil loss in semiarid tropical rangelands of Australia. *In:* Proceedings of the IV Congress International des Terres de Parcours, Montpellier, France. CIRAD, Montpellier, France. pp. 153-155.

Queensland Audit Office, 2015. Managing water quality in Great Barrier Reef catchments. Report 20: 2014-15. Queensland Audit Office, 101 pp.

Queensland Floods Commission of Inquiry, 2012. Chapter 13: Mining. Queensland Government, pp. 351-385. www.floodcommission.qld.gov.au/__data/assets/pdf_file/0017/11717/QFCI-Final-Report-Chapter-13-Mining.pdf.

Racke, K.D., Skidmore, M.W., Hamilton, D.J., Unsworth, J.B., Miyamoto, J., Cohen, S.Z., 1997. Pesticide fate in tropical soils. Pure and Applied Chemistry, 69, 1349-1371.

Rasiah, V., Armour, J.D., Nelson, P.N., 2013. Nitrate in shallow fluctuating groundwater under sugarcane: Quantifying the lateral export quantities to surface waters. Agriculture, Ecosystems & Environment, 180, 103-110.

Robson, B.J., Dourdet, V., 2015. Prediction of sediment, particulate nutrient and dissolved nutrient concentrations in a dry tropical river to provide input to a mechanistic coastal water quality model. Environmental Modelling & Software, 63, 97-108.

Rohde, K., McDuffie, K., Agnew, J., 2013. Paddock to Sub-catchment Scale Water Quality Monitoring of Sugarcane Management Practices. Final Report 2009/10 to 2011/12 Wet Seasons, Mackay Whitsunday Region. Department of Natural Resources and Mines, Queensland Government for Reef Catchments (Mackay Whitsunday Isaac) Limited, Australia.

Ross, D.J., 2003. Acid Sulfate Soils Keppel Sands - Yeppoon Area Central Queensland Coast. Department of Natural Resources and Water, Rockhampton. 41 pp.

Ross, D.J., 2004. Acid Sulfate Soils Tannum Sands - Gladstone Area Central Queensland Coast. Department of Natural Resources & Mines, Rockhampton. 39 pp.

Ross, D.J., 2005. Acid Sulfate Soils of the Narrows Area, Central Queensland Coast. Department of Natural Resources & Mines, Rockhampton. 42 pp.

Ross, D.J., 2007. Acid Sulfate Soils, Bajool - Port Alma Area, Central Queensland Coast. Department of Natural Resources and Water, Rockhampton. 44 pp.

Ross, D.J., 2008. Acid Sulfate Soils Corio Bay Area Central Queensland Coast. Department of Natural Resources and Water, Rockhampton. 41 pp.

Roth, C., 2004. A framework relating soil surface condition to infiltration and sediment and nutrient mobilisation in grazed rangelands of north-eastern Queensland. Earth Surface Processes and Landforms, 29, 1093-1104.

Sanchez-Bayo, F., Hyne, R.V., 2011. Comparison of environmental risks of pesticides between tropical and nontropical regions. Integrated Environmental Assessment and Management, 7, 577-586.

Saraswat, D., Frankenberg, J.R., Pai, N., Ale, S., Daggupati, P., Doulgas-Mankin, K.R., Youssef, M., 2015. Hydrologic and water quality models: documentation and reporting procedures for calibration, validation, and use. Transactions of ASABE, 58(6), 1787-1797. doi:10.13031/trans.57.10707.

Sarmah, A.K., Meyer, M.T., Boxall, A.B., 2006. A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (VAs) in the environment. Chemosphere, 65, 725-759.

Scanlan, J.C., 2002. Some aspects of tree-grass dynamics in Queensland's grazing lands. The Rangeland Journal, 24, 56-82.

Scanlan, J.C., Pressland, A.J., Myles, D.J., 1996. Run-off and soil movement on mid-slopes in North-east Queensland grazed woodlands. The Rangeland Journal, 18, 33-46.

Scott, P.D., Bartkow, M., Blockwell, S.J., Coleman, H.M., Khan, S.J., Lim, R., McDonald, J.A., Nice, H., Nugegoda, D., Pettigrove, V., Tremblay, L.A., Warne, M.S.J., Leusch, F.D.L., 2014. A national survey of trace organic contaminants in Australian rivers. Journal of Environmental Quality, 43, 1702-1712.

Shaw, M., Silburn, D.M., Rojas-Ponce, S., Lewis, S.E., Davis, A., 2013. Herbicide degradation on Queensland cropping soils and crop residue half-lives measured in a controlled environment. Report to the Reef Rescue Water Quality Research & Development Program. Reef and Rainforest Research Centre Limited, Cairns. 66 pp.

Shaw, R.J, 1995. A unified soil proproerty and sodicity model of salt leaching and water movement. PhD thesis, Department of Agriculture, University of Queensland, Brisbane. 283 pp.

Shellberg, J., Brooks, A., Spencer, J., 2010. Land-use change from indigenous management to cattle grazing initiates the gullying of alluvial soils in northern Australia. *In:* Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world, Brisbane, Australia, 1-6 August 2010. Symposium 4.3.1 Impacts of land use change in unsustainable ecosystems. pp. 59-62.

Shellberg, J.G., Brooks, A.P., Rose, C.W., 2013. Sediment production and yield from an alluvial gully in northern Queensland, Australia. Earth Surface Processes and Landforms, 38, 1765-1778.

Shellberg, J.G., Spencer, J., Brooks, A.P., Pietsch, T.J., 2016. Degradation of the Mitchell River fluvial megafan by alluvial gully erosion increased by post-European land use change, Queensland, Australia. Geomorphology, 266, 105-120.

Silburn, D.M., Carroll, C., Ciesiolka, C.A.A., deVoil, R.C., Burger, P., 2011. Hillslope runoff and erosion on duplex soils in grazing lands in semi-arid central Queensland. I. Influences of cover, slope, and soil. Soil Research, 49, 105-117.

Simon, A., 2014. Channel and bank stability of selected reaches of the Burnett River System, Report prepared by Cardno Entrix to the Burnett Mary Regional group.

Simon, A., Collison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms, 27, 527-546.

Simpson, B., Ruddle, L., Hargreaves, P., Ham, G., Cavanagh, J., Rayment, G.E., 2000. Pesticides and water quality. *In:* K. Bristow and D. Popham (eds.). *Water in the Australian Sugar Industry*. Cooperative Centre for Sustainable Sugar Production, Townsville. pp. 49–55.

Simpson, S.L., Batley, G.E., Chariton, A.A., 2013. Revision of the ANZECC/ARMCANZ Sediment Quality Guidelines. CSIRO Land and Water, Sydney. 128 pp.

Sinclair Knight Mertz, 2012. Nathan Dam and Pipelines Environment Impact Assessment, Chapter 14: Surface Water. SunWater, Place of publication. 70 pp. http://eisdocs.dsdip.qld.gov.au/Nathan%20Dam%20and%20Pipelines/AEIS/chapters/part-b-14-surface-water.pdf.

Siriwardena, L., Finlayson, B.L., McMahon, T.A., 2006. The impact of land use change on catchment hydrology in large catchments: The Comet River, Central Queensland, Australia. Journal of Hydrology, 326, 199-214.

Smith, D.G., 1976. Effect of Vegetation on Lateral Migration of Anastomosed Channels of a Glacier Meltwater River. Geological Society of American Bulletin, 87, 857-860.

Smith, J., Douglas, G.B., Radke, L.C., Palmer, M., Brooke, B.P., 2008. Fitzroy River Basin, Queensland, Australia. III. Identification of sediment sources in the coastal zone. Environmental Chemistry, 5, 231-242.

Smith, R.A., Warne, M.S.J., Mengersen, K., Turner, R.D.R., 2016a. An improved method for calculating toxicity-based pollutant loads: Part 1. Method development. Integrated Environmental Assessment and Management, 13(4), 746-753. doi:10.1002/ieam.1854.

Smith, R.A., Warne, M.S.J., Mengersen, K., Turner, R.D.R., 2016b. An improved method for calculating toxicity-based pollutant loads: Part 2. Application to contaminants discharged to the Great Barrier Reef, Queensland, Australia. Integrated Environmental Assessment and Management, 13(4), 754-764. doi:10.1002/ieam.1860

Spencer, J., Brooks, A., Curwen, G., Tews, K., 2016. A disturbance index approach for assessing water quality threats in Eastern Cape York. A report to South Cape York Catchments for the Cape York Water Quality Improvement Plan by the Australian Rivers Institute, Griffith University. 42 pp.

State of Queensland 2016. Great Barrier Reef Report Card 2015. Australian and Queensland governments. http://www.reefplan.qld.gov.au/measuring-success/report-cards/2015/

Takesue, R.K., Bothner, M.H., Reynolds, R.L., 2009. Sources of land-derived runoff to a coral reef-fringed embayment identified using geochemical tracers in nearshore sediment traps. Estuarine, Coastal and Shelf Science, 85, 459-471.

Tappin, A.D., 2002. An examination of the fluxes of nitrogen and phosphorus in temperate and tropical estuaries: Current estimates and uncertainties. Estuarine Coastal and Shelf Science, 55, 885-901.

Taylor, M.P., 2015. Atmospherically deposited trace metals from bulk mineral concentrate port operations. Science of the Total Environment, 515, 143-152.

Terrain NRM, 2015. Wet Tropics Water Quality Improvement Plan 2015-2020. Terrain NRM, Innisfail. 232 pp. www.terrain.org.au/Projects/Water-Quality-Improvement-Plan.

The National Committee on Soil and Terrain, 2009. Australian soil and land survey field handbook, 3rd Edition. CSIRO Publishing, Collingwood. 246 pp.

Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer Valley, southeast Queensland, Australia. Geomorphology, 197, 156-169.

Thompson, C., Croke, J., Grove, J., Khanal, G., 2013. Spatio-temporal changes in river bank mass failures in the Lockyer Valley, Queensland, Australia. Geomorphology, 191, 129-141.

Thorburn, P.J., Wilkinson, S.N., 2013. Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments. Agriculture, Ecosystems and Environment, 180, 192-209.

Thorburn, P.J., Wilkinson, S.N., Silburn, D.M., 2013. Water quality in agricultural lands draining to the Great Barrier Reef: Causes, management and priorities. Agriculture, Ecosystems & Environment, 180, 4-20.

Thornton, C.M., Cowie, B.A., Freebairn, D.M., Playford, C.L., 2007. The Brigalow Catchment Study: II. Clearing brigalow (*Acacia harpophylla*) for cropping or pasture increases runoff. Australian Journal of Soil Research, 45, 496-511.

Tims, S.G., Everett, S.E., Fifield, L.K., Hancock, G.J., Bartley, R., 2010. Plutonium as a tracer of soil and sediment movement in the Herbert River, Australia. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 268, 1150-1154.

Tindall, D., Marchand, B., Gilad, U., Goodwin, N., Denham, R., Byer, S., 2014. Gully mapping and drivers in the grazing lands of the Burdekin catchment. RP66G Synthesis Report. Queensland Department of Science, Information Technology, Innovation and the Arts. Brisbane. 119 pp. publications.qld.gov.au/dataset/99266001-0d3a-4114-8904-a5f7f8262008/resource/ce81fc22-63f9-4627-be1e-f57ae177f6aa/download/gullymappingburdekinsynthesisreportrp66gfinal.pdf.

Turner, R.D.R., Huggins, R.L., Wallace, R.M., Smith, R.A., Vardy, S., J Warne, M.S.J., 2012. Sediment, Nutrient and Pesticide Loads: Great Barrier Reef Catchment Loads Monoitoring 2009-2010. Department of Science, Information Technology, Innovation and the Arts, Brisbane. www.reefplan.qld.gov.au/measuring-success/paddock-to-reef/assets/2009-2010-gbr-catchment-loadsreport.pdf.

Turner, R., Huggins, R., Wallace, R., Smith, R., Vardy, S., Warne, M.S.J., 2013. Loads of sediment, nutrients and pesticides discharged from high priority Queensland rivers in 2010-2011. Great Barrier Reef Catchment Loads Monitoring Program, Department of Science, Information Technology, Innovation and the Arts, Brisbane. pp. www.reefplan.qld.gov.au/measuringsuccess/paddock-to-reef/assets/2010-2011-gbr-catchment-loads-report.pdf

Unger, C., Lechner, A.M., Glenn, V., Edraki, M., Mulligan, D., 2012. Mapping and prioritising rehabilitation of abandoned mines in Australia. Life-of-Mine Conference 2012 (AusIMM), Brisbane, Australia, 10-12 July 2012. pp. 259-266.

Unger, C.J., Lechner, A.M., Kenway, J., Glenn, V., Walton, A., 2015. A jurisdictional maturity model for risk management, accountability and continual improvement of abandoned mine remediation programs. Resourource Policy, 43, 1-10.

United Nations Environment Programme, 2009. Marine Litter: A Global Challenge. UNEP, Nairobi, Kenya, 234 pp.

Verburg, K., Cresswell, H.P., Bende-Michl, U., 2011. Spatial diagnosis of catchment water quality. AWA Catchment Management Conference, Wangaratta, Australia. 5 pp.

Verburg, K., Harvey. T.G., Muster, T.H., Brennan McKellar, L.E., Thorburn, P.J., Biggs, J.S., Di Bella, L.P., Wang, W., 2014. Use of enhanced efficiency fertilisers to increase fertiliser nitrogen use efficiency insugarcane. *In:* M.J. Bell (ed.). *A review of nitrogen use efficiency in sugarcane*. SRA Research Report. Sugar Research Australia, Brisbane. pp. 229–295.

Visser, F., Roth, G.H., Wasson, R.J., Govers, G., 2007. A sediment budget for a cultivated floodplain in tropical North Queensland, Australia. Earth Surface Processes and Landforms, 32, 1475-1490.

Walker, G.S., Brunskill, G.J., 1996. Detection of anthropogenic and natural mercury in sediments from the Great Barrier Reef lagoon The Great Barrier Reef Science, Use and Management. Great Barrier Marine Park Authority, James Cook University. pp. 30-33.

Wallace, R., Huggins, R., Smith, R., Turner, R., Vardy, S., Warne, M.S.J., 2014. Total suspended solids, nutrient and pesticide loads (2011-2012) for rivers that discharge to the Great Barrier Reef. Great Barrier Reef Catchment Loads Monitoring Program. Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Wallace, R., Huggins, R., Smith, R., Turner, R., Garzon-Garcia, A., Warne, M.S.J., 2015. Total suspended solids, nutrient and pesticide loads (2012-2013) for rivers that discharge to the Great Barrier Reef. Great Barrier Reef Catchment Loads Monitoring Program. Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Wallace, R., Huggins, R., King, R.S., Gardiner, R., Thomson, B., Orr, D., Ferguson, B., Taylor, C., Severino, Z., Smith, R.A., Warne, M.S.J., Turner, R., Mann, R.M., 2016. Total suspended solids, nutrient and pesticide loads (2014-2015) for rivers that discharge to the Great Barrier Reef. Great Barrier Reef Catchment Loads Monitoring Program. Department of Science, Information Technology and Innovation, Brisbane.

Wallbrink, P., Martin, C., Wilson, C., 2001. Contribution of sediment and sediment bound P from different landuses to streams in temperate and tropical Australia. *In:* I. Rutherfurd, G. Brierley, S. Bunn, F. Sheldon and C. Kenyon (eds.). *Proceedings of the Third Australian Stream Management Conference*. Cooperative Research Centre for Catchment Hydrology, Brisbane.

Walling, D.E., Moorehead, P.W., 1989. The particle size characteristics of fluvial suspended sediment: an overview. Hydrobiologia, 176/177, 125-149.

Walling, D.E., Owens, P.N., Waterfall, B.D., Leeks, G.J.L., Wass, P.D., 2000. The particle size characteristics of fluvial suspended sediment in the Humber and Tweed catchments, UK. Science of the Total Environment, 251, 205-222.

Walton, R.S., Hunter, H.M., 2009. Isolating the water quality responses of multiple land uses from stream monitoring data through model calibration. Journal of Hydrology, 378, 29-45.

Waters, D., Carroll, C., Ellis, R., McCloskey, G., Hateley, L., Packett, R., Dougasll, C., Fentie, B., 2013. Catchment modelling scenarios to inform GBR water quality targets. *In:* J. Piantadosi, R.S. Anderssen and J. Boland, (eds.). *20th International Congress on Modelling and Simulation*. 1-6 December 2013, Adelaide. pp. 3204-3210. www.mssanz.org.au/modsim2013/.

Waters, D., Carroll, C., Ellis, R., Hateley, L., McCloskey, G., Packett, R., Dougall, C., Fentie, B., 2014. Modelling reduction of pollutant loads due to improved management practices in the Great Barrier Reef catchments - Whole of GBR, Technical Report, Volume 1. Quenssland Department of Natural Resource and Mines, Toowoomba.

Wauchope, R.D., Yeh, S., Linders, J.B.H.J., Kloskowski, R., Tanaka, K., Rubin, B., 2002. Pesticide soil sorption parameters: theory, measurement, uses, limitations and reliability. Pest Management Science, 58, 419–45.

Waycott, M., Longstaff, B.J., Mellors, J., 2005. Seagrass population dynamics and water quality in the Great Barrier Reef region: A review and future research directions. Marine Pollution Bulletin, 51, 343-350.

Webster, A.J., Bartley, R., Armour, J.D., Brodie, J.E., Thorburn, P.J., 2012. Reducing dissolved inorganic nitrogen in surface runoff water from sugarcane production systems. Marine Pollution Bulletin, 65, 128-135.

Webster, I.T., Ford, P.W., 2010. Delivery, deposition and redistribution of fine sediments within macrotidal Fitzroy Estuary/Keppel Bay: Southern Great Barrier Reef, Australia. Continental Shelf Research, 793-805.

Wilkinson, S.N., 2008. Testing the capability of a sediment budget model for targeting remediation measures to reduce suspended-sediment yield. *In: Proceedings of Sediment Dynamics in Changing Environments*, December 2008. IAHS Publ. #325. Christchurch, New Zealand. pp. 559-566.

Wilkinson, S.N., Hancock, G.J., Bartley, R., Hawdon, A.A., Keen, R., 2013. Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin, Queensland, Australia. Agriculture, Ecosystems and Environment, 180, 90-102.

Wilkinson, S.N., Bastin, G., Stokes, C.J., Hawdon, A.A., Chewings, V.H., Kinsey-Henderson, A.E., Nicholas, D.M., Abbott, B.N., McKellar, K., Kemei, J., 2014a. Improving grazing management practices to enhance ground cover and reduce sediment loads, Report to the Reef Rescue Water Quality Research & Development Program. Reef and Rainforest Research Centre Limited, Cairns.

Wilkinson, S.N., Dougall, C., Kinsey-Henderson, A.E., Searle, R., Ellis, R., Bartley, R., 2014b. Development of a time-stepping sediment budget model for assessing land use impacts in large river basins. Science of the Total Environment, 468-469, 1210-1224.

Wilkinson, S.N., Olley, J.M., Furuichi, T., Burton, J., Kinsey-Henderson, A.E., 2015a. Sediment source tracing with stratified sampling and weightings based on spatial gradients in soil erosion. Journal of Soils Sediments, 15(10), 2038–2051.

Wilkinson, S.N., Hawdon, A.A., Hairsine, P.B., Austin, J., 2015b. Gully Toolbox: A technical guide for the Reef Trust Gully Erosion Control Programme 2015-16. CSIRO, Report to the Department of the Environment (Reef Program).

Wilkinson, S.N., Bartley, R., Hairsine, P.B., Bui, E.N., Gregory, L., Henderson, A.E., 2015b. Managing gully erosion as an efficient approach to improving water quality in the Great Barrier Reef lagoon. Report to the Department of the Environment (Reef Program).

Wood, P.J., Armitage, P.D., 1997. Biological effects of fine sediment in the lotic environment. Environmental Management, 21, 203-217.

Wooldridge, S.A., Brodie, J.E., Kroon, F.J., Turner, R.D., 2015. Ecologically based targets for bioavailable (reactive) nitrogen discharge from the drainage basins of the Wet Tropics region, Great Barrier Reef. Marine Pollution Bulletin, 97, 262-272.

Xiang, S.R., Doyle, A., Holden, P.A., Schimel, J.P., 2008. Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface California grassland soils. Soil Biology and Biochemistry, 40, 2281-2289.

Xiao, F., Halbach, T.R., Simcik, M.F., Gulliver, J.S., 2012. Input characterization of perfluoroalkyl substances in wastewater treatment plants: Source discrimination by exploratory data analysis. Water Research, 46, 3101-3109.

Yunker, M.B., Macdonald, R.W., Vingarzan, R., Mitchell, R.H., Goyette, D., Sylvestre, S., 2002. PAHs in the Fraser River basin: a critical appraisal of PAH ratios as indicators of PAH source and composition. Organic Geochemistry, 33, 489-515.

Appendix

Table 20: Average annual measured nitrogen loads for each of the 20 sites in the GBR catchments. (Source: Garzon-Garcia et al., 2015; Joo et al., 2011; Turner et al., 2013; Turner et al., 2012; Wallace et al., 2016; Wallace et al., 2015; Wallace et al., 2014). The datasets were measured during events over three to nine years; sites with an * are based on two years only.

NRM region	Catchment	Gauging station	River and site name	Years of data	Number of samples	TN (t)	PN (t)	N0x-N (t)	NH4-N (t)	DIN(t)	DON (t)
Cape York	Normanby	105107A	Normanby River at Kalpowar Crossing	9	264	1,600 ± 1,600	300 ± 170	40 ± 21	35 ± 18	75 ± 37	740 ± 310
Wet Tropics	Barron	110001D	Barron River at Myola	9	590	900 ± 600	600 ± 420	45 ± 22	10 ± 6	55 ± 27	270 ± 170
		110002A	Barron River at Mareeba	3	60	270 ± 160	120 ± 110	33 ± 11	5 ± 3	38 ± 13	110 ± 50
		110003A	Barron River at Picnic Crossing	3	371	100 ± 37	30 ± 16	34 ± 3	2 ± 1	36 ± 4	30 ± 20
	Johnstone	1120049	North Johnstone River at Tung Oil	9	306	1,300 ± 800	830 ± 690	269 ± 86	14 ± 4	283 ± 88	230 ± 80
		112101B	South Johnstone River at Upstream Central Mill	9	492	600 ± 300	360 ± 230	141 ± 69	7 ± 3	147 ± 72	90 ± 40
	Tully	113006A	Tully River at Euramo	9	1,491	1,600 ± 600	440 ± 230	699 ± 251	32 ± 13	731 ± 258	430 ± 150
		113015A	Tully River at Tully Gorge National Park	5	311	400 ± 200	160 ± 140	118 ± 59	11 ± 5	129 ± 60	110 ± 50
	Herbert	116001F	Herbert River at Ingham	9	420	3,100 ± 2,300	1,240 ± 1,350	869 ± 594	52 ± 39	921 ± 615	880 ± 680
Burdekin	Haughton	119003A	Haughton River at Powerline*	2	37	100 ± 80	30 ± 26	26 ± 23	2 ± 2	28 ± 25	43 ± 32
		119101A	Barratta Creek at Northcote	6	649	330 ± 240	90 ± 90	76 ± 14	6 ± 3	82 ± 13	130 ± 90
	Burdekin	120001A	Burdekin River at Home Hill	9	436	12,500 ± 10,400	7,450 ± 6,860	1,193 ± 739	190 ± 248	1,382 ± 863	3,580 ± 2,950
		120002C	Burdekin River at Sellheim	9	171	7,300 ± 7,400	5,250 ± 5,770	243 ± 115	56 ± 50	298 ± 154	1,610 ± 1,600
		120302B	Cape River at Taemas	7	367	1,200 ± 700	680 ± 480	38 ± 43	10 ± 5	47 ± 44	460 ± 270
		120301B	Belyando River at Gregory Development Road	7	452	1,200 ± 1,100	540 ± 560	13 ± 10	16 ± 12	29 ± 21	600 ± 530
		120310A	Suttor River at Bowen Development Road	7	182	700 ± 500	270 ± 190	17 ± 11	11 ± 9	28 ± 15	400 ± 280
		120205A	Bowen River at Myuna	3	112	1,500 ± 1,200	1,160 ± 1,060	56 ± 20	29 ± 23	85 ± 41	180 ± 100
Mackay Whitsunday	O’Connell	1240062	O’Connell River at Caravan Park	4	86	400 ± 280	250 ± 190	23 ± 17	18 ± 10	36 ± 21	87 ± 88
		124001B	O’Connell River at Stafford’s Crossing	3	55	200 ± 30	70 ± 20	15 ± 7	4 ± 1	18 ± 8	90 ± 20

	Pioneer	125013A	Pioneer River at Dumbleton Pump Station	9	657	1,400 ± 1,100	780 ± 750	230 ± 150	41 ± 23	270 ± 170	310 ± 170
		125004B	Cattle Creek at Gargett	3	39	800 ± 230	420 ± 250	107 ± 28	12 ± 10	137 ± 11	240 ± 60
	Plane	126001A	Sandy Creek at Homebush	6	262	280 ± 170	120 ± 80	45 ± 22	6 ± 6	51 ± 26	100 ± 70
Fitzroy	Fitzroy	1300000	Fitzroy River at Rockhampton	9	338	10,800 ± 10,600	5,100 ± 5,200	1,200 ± 1,000	160 ± 160	1,340 ± 1,100	4,390 ± 4,500
		130206A	Theresa Creek at Gregory Highway	6	75	770 ± 750	450 ± 460	56 ± 58	10 ± 8	66 ± 62	240 ± 220
		130504B	Comet River at Comet Weir	6	104	1,900 ± 1,600	1,070 ± 920	192 ± 197	41 ± 43	233 ± 238	730 ± 740
		130302A	Dawson River at Taroom	4	109	1,740 ± 2,600	1,030 ± 1,580	51 ± 46	23 ± 35	74 ± 80	790 ± 1,240
Burnett Mary	Burnett	136014A	Burnett River at Ben Anderson Barrage HW	9	457	3,400 ± 5,800	2,060 ± 3,660	276 ± 479	158 ± 248	239 ± 465	930 ± 1,460
		136002D	Burnett River at Mt Lawless	6	396	3,140 ± 6,200	2,160 ± 4,310	76 ± 118	49 ± 90	125 ± 208	900 ± 1,700
		136094A	Burnett River at Jones Weir Tail Water	6	297	1,900 ± 3,500	1,050 ± 1,950	86 ± 148	54 ± 91	140 ± 239	700 ± 1,320
		136106A	Burnett River at Eidsvold	5	220	600 ± 1,000	280 ± 460	43 ± 57	21 ± 31	63 ± 88	270 ± 430
	Mary	138014A	Mary River at Home Park*	2	176	1,000 ± 1,200	420 ± 520	273 ± 278	21 ± 24	294 ± 302	320 ± 390
		138008A	Tinana Creek at Barrage Head*	2	146	150 ± 10	30 ± 3	23 ± 13	6 ± 1	28 ± 15	90 ± 10

Table 21: Average annual measured phosphorus loads for each of the 32 sites in the GBR catchments. (Source: Garzon-Garcia et al., 2015; Turner et al., 2013; Turner et al., 2012; Wallace et al., 2015; Wallace et al., 2014)**.** The datasets were measured during events over three to nine years; sites with an * are based on two years only**.**

NRM region	Basin	Gauging station	River and site name	Years of data	Number of samples	TP (t)	DIP (t)	PP (t)	DOP (t)
Cape York	Normanby	105107A	Normanby River at Kalpowar Crossing	9	264	150 ± 75	19 ± 11	93 ± 39	44 ± 41
Wet Tropics	Barron	110001D	Barron River at Myola	9	590	150 ± 118	9 ± 8	131 ± 103	15 ± 14
		110002A	Barron River at Mareeba	3	60	70 ± 50	15 ± 10	49 ± 39	5 ± 2
		110003A	Barron River at Picnic Crossing	3	371	20 ± 11	2 ± 1	15 ± 10	2 ± 1
	Johnstone	1120049	North Johnstone River at Tung Oil	9	306	300 ± 221	15 ± 6	293 ± 187	37 ± 39
		112101B	South Johnstone River at Upstream Central Mill	9	492	150 ± 98	9 ± 4	132 ± 87	17 ± 17
	Tully	113006A	Tully River at Euramo	9	1,491	150 ± 94	20 ± 17	118 ± 73	58 ± 42
		113015A	Tully River at Tully Gorge National Park	5	311	40 ± 35	2 ± 1	34 ± 29	17 ± 13
	Herbert	116001F	Herbert River at Ingham	9	420	380 ± 409	41 ± 32	301 ± 333	89 ± 83
Burdekin	Haughton	119003A	Haughton River at Powerline*	2	37	15 ± 13	5 ± 5	9 ± 8	1 ± 1
		119101A	Barratta Creek at Northcote	6	649	50 ± 50	14 ± 8	24 ± 24	8 ± 8
	Burdekin	120001A	Burdekin River at Home Hill	9	436	3,970 ± 3,179	421 ± 315	3,426 ± 2,783	262 ± 333
		120002C	Burdekin River at Sellheim	9	171	2,640 ± 2,582	174 ± 163	2,334 ± 2,411	121 ± 130
		120302B	Cape River at Taemas	7	367	200 ± 140	11 ± 6	179 ± 136	30 ± 22
		120301B	Belyando River at Gregory Development Road	7	452	270 ± 248	72 ± 66	182 ± 171	28 ± 26
		120310A	Suttor River at Bowen Development Road	7	182	160 ± 114	33 ± 27	102 ± 59	30 ± 42
		120205A	Bowen River at Myuna	3	112	790 ± 810	29 ± 21	734 ± 800	7 ± 5
Mackay Whitsunday	O’Connell	1240062	O’Connell River at Caravan Park	4	86	68 ± 63	13 ± 10	74 ± 58	3.6 ± 1.9
		124001B	O’Connell River at Stafford’s Crossing	3	55	20 ± 6	5 ± 1	14 ± 5	2 ± 1
	Pioneer	125013A	Pioneer River at Dumbleton Pump Station	9	657	310 ± 280	50 ± 30	230 ± 220	22 ± 28
		125004B	Cattle Creek at Gargett	3	39	150 ± 65	27 ± 6	117 ± 59	6 ± 1
	Plane	126001A	Sandy Creek at Homebush	6	262	80 ± 50	33 ± 20	40 ± 28	7 ± 6

NRM region	Basin	Gauging station	River and site name	Years of data	Number of samples	TP (t)	DIP (t)	PP (t)	DOP (t)
Fitzroy	Fitzroy	1300000	Fitzroy River at Rockhampton	9	338	4,300 ± 4,500	1,280 ± 1,500	2,800 ± 2,700	320 ± 480
		130206A	Theresa Creek at Gregory Highway	6	75	290 ± 271	68 ± 62	208 ± 213	12 ± 10
		130504B	Comet River at Comet Weir	6	104	1,070 ± 847	320 ± 310	712 ± 513	40 ± 38
		130302A	Dawson River at Taroom	4	109	740 ± 1,150	383 ± 617	294 ± 430	50 ± 78
Burnett Mary	Burnett	136014A	Burnett River at Ben Anderson Barrage HW	9	457	790 ± 1,385	82 ± 142	680 ± 1,190	46 ± 88
		136002D	Burnett River at Mt Lawless	6	396	860 ± 1,743	75 ± 143	753 ± 1,521	47 ± 91
		136094A	Burnett River at Jones Weir Tail Water	6	297	440 ± 819	53 ± 101	368 ± 676	34 ± 63
		136106A	Burnett River at Eidsvold	5	220	160 ± 281	50 ± 89	99 ± 173	15 ± 23
	Mary	138014A	Mary River at Home Park*	2	176	180 ± 221	15 ± 19	155 ± 193	10 ± 12
		138008A	Tinana Creek at Barrage Head*	2	146	10 ± 1	0.4 ± 0.1	7 ± 0.4	2 ± 0.2

Table 22: Modelled annual average estimates of total dissolved inorganic nitrogen (DIN) loads (tonnes per year) for the Great Barrier Reef basins. (Source: Derived from McCloskey et al. 2017b).

AWRAC basin	Nature conservation	Dryland cropping	Forestry	Open and closed grazing	Horticulture	Irrigated cropping	Sugarcane	Urban	Bananas	Dairy	Other including point sources	Total
Jacky Jacky	61	-	-	6	-	-	-	0	-	-	0	67
Olive Pascoe	78	-	-	20	-	-	-	-	-	-	0	98
Lockhart	48	-	-	1	-	-	-	0	-	-	0	49
Stewart	30	-	0	1	-	-	-	-	-	-	0	31
Normanby	35	1	0	68	-	0	-	0	0	-	1	105
Jeannie	29	0	0	5	0	-	-	0	-	-	1	35
Endeavour	22	0	1	16	0	0	-	1	0	-	0	40
Daintree	184	0	159	18	1	1	94	15	0	-	6	478
Mossman	45	0	0	2	0	0	98	9	-	-	6	160
Baron	28	0	12	14	1	6	49	19	0	1	23	152
Mulgrave-Russell	388	0	2	20	10	1	393	52	9	15	44	934
Johnstone	328	5	3	85	8	3	415	51	112	31	46	1,059
Tully	285	0	8	21	4	0	314	22	115	1	7	777
Murray	113	-	21	13	3	0	244	6	10	-	4	414
Herbert	264	2	42	203	1	6	966	20	-	3	15	1,522
Black	34	0	5	22	5	-	21	3	-	-	1	97
Ross	14	0	1	27	3	0	-	8	-	-	127	180
Haughton	26	0	1	61	10	4	902	12	-	-	0	1,016
Burdekin	143	14	13	744	0	2	185	1	-	-	2	1,104
Don	7	0	0	79	19	4	68	1	-	-	0	178
Proserpine	31	-	13	98	1	1	153	11	0	0	2	310

AWRAC basin	Nature conservation	Dryland cropping	Forestry	Open and closed grazing	Horticulture	Irrigated cropping	Sugarcane	Urban	Bananas	Dairy	Other including point sources	Total
O'Connell	21	-	8	94	0	0	192	8	0	0	3	325
Pioneer	11	-	13	26	0	-	188	12	0	0	6	256
Plane	5	0	7	66	0	-	353	7	0	0	26	464
Styx	5	0	4	80	0	-	0	0	-	-	2	91
Shoalwater	55	-	0	43	-	-	0	0	-	-	2	100
Water Park	42	0	11	7	0	-	0	3	-	-	2	65
Fitzroy	38	38	48	597	2	-	0	7	-	-	69	799
Calliope	2	0	3	39	0	-	0	1	-	-	2	47
Boyne	5	-	2	28	0	-	0	1	-	-	1	37
Baffle	5	0	2	37	1	0	8	3	-	-	0	58
Kolan	1	0	1	15	1	0	57	2	-	-	1	78
Burnett	2	8	4	67	2	4	138	5	-	-	16	246
Burrum	3	0	4	10	2	0	168	5	-	-	7	199
Mary	16	0	27	117	8	3	208	52	-	-	28	459