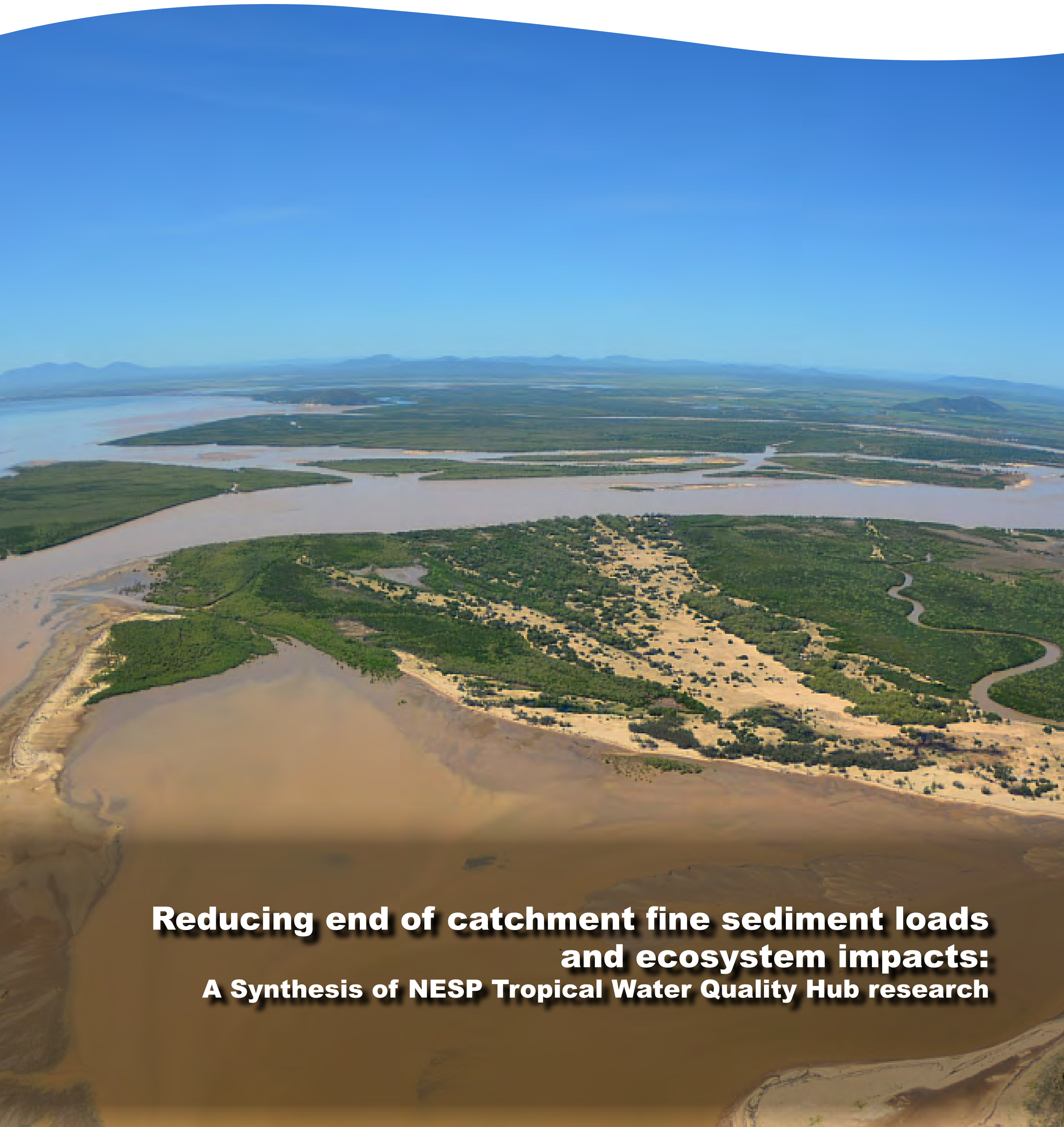
Tropical Water Quality Hub

National Environmental Science Programme

Synthesis Report



Reducing end of catchment fine sediment loads and ecosystem impacts:
A Synthesis of NESP Tropical Water Quality Hub research

The Tropical Water Quality Hub is funded by the Australian Government's National Environmental Science Program

Reducing end of catchment fine sediment loads and ecosystem impacts

A synthesis of NESP Tropical Water Quality Hub research

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Supported by the Australian Government's
National Environmental Science Program
Project 6.4 Reducing end-of-catchment fine sediment loads and ecosystem impacts

National Library of Australia Cataloguing-in-Publication entry:
978-1-925514-99-5

This report should be cited as: Compiled by Pineda, M-C and Waterhouse, J. (2021) Reducing end of catchment fine sediment loads and ecosystem impacts: A synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (70pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub.

The Tropical Water Quality Hub is part of the Australian Government's National Environmental Science Program and is administered by the Reef and Rainforest Research Centre Limited (RRRC). The NESP TWQ Hub addresses water quality and coastal management in the World Heritage listed Great Barrier Reef, its catchments and other tropical waters, through the generation and transfer of world-class research and shared knowledge.

Cover photographs: (front) Burdekin River mouth. Image: Matt Curnock. (back) Griffith University researchers undertaking an RTK survey to ground truth alluvial gully mapping in the Bowen catchment. Image: Justin Stout.

This report is available for download from the NESP Tropical Water Quality Hub website:
http://www.nesptropical.edu.au

www.synthesis.nesptropical.edu.au

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ACRONYMS AND ABBREVIATIONS

AIMS .... Australian Institute of Marine Science
BBB .... Bowen, Broken and Bogie (rivers)
BPN .... Bioavailable particulate nitrogen
I_{bPAR} .... Benthic photosynthetic active radiation
CDOM .... Chromophoric dissolved organic matter
CERF .... Commonwealth Environmental Research Facility
CRC Reef ..... Cooperative Research Centre for the GBRWHA
CSIRO .... Commonwealth Scientific and Industrial Research Organization
DAWE .... Department of Agriculture, Water and the Environment
DEM .... Digital elevation models
DIN .... Dissolved inorganic nitrogen
DOC .... Dissolved organic carbon
EC .... Effective concentration
EOS .... End of system
ETRs .... Ecologically relevant targets
GBR .... Great Barrier Reef
GBRMPA ..... Great Barrier Reef Marine Park Authority
GBRWHA ..... Great Barrier Reef World Heritage Area
JCU .... James Cook University
LED .... Light emitting diode
LiDAR .... Airborne light detection and ranging
MTSRF .... Marine and Tropical Science Research Facility
NERP .... National Environment Research Program
NESP .... National Environmental Science Program
NMR .... Nuclear magnetic resonance
NTU .... Nephelometric turbidity unit
PAR .... Photosynthetically active radiation
POC .... Particulate organic carbon
PSU .... Practical salinity unit
RIMReP .... Reef 2050 Integrated Monitoring and Reporting Program
RRRC .... Reef and Rainforest Research Centre
SPM .... Suspended particulate matter
TNSC .... Total non-structural carbohydrates
TSS .... Total suspended solids
TWQ .... Tropical Water Quality
UQ .... University of Queensland
WQ .... Water quality
WQI .... Water quality indicator

ACKNOWLEDGEMENTS

We acknowledge the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub for providing funding for the research projects reported here. We also acknowledge the various individuals, research institutions and universities who have delivered innovative and applied science under the NESP Tropical Water Quality Hub with the goal of informing and improving management of Great Barrier Reef water quality. For the projects reported here, this includes the Australian Institute of Marine Science (AIMS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Griffith University (GU) and James Cook University (JCU). We are particularly grateful for the contributions from lead researchers, and in particular the review provided by Barbara Robson and Ross Jones (AIMS), Rebecca Bartley (CSIRO), Andrew Brooks (GU), and Catherine Collier, Zoe Bainbridge and Stephen Lewis (JCU). We would like to acknowledge the external peer review of the report undertaken by Dr David Haynes which improved the clarity of the report and added value to the overall output. Subsequent review by the NESP TWQ Hub Steering Committee contributed to further refine the final version.

EXECUTIVE SUMMARY

The Great Barrier Reef (GBR) is one of the world's greatest natural assets. Threats to the GBR are multiple, cumulative, and increasing, and signs of major ecosystem deterioration are being observed. The main driver of this deterioration is increased water temperatures caused by global climate change, although increased pollutant loads contained in catchment run-off, coastal development and anthropogenic use are also important threats to the GBR.

Action(s) at a national level to mitigate and adapt to climate change are essential, as is a strong focus on local and regional management actions to maximise GBR ecosystem resilience to a changing climate. Poor water quality resulting from the discharge of increased nutrient and fine sediment loads and pesticides from adjacent catchments is one of the most important threats to the GBR that can be potentially mitigated by management measures undertaken at local and regional scales.

Of these, fine sediment (<20 μm) inputs into the GBR lagoon inner shore reefs are a major water quality stressor that can cause multiple ecological impacts to GBR ecosystems. These impacts can include reduction in benthic light quantity and quality, smothering of benthic organisms, direct disturbance by suspended particles and impacts resulting from exposure to increased loads of bioavailable nutrients associated with sediment particles. A 25% reduction in anthropogenic end-of-catchment fine sediments loads was set as a target to be achieved by 2025 under the Reef 2050 Water Quality Improvement Plan (WQIP 2017-2022) to help improve reef resilience.

A cluster of corresponding research projects was undertaken within the National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub to assist in the identification and improvement of interventions that reduce catchment sediment loss mechanisms. This also requires an improved understanding of sediment sources, and its transport mechanisms, environmental fate and ultimate impact on reef ecosystems. The outcomes of these NESP TWQ Hub projects have:

- Refined understanding of sediment transport and resuspension dynamics from catchment to reef, as well as understanding of the impacts of dredging operations on sediment induced reduction in quantity and quality of benthic light.
- Examined where sediment disperses to in the marine environment and determined how to optimally measure, monitor and report on its dispersion.
- Simulated changes to environmental conditions caused by sediment inputs and investigated the implications for coastal and marine coral and seagrass communities.
- Used tracing techniques to investigate the most environmentally relevant sediment characteristics and sources.
- Investigated and trialled remediation methods for gully and streambank erosion.
- Developed techniques for measurement and evaluation of water quality outcomes.

This synthesis of research findings takes a 'sea to source' approach, beginning with sediment fate and impact in the GBR (i.e., impacts upon key marine habitats, such as coral and seagrass), the spatial extent of these impacts in the GBR, and new methods for measuring and reporting on reduced light availability as a result of catchment-derived sediment in the marine environment. This is then followed by an analysis of the delivery of sediments and transformation and mobilisation of nutrients attached to sediments, including fate and dispersion of catchment-derived sediments once in the marine environment. The synthesis concludes with an evaluation of the approaches for remediating the previously identified dominant sources of sediment (gullies and streambanks). Finally, this synthesis provides advice on the practical on-ground actions for land and sea managers, policy implications and remaining gaps for future research and management investments.

Overall conclusions are included in the final section of the report, and include the following highlights, from sea to source:

Sediment fate and impact in the GBR

- Pulsed delivery of flood plume sediment and particulate nutrients to inshore coral reef sites results in an increase in macroalgae cover (and potential deposition of marine snow).
- Chronic persistent turbidity (and reduced photic depth) occurs for long periods as a result of considerable disturbance and resuspension or new sediment delivery in areas of poor flushing.
- Increased suppression of light occurs in shallow (~ 5 m) turbid environments within flood plumes and this continues for extended timeframes (months) following flooding.
- For considerable (environmental) impact to occur in seagrass meadows, large consecutive flooding events are typically required, over 2-3 years.

Sediment characteristics and delivery

- The most ‘damaging’ sediment sources are the fine (<20 µm), organic-rich (bacteria) sediment which travels furthest in the GBR and has the capacity to release dissolved nutrients and influence turbidity (and macroalgae) regimes in the inshore GBR.
- River plume sediment is sourced predominantly from subsurface erosion.
- The release of dissolved inorganic nitrogen from sediment laden plumes has confirmed that bioavailable particulate nitrogen is an important source of nutrients.
- The rate of fine sediment erosion is dependent on soil type, and black soils (vertosol) are a major sediment and particulate nutrient source.

Managing and reducing catchment sources of sediment to the GBR

- A gully characterisation framework was developed which allows prioritisation of effort in the landscape in a cost-effective way.
- Assessment of the diversity of gully forms confirmed that a range of management interventions will be required for their effective treatment.
- Large scale engineering solutions have proven to be successful and, in many cases, highly effective in reducing sediment losses cost effectively from active alluvial gullies.
- Treating the small number of high yielding gullies using intensive remediation techniques is central to any strategy to achieve catchment water quality targets by 2025 and beyond. However, the targets will not be achieved by treating these high yielding (typically alluvial gullies) alone. Some lower yielding gullies need to be treated as well, and the most cost-effective approach is to treat gullies that are close to high yielding gullies at the same time that the high yielding gullies are being treated to maximise efficiencies.
- Treatment of the gully area itself can yield large benefits, but management of the surrounding catchment area is also important.

- Porous check dams constructed from sticks and logs, in combination with stock exclusion fencing, appear to have a major impact on the amount of vegetation that stabilises gullies floors and is linked with an improvement in water quality. This is most relevant at small scale activities involving landholders as part of whole of farm management strategies.
- The reduction of livestock grazing pressures within and around gullies in hillslope drainage lines is a primary component of an integrated gully management strategy.
- Total erosion rates varied considerably among source areas and sampling years, with higher rates amongst alluvial gullies, channels banks and beds.
- Remediation costs vary between locations and methods. There is an urgent need for the application of a standard cost- effective metric across investment programs.

This NESP TWQ Hub research has been conducted in collaboration with a wide range of stakeholder groups and is of interest to an even larger audience. The research findings are significant to the future management of the GBR and its catchments. Future programs should ensure that these results are built on and continue to be communicated in a way that can be fully understood and utilised by a range of interested people. This will ensure that the legacy of the program will continue well into the future.

1.0 INTRODUCTION

1.1 NESP Tropical Water Quality Hub

The Australian Government, through the National Environmental Science Program (NESP), has funded $145 million of research effort in environmental and climate science since 2015. All NESP-funded projects have been focused on generating practical and applied research to improve environmental management decision-making processes. The program builds on its predecessors (the National Environment Research Program (NERP) and the Australian Climate Change Science Program (ACCP) undertaken to support better understanding, management and conservation of Australia's environment (Department of Agriculture Water and the Environment (DAWE), 2020).

The Tropical Water Quality (TWQ) Hub[1] was one of six multi-disciplinary research hubs within NESP, investing AU$31.98 million on delivering innovative research to maintain and improve tropical water quality from catchment to reef (NESP, 2020), primarily in Great Barrier Reef (GBR) and adjacent tropical waters. It was structured into three main themes (or research priorities):

Theme 1: Improved understanding of the impacts, including cumulative impacts, and pressures on priority freshwater, coastal and marine ecosystems and species;
Theme 2: Maximising the resilience of vulnerable species to the impacts of climate change and climate variability by reducing other pressures, including poor water quality; and
Theme 3: Natural resource management improvements based on a sound understanding of (long-term) trends in the status of priority species and systems.

Research projects within the TWQ Hub covered a wide spectrum of fields ranging from genes to ecosystems, and included study of species such as the damaging crown-of-thorns starfish, iconic organisms such as dugong and marine turtles, resilience of seagrass and coral reefs, as well as study of the source, impacts and management responses of and to sediments and nutrients in the marine environment. The TWQ Hub research had a strong focus on cumulative impacts and climate resilience and sought to build indigenous connections and capacity in management of Queensland sea country.

The NESP TWQ Hub was delivered through a collaborative, multi-disciplinary research network composed of six leading Australian universities and research institutions, including the Australian Institute of Marine Science (AIMS), James Cook University (JCU), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Central Queensland University (CQU), University of Queensland (UQ) and Griffith University (GU), coordinated through the Reef and Rainforest Research Centre (RRRC) and under the guidance of a Steering Committee including a range of key end-users. These partner institutions have collaborated for over 20 years and have established an extensive network of research end-users, including government, industry, non-government organisations, Traditional Owners and other community groups. The partners contributed to the hub through co-funded research programs (via in-kind contributions to specific projects through staff expertise or research facilities and

[1] https://nesptropical.edu.au/

resources), and contributed to the success of the TWQ Hub while fostering partnerships across the other hubs and with a wide range of relevant stakeholders.

This report is one in a series of technical reports designed to synthesize the findings of NESP TWQ Hub research on topical issues most relevant to policy and stakeholder groups. These include: Improving coral reef condition through better informed resilience-based management (Pineda & Johnson, 2021), innovations in crown of thorns starfish control on the GBR (Erdmann *et al.*, 2021), reducing end of catchment fine sediment loads and ecosystem impacts (this report; Pineda & Waterhouse, 2021), overcoming barriers to reducing nitrogen losses to the GBR (Waterhouse & Pineda, 2021), restoring ecosystems from catchment to reef (Pineda *et al.,* 2021), influencing agriculture practice behaviour change and trust frameworks (James, 2021), and learnings from applied environmental research programs (Long, 2021). The reports are supported by the individual research publications, in addition to several case studies and fact sheets accessible through a dedicated website[2].

1.2 The importance of sediment inputs to the GBR: Context

The GBR is one of the worlds' greatest natural assets. Its beauty and overall functionality still endure, but signs of major ecosystem deterioration are being increasingly observed (see for example GBRMPA, (2019). Despite some positive outcomes obtained over past years from management initiatives and local actions, the GBR is still facing significant pressures at a larger scale. The Great Barrier Reef Marine Park Authority (GBRMPA) stated in their most recent Outlook Report (GBRMPA, 2019) that 'Australia is caring for a changed and less resilient Reef', and reinforced the need to restore GBR resilience through mitigation of climate change impacts, and through the effective implementation of the Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan) (Commonwealth of Australia, 2018a).

Threats to the GBR are multiple, cumulative and increasing and include climate change, coastal development, catchment run-off and direct use (GBRMPA, 2019; Waterhouse *et al.*, 2017). Of these, climate change is the critical long-term threat to coral reefs worldwide, causing seawater temperature increases, altered weather patterns, ocean acidification and sea level rise. Increasing seawater temperatures and marine heat waves caused successive bleaching events in the GBR in 1998, 2002, 2016, 2017 and 2020 followed by widespread coral loss and flow-on effects on overall ecosystem health (Cantin et al., 2021). The GBR's key habitats have a natural resilience to acute physical disturbances such as tropical cyclones and marine heatwaves. However, climate change is exacerbating both acute and chronic disturbances, reducing recovery windows and limiting resilience capability (GBRMPA, 2019). Action(s) at a global and national level to mitigate and adapt to climate change are essential, as is a strong focus on local and regional management actions to maximise GBR ecosystem resilience in the face of a variable and changing climate (Commonwealth of Australia, 2018a).

Poor water quality, mostly attributed to land-based run-off including increased loads of nutrients, fine sediments and pesticides from the adjacent catchments, is another major driver of change within the GBR. Knowledge of water quality impacts on GBR ecosystems were synthesised in the [2017 Scientific Consensus Statement]: Land use impacts on Great Barrier Reef water quality and ecosystem condition (Waterhouse *et al.* 2017), building on previous

[2] NESP Tropical Water Quality Hub – Hub Synthesis

statements. Updates based on the NESP-funded research are included in this report and in the synthesis of NESP-funded nutrient (Waterhouse & Pineda 2021) and GBR resilience-related research (Pineda & Johnson, 2021). Of specific relevance to this report, fine sediment inputs into the GBR lagoon can cause important ecological impacts such as reduction in benthic light quantity and quality, sedimentation or smothering of benthic organisms, direct disturbance by suspended particles and increased loads of bioavailable nutrients associated with the sediment particles (Bainbridge *et al.*, 2018). A wide range of NESP TWQ Hub projects have focussed on the source, transport, fate and impact of sediments on estuarine, coastal and reef ecosystems. These projects support the implementation of the Reef 2050 Plan (Commonwealth of Australia, 2018a) and Reef 2050 Water Quality Improvement Plan 2017-2022 (Australian Government and Queensland Government, 2018) (Reef 2050 WQIP) water quality targets aiming to reduce the loss of sediments from catchment to the environment (Australian Government and Queensland Government, 2018; Commonwealth of Australia, 2018b).

1.3 Current policy and management direction relevant to managing GBR sediment inputs

As climate change becomes the dominant driver of GBR health outcomes, there is recognition that major disturbance events will become more frequent (e.g. mass thermal bleaching) and/or intense (e.g. cyclones)[3], placing extra pressure on the ability of reef ecosystems to recover. Degraded water quality occurring during periods of disturbance and recovery can further exacerbate the effects of these events on GBR ecosystems. As GBR managers cannot directly act upon the drivers of global warming, it is critical to maintain and enhance coral reef resilience at local, regional and reef-wide scales. Maintenance of water quality conditions that protect ecosystem health is an important factor for supporting reef resilience. While some improvements have been achieved in end-of-catchment pollutant loads on a regional scale due to modest improvements in agricultural land management practices (see Reef 2050 WQIP investment table[4]) and through addressing erosion hotspots (e.g. Reef Trust investments), poor water quality continues to affect inshore and some midshelf areas of the GBR (GBRMPA, 2019; Schaffelke *et al.*, 2017). As a result, the Reef 2050 WQIP (Australian Government and Queensland Government, 2018), underpinned by the 2017 Scientific Consensus Statement (Waterhouse *et al.*, 2017) and nested within the Reef 2050 Plan (Commonwealth of Australia, 2018a), establishes the guidelines, policies and programs, as well as monitoring and reporting frameworks required to improve the quality of water flowing from adjacent catchments to the GBR.

To meet the desired water quality targets across the GBR catchments (i.e. 60% reduction in nitrogen, 20% reduction in nutrients and 25% reduction in fine sediments loads that reach the end-of-catchment by 2025 at a reef-wide scale; and specific regional and catchment level targets), additional measures such as improvements to governance (i.e. more adaptive, participatory and transdisciplinary approaches), program design and delivery and evaluation systems are also urgently needed (Eberhard *et al.*, 2017). However, the annual Reef water quality report cards, which detail progress against the Reef 2050 WQIP targets, and the annual Marine Monitoring Program reports (Gruber *et al.*, 2020) show that the overall condition of the

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[3] http://www.bom.gov.au

[4] https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0019/46117/reef-2050-wqip-investment.pdf

inshore marine environment (water quality, seagrass and coral) remains poor. Positive progress has been made in some specific targets such as dissolved inorganic nitrogen (i.e. overall annual reduction of 4.3%) and specific examples at the regional/catchment scale (e.g. for fine sediment loads and pesticide targets in the Burnett Mary region)[5] (Australian Government and Queensland Government, 2019). However, due to the dynamic nature of the interconnected catchment to reef landscape, the influence of external factors and time lags associated with management intervention and water quality response, it will take many years to achieve measurable improvements in GBR marine water quality as a result of land management improvements; however, long term monitoring programs provide the trend analyses required to show improvement over time (Gruber *et al.*, 2020).

To better manage sediment losses and prioritise remedial actions, it is important to be able to understand and contextualise the issues that are involved in improved sediment management, from managing catchment sources, to defining which types of sediment cause the most harm in the marine environment. This report provides a narrative synthesis to bring all these threads together. Synthesis of this new knowledge assists prioritisation of practical on-ground actions for land and sea managers, highlights policy implications and identifies remaining gaps for future research and management investments.

1.4 Timeline of GBR sediment-related research

The National Environmental Science Program (NESP, 2015-2021) built on predecessor national programs: National Environmental Research Program (NERP, 2011-2015), Commonwealth Environmental Research Facilities (CERF, 2005-2011), including the Marine and Tropical Sciences Research Facility (MTSRF) program administered by the Reef and Rainforest Research Centre (RRRC), and programs funded by the Queensland Government (e.g. Reef Water Quality Science Program) and CSIRO among others (e.g. CSIRO Water for a Healthy Country Research Flagship, 2003-2008). Additional collaborative research in the GBR funded by the Australian Government prior to 2006 was led by The Cooperative Research Centre for the Great Barrier Reef World Heritage Area (CRC Reef) (1999-2006) and contributed to creating the basis for topics such as water quality monitoring, crown-of-thorns starfish and box jellyfish research, impacts of ports and shipping, global warming and climate change effects and Torres Strait marine research. During this period, the knowledge of the sources, delivery and fate of fine sediment in the GBR has improved considerably and has included important findings critical for guiding management actions to reduce end of catchment loads of fine sediment. Figure 1 summarises the key research findings and associated literature that highlights this progress.

[5] https://reportcard.reefplan.qld.gov.au/

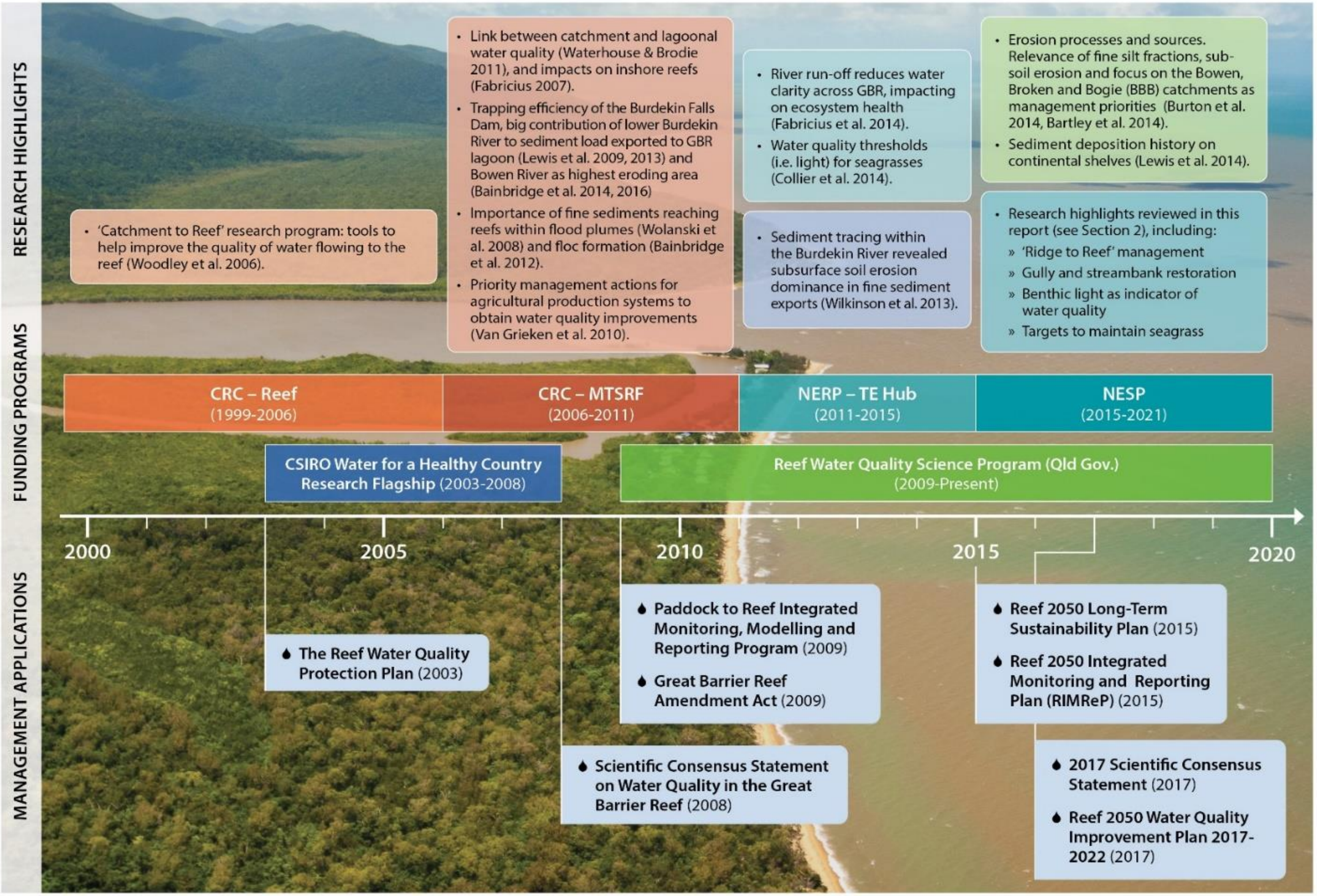


Figure 1. Diagram illustrating the progress of knowledge related to the sources, delivery, fate and management of fine sediment in the GBR and its catchments.

For example, water quality research funded through the CRC-Reef (1999-2006) covered issues such as GBR nutrient budgets, fluxes to the GBR from the variety of sources including delivery mechanisms such as flood plumes, initial investigations of impacts of nutrients and sediments on coral communities and some of the first samplings in the marine environment for agricultural pesticides. In addition, their 'Catchment to Reef' research program (2002) addressed gaps in knowledge, refocussed some of the research effort to further quantify impacts of sediments, nutrients and pesticides, and began to explore links between catchments and the Reef, while providing tools to help improve the quality of water flowing to the GBR (Figure 1) (Woodley *et al.*, 2006).

Subsequently, the MTSRF program (2005-2011) contributed to a better understanding of priority areas and agricultural practices for pollutant generation (van Grieken *et al.*, 2010; Waterhouse & Brodie, 2011), identified the importance of fine sediments reaching the inshore reefs within flood plumes (Wolanski *et al.*, 2008), and the formation and re-suspension of flocs (Bainbridge *et al.*, 2012) and associated ecological impacts (Fabricius, 2007). The high trapping efficiency of the Burdekin Falls Dam was also described together with the significant contribution of the lower Burdekin River to the sediment load exported to the GBR lagoon (Lewis *et al.*, 2009, 2013), with the Bowen River catchment being identified as the highest eroding area influencing the GBR in terms of fine sediment load generation and delivery (Bainbridge *et al.*, 2016; Bainbridge *et al.*, 2014). Additionally, concentration-based thresholds of concern were developed for several water quality variables and ecosystem components and were thereafter applied to water quality guidelines for the GBR (Figure 1) (reviewed in Devlin & Waterhouse, 2010; Waterhouse & Devlin, 2011).

Results of NERP-funded research on water quality were synthesised by Devlin *et al.* (2015), and had a strong focus on priority pollutants, cumulative pressures on key ecosystems, identification of priority areas or actions for managers and monitoring and evaluation of long-term historical water quality. NERP water quality projects advanced understanding of both catchment and marine processes that impact on GBR water quality and impacts on the resilience and health of key GBR ecosystems. The NERP Tropical Ecosystems Hub generated significant outcomes to help inform the design and implementation of water quality monitoring, evaluation and conservation programs. For instance, it advanced understanding of the extent and influences of river run-off on water clarity and its impacts on inshore reefs (Fabricius *et al.*, 2014) and seagrasses (Collier *et al.*, 2014) (Figure 1). Projects linking catchment changes to the water quality condition of the GBR allowed assessment of the main pressures driving change, and also provided information on the resilience of the GBR to withstand change, and on our ability to manage and reduce those pressures to provide a pathway to recovery (Devlin *et al.*, 2015).

Additional funding through the Water for a Healthy Country Research Flagship (CSIRO) and the Reef Water Quality Science Program (Queensland Government) demonstrated significant subsurface soil erosion and other erosion processes and sources in the Burdekin catchment (Burton *et al.*, 2014; Wilkinson *et al.*, 2013), and allowed completion of a review of the major contribution of the Bowen and Burdekin catchments to the total clay and fine silt fractions delivered to the GBR lagoon (Bartley *et al.*, 2014). This research led to a focus on the significant fine sediment losses from the Bowen, Broken and Bogie catchments in the Burdekin Basin, and highlighted the importance of sub-surface erosion as a priority for on-ground remediation actions (Bartley *et al.*, 2014). The sediment deposition history on continental shelves was also addressed along with implications for the calculation of accumulation rates on the GBR (Lewis *et al.*, 2014).

Despite the success of precursor programs, knowledge gaps were identified regarding some topics such as water quality research and cumulative impacts in the GBR. Some examples included i) the study of fine sediment delivery from activities such as dredging and its potential effects on light availability for GBR ecosystems; ii) further research on pesticide uses, pathways, thresholds and potential alternatives; iii) better understanding of cumulative impacts in order to develop measurable climate- and regionally adjusted water quality targets and cumulative impact guidelines; and iv) multi-generational experiments to assess the potential acclimation and adaptation of ecologically key species to cumulative impacts. Finally, the utilisation of remote sensing and monitoring of seagrass condition demonstrated a strong potential of the use of satellite imagery to measure ecological change (Devlin *et al.*, 2015). Thus, it was suggested that future work had to focus on the development of this technique as well as the integration of *in-situ*, site-specific water quality logger data, and experimental approaches (aquaria based) to further investigate effects of water quality on seagrasses and other tropical marine organisms (Devlin *et al.*, 2015).

2.0 NESP TWQ HUB RESEARCH HIGHLIGHTS: SEDIMENT SEA TO SOURCE

Projects ranging from assessment of the ecological thresholds of seagrass to fine sediment exposure, tracking the dispersion of fine soil particles and repairing gullies in grazing lands were commissioned through NESP TWQ Hub (2015-2021). These Projects were developed around the research priority to seek solutions to sediment reduction in the GBR lagoon through an understanding of sediment sources, sediment suspension, the impacts of dredging, gully rehabilitation and improved management in upper and lower catchments of the GBR area (as illustrated in Figure 2). In addition to managing the sources of sediments, research also examined where sediment disperses in the marine environment and how to monitor, measure and report on its dispersion and any resultant impact on coral and seagrass communities. Therefore, this summary report has adopted a 'sea to source' logic, recognising that a better understanding of the most important characteristics of fine sediments on ecosystem health impacts, and improved knowledge of the transport and delivery processes associated with this material enables managers to target management efforts in the GBR catchment both spatially and temporally. This is supported by investigation of the most efficient management actions for these fine sediment characteristics (Figure 2) (projects summarised in Table A1.1, Appendix).

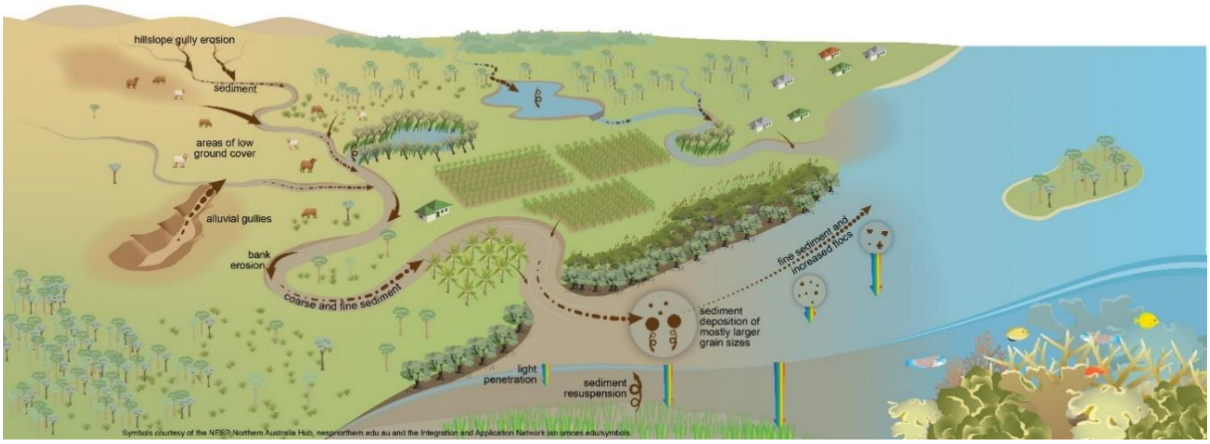


Figure 2. Diagram illustrating the catchment to reef fate of sediments.

2.1 Sediment fate and impact in the GBR

2.1.1 Ecological impacts of fine sediment on GBR ecosystems

Importance of sediment characteristics and impacts

As summarised by Bainbridge *et al.*, (2018) terrestrial sediment can reach the ocean in flood plumes caused by runoff, and usually most of the nutrient-enriched finer sediment load settles initially within the estuary or near the river mouth. Some suspended particulate matter (SPM) can also be transported over long distances (> 50 Km) [6] and transformed into large and easily

[6] Average width of the GBR is between 60-250 Km. (GBRMPA).

re-suspendable, organic-rich sediment flocs. These flocs lead to prolonged reductions in water clarity (i.e. days to months, depending on flow volume, wind speed and direction, ocean currents, and other physical and bio-geochemical processes), impacting mostly inshore but sometimes midshelf and even offshore coral reefs, seagrass and fish communities (Figure 3). For marine organisms and ecosystems, SPM and specifically, 'organic-rich sediment', is considered one of the most detrimental forms of sediment, as it can adhere to coral tissue and seagrass leaves, making it very difficult for these species to remove, as opposed to organic-poor calcareous offshore sediments. Organic-rich sediments can also be easily resuspended due to their low density, they can cause reductions in water clarity for extended periods, reduce pH and oxygen conditions locally, and their darker colour increases light attenuation in the water column (Bainbridge *et al.*, 2018; Lewis *et al.*, 2018).

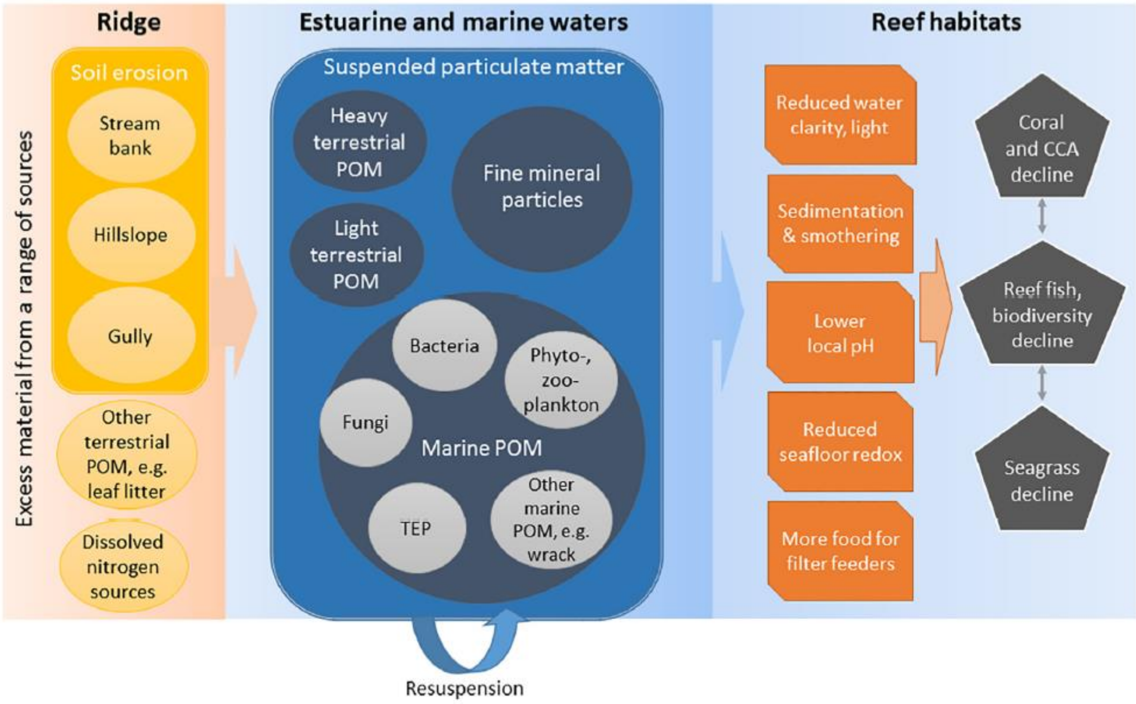
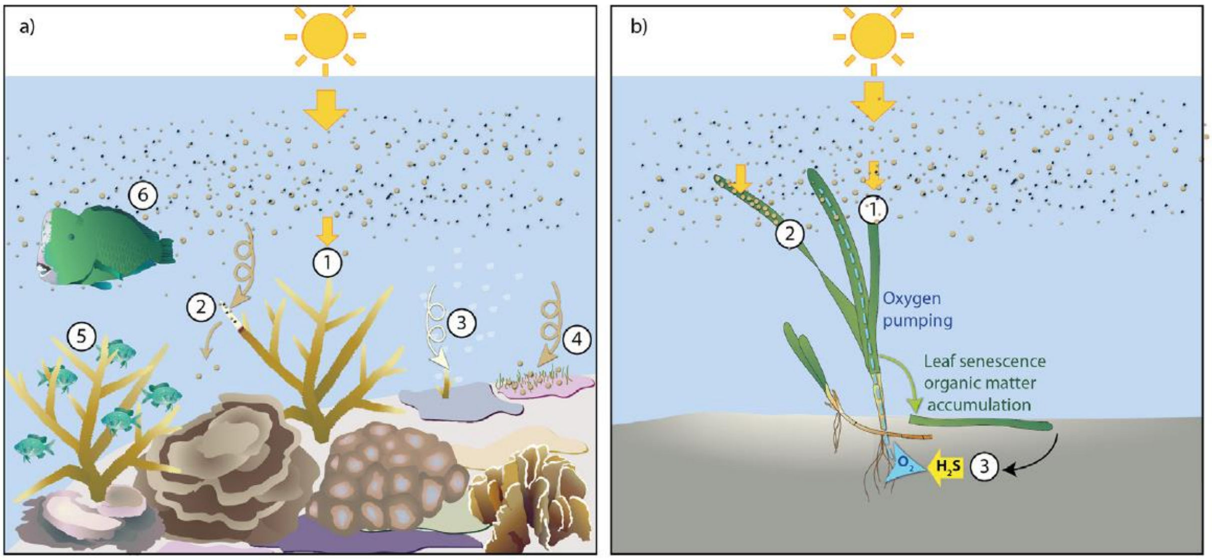


Figure 3. Conceptual diagram of suspended particulate matter sources, transport processes and tropical marine ecosystem impacts across the ridge to reef continuum. POM, particulate organic matter; mPOM, marine-derived particulate organic matter; TEP, transparent exopolymer particles; CCA, crustose coralline algae. Source: *Bainbridge* et al., *(2018)*.

Coral reef and seagrass responses

Fine sediments and SPM (i.e. particulate organic matter and mineral sediment) can cause stress on the marine environment through light reduction, disturbance by suspended particles, and sedimentation (Figure 4). Increase in light attenuation and change in the spectral composition of light reduces the availability of photosynthetically usable light for benthic communities and is a major stressor. Water clarity is one of the strongest water quality indicators and a strong predictor for ecosystem change, with resulting ecological impacts depending on the intensity and duration of exposure, preceding and co-occurring environmental conditions and the type of communities being affected. Overall reduced water clarity usually leads to slower growth or even loss of photosynthetic organisms such as corals and seagrasses (Bainbridge *et al.*, 2018). Work conducted through the NESP TWQ Hub provides further evidence that water clarity and benthic light intensity is predictive of both changes in coral community resilience and seagrass habitat suitability (Robson *et al.*, 2020).



1. SPM attenuates light
2. SPM is not easily removed from coral surfaces, and may contain disease vectors
3. TEP ('marine snow') enhances mortality of juveniles
4. SPM negatively affects CCA and facilitates their overgrowth by turf algae
5. SPM affects fish habitat through the mechanisms described above
6. SPM directly affects fish, including their foraging, gill function and metabolism

1. Sunlight attenuated by SPM, reducing photosynthesis and oxygen production
2. Sediment settles on leaves reducing oxygen production and diffusion
3. Oxygen extrusion reduced when deposited SPM impacts biogeochemical processes

Figure 4. Summary of the effects of suspended particulate matter (SPM) on (a) coral reefs and reef fish, and (b) seagrasses Source: *Bainbridge* et al.*, (2018)*.

Coral reefs

Effects of sediments on corals have been reviewed elsewhere (e.g. Bainbridge *et al.*, 2018; Jones *et al.*, 2020b) but in brief, some coral reef species are highly sensitive to reduced water clarity, as their photo-symbionts (i.e. zooxanthellae) require light for photosynthesis (Bessell-Browne *et al.*, 2017; Erftemeijer *et al.*, 2012). For instance, NESP TWQ Hub research led by Fabricius and Robson show that coral growth and recruitment are both reduced when daily integrated benthic light is reduced, for instance due to reduced water quality (DiPerna *et al.*, 2018; Robson *et al.*, 2019; Strahl *et al.*, 2019). In other cases, sediments in suspension can additionally affect corals' early life history stages, including fertilisation, larvae development and recruitment (Humanes *et al.*, 2016; Jones *et al.*, 2015). Sedimentation can also affect some coral life history stages, and its effects are highly dependent on the sediment properties (i.e. particle size, contents of organic matter, nutrients, pollutants) (Ricardo *et al.*, 2018) (Figure 4).

New NESP TWQ Hub research (Jones *et al.*, 2020a) demonstrated that suspended sediments in the water column not only decreased total benthic light availability but caused a change in the light spectrum, with relatively greater loss of more photosynthetically usable blue light, and a shift towards green light (with a peak at 575 nm). This spectral shift is important as it results in a loss in both the quality and quantity of light, and has been replicated in laboratory experiments in order to properly evaluate pressure-response relationships of turbidity on corals and sponges (Jones *et al.*, 2020a).

Jones' team additionally addressed how sediment characteristics influenced the fertilisation success of corals, finding that fertilisation was highly sensitive to inshore organic-clay rich sediments and bentonite clay (i.e. common in fluvial discharge) at < 5 mg L^{-1}, probably due to the organic matter within these sediments which could prompt flocculation of coral sperm, thus reducing fertilisation rates. In contrast, terrigenous sediments of lower organic matter affected fertilisation only at higher concentrations similar to those produced by dredging operations or during storm events. Carbonate-based suspended sediments were found to have very minor effect on coral fertilisation success rates, even at low sperm concentrations. The study concluded that it is therefore important that efforts to reduce mineral clays and nutrients entering tributaries are continued, and dredging projects that generate or disturb (e.g. dredge, drill or resuspend) nutrient and clay rich sediment types are regulated, especially during critical environmental periods such as multi-species synchronous coral spawning events (Ricardo *et al.*, 2018).

While dredging and the direct impacts of river plumes can cause acute impacts on corals, Robson's team focused on chronic impacts of smaller but longer-term reductions in water clarity and benthic light. Data from remote sensing (satellite ocean colour observations) showed that reduced water clarity can be observed in nearshore and occasionally mid-shelf regions during river plumes and resuspension events, and that chronic light stress associated with reduced water clarity is predictive of deterioration in reef community resilience (Robson *et al.*, 2020).

Seagrasses

Seagrass meadows are highly sensitive to climatic conditions and environmental pressures such as water quality. Collier's team used more than 20 years of historical seagrass biomass data (1995-2018) from 25 seagrass communities to develop desired state benchmarks. Results showed a historical, decadal-scale cycle of decline and recovery to desired state in coastal intertidal communities (Carter *et al.*, 2021). Researchers found that a number of the estuarine and coastal subtidal communities have not recovered to desired state biomass in recent years. The declines were correlated with extreme weather events that included high rainfall and SPM discharge which reduced light for extended periods, but the processes governing recovery are not yet adequately understood (Carter *et al.*, 2021).

Decreased light availability in seagrass meadows causes biochemical, physiological and morphological changes, as well as reduced growth rates and can even lead to mortality within days-years depending on species (Chartrand *et al.*, 2018; Collier *et al.*, 2016a; Collier *et al.*, 2012; Longstaff & Dennison, 1999; O'Brien *et al.*, 2018) (Figure 4). Threshold tolerance limits of seagrasses to SPM can be used to set water clarity targets and/or to assess ecological risk (Lambert *et al.*, 2019; Waterhouse *et al.*, 2017). Tolerance limits of seagrasses are affected not only by the effects of SPM concentrations on water quality but also by the duration and periodicity of exposure, and can vary substantially depending on factors including species, morphologies, life stages, and acclimation (Bainbridge *et al.*, 2018; Erftemeijer *et al.*, 2012).

Collier's team (Collier *et al.*, 2016b) studied light thresholds for seagrasses in the GBR, to assess the impact of change in water quality and the light environment from anthropogenic activities such as coastal and port development. The study found colonising species to be the most sensitive to light reduction and to have the most limited light thresholds (2 to 6 mol m^{-2} d^{-}

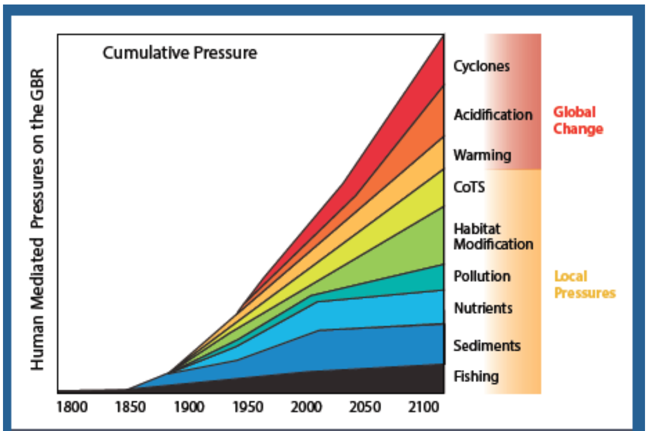
^{1}) and shortest time to impact (14-28 days). Opportunistic and persistent species exhibited higher light thresholds (5-6 mol m^{-2} d^{-1}) and longer times to impact (28-50, and 50 days, respectively). Thresholds for long-term maintenance of seagrasses were also proposed, with 10-13 mol m^{-2} d^{-1} likely to prevent light limitation for the long-bladed species, although deep water species require less light (Collier *et al.*, 2016b). Recent work relating remote sensing observations of benthic light to observed seagrass presence/absence provides further support for a light threshold around 10 to 12 mol m^{-2} d^{-1} for long-term community maintenance and to avoid chronic impacts (Robson *et al.*, 2020).

Cumulative impacts

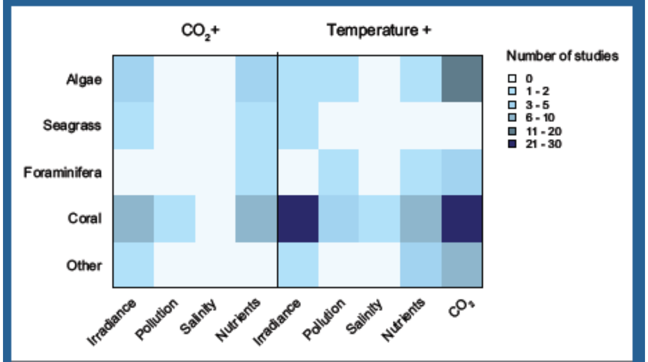
The GBR is affected by multiple local and global stressors simultaneously (Pineda *et al.*, 2021). Local water quality stressors including increased sediment and nutrient loads and/or presence of pesticides are acting in combination with other pressures such as global climate change (i.e. increased water temperature, acidification and associated bleaching events) (e.g. Hughes *et al*., 2003). NESP TWQ Hub research addressed some of those pressures in combination and their cumulative impacts on the GBR. For instance, a review of case studies of cumulative impacts of global and local pressures on coral reef organisms showed that some important interactions such as ocean acidification and salinity or ocean acidification and pollution still remained relatively unstudied (Figure 5) (Uthicke *et al.*, 2016). The authors concluded that future work had to focus in understanding the interactions between 'manageable' pressures, specifically light/turbidity and sediment-bound pollutants (including nutrients), and 'global (and essentially unmanageable)' pressures such as ocean acidification and ocean warming, and a list of research topics was provided to prioritize and guide subsequent projects (Uthicke *et al.*, 2016). Subsequently, experimental assessment of concentration-response relationships were undertaken for selected habitat-builder organisms (including corals, seagrasses, macroalgae and foraminifera) under local stressors (sediments and/or herbicides) and different climate scenarios (Uthicke *et al.*, 2020). Albeit responses depended on the organisms and response variable, the combined stresses created an overall worse outcome for the organisms than when pressures were applied in isolation. These results highlighted the need to adjust water quality guidelines to take into account projected seawater temperature increases.

The linkages between water quality and the thermal tolerance of GBR coral reefs were also quantified, with a special focus on coral's ability to resist and recover from bleaching events, such as those experienced in the GBR in 1998, 2002, 2016, 2017 and 2020 (Cantin *et al.*, 2021). Aquaria experiments at the National Sea Simulator facility investigated which water quality parameters (i.e. nutrients, light, turbidity) affected corals' thermal tolerance and how temperature and water quality exposure histories affected bleaching susceptibility and recovery. Results showed that water quality influences coral health mostly through the cascade effects caused by excess nutrient availability (specifically nitrogen and phosphorus), which causes the shift of symbiont algae from a mutualistic to a parasitic relationship. The study concluded that stable metabolic compatibility between the coral host and algal symbiont can ameliorate bleaching and increase resilience to environmental stress. Furthermore, historical nutrient conditions may adversely influence host-symbiont metabolic capability, and therefore increase bleaching susceptibility (Morris *et al.*, 2019).

Field studies can also contribute to a better understanding of cumulative impacts that have occurred and the inherent ability of a reef to recover (i.e. reef resilience). Research results revealed significant declines in live hard coral and fish abundances within the Keppel Islands (southern GBR) after reefs were exposed to cumulative pressures in preceding years (i.e. coral bleaching event, river flood plumes containing high total suspended sediment (TSS) concentrations and a category 5 cyclone), despite the protection status (i.e. zoning; Williamson *et al.*, 2016). However, a small percentage of reefs (ca. 13%) remained relatively healthy (i.e. with at least 45% cover of live hard coral) by 2015 and were identified as ‘key’ refuges. These refuge reefs provide important local stores of coral reef biodiversity, and they could contribute to the replenishment and recovery of the degraded reefs through future larval supply.



Pressures on the Great Barrier Reef (modified after Duarte 2013: http://theconversation.com/auditing-the-seven-plagues-of-coastal-ecosystems-13637). Timing and magnitude of presures are not to scale and for illustrative purposes only



The number of studies identified that address the combined effects of global and local pressures on five major groups of GBR organisms

Figure 5. Cumulative pressures on the GBR (top) (modified from Duarte 2014 in The Conversation, https://theconversation.com/auditing-the-seven-plagues-of-coastal-ecosystems-13637) and number of studies identified for the combined global versus local pressures on five major groups of GBR organism (bottom). Source: Uthicke et al., (2016).

Improvements in spatial and temporal knowledge

Recent advances in optical models have enabled accurate mapping of areas impacted by sediment deposition and reduced water clarity associated with river flood plumes. The eReefs[7]

[7] http://ereefs.info

marine models for the GBR provide large-scale, near real-time modelling of relevant processes in open access format at a level of detail not previously available, including the effect of each suspended sediment component on light quality and quantity (PAR) through the water column. Recent work with these models has demonstrated the possible role of very fine mineral sediment and organic flocs in delivering terrestrially-derived materials to the outer reef, although reduced water clarity in the mid- and outer reef following high flow years could also be explained by transport of nutrients in the form of phytoplankton (reviewed in Bainbridge *et al.*, 2018). New remote sensing algorithms developed through NESP TWQ Hub research also allow mapping of spectral light attenuation and daily integrated benthic PAR at a 1km scale over the whole GBR (Magno-Canto *et al.*, 2019, 2020). These data products have been made available through eAtlas as a NESP TWQ Hub data product, via https://eatlas.org.au/nesp-twq-5/benthic-light-5-3.

Poor water quality reduces the penetration of light to the sea-floor and reef habitats that may otherwise support corals and seagrass beds. A new water quality indicator (WQI) for benthic light (I_{bPAR}) was delivered by Robson's team to relate benthic light to ecological outcomes across the whole GBR (Robson *et al.*, 2019; Robson *et al.*, 2020). I_{bPAR} was initially measured using satellite data and validated through *in-situ* light loggers, and was used to quantify and map benthic irradiance through the GBR near-daily over a 14-year period (2002-2017). Combining threshold values for ecological health with I_{bPAR} allowed researchers to map year-to-year changes in areas that receive sufficient light to support growth and recruitment of common coral and seagrass species. The maps illustrated declines in suitable habitat in years following major flood events, especially in coastal regions influenced by the Fitzroy and Burdekin Rivers (Figure 6). The new indicator allows the estimation of trends and prediction of ecological consequences of human activities, such as agricultural run-off. The index does not require expensive *in-situ* monitoring as it can be calculated from either satellite observations or eReefs model outputs, is responsive to human activities and year-to-year variations in runoff, can be easily automated for incorporation into the Reef water quality Report Cards, and is of direct ecological relevance (Robson *et al.*, 2019; Robson *et al.*, 2020). However, further consideration of the implications of cloud cover, particularly in the wet season, leading to potential gaps in the remotely sensed dataset are required.

The advances in the models described above enabled seagrass habitat suitability and seagrass community diversity to be assessed. That analysis identified 88,331 km^2 of potential seagrass habitat (~26 % of the area of the GBR) and 36 seagrass community types distributed across that area in the GBR (Carter *et al.*, 2021). Improvements to the seagrass distribution and community models can be used to influence marine spatial planning and environmental protection initiatives, including reduction of SPM losses from catchments.

Affordable underwater multi-spectral sensors for routine light monitoring have also recently become available and their use offers considerable opportunities to further quantify, interpret and then assess the risk of sediment and nutrient run-off in the inner GBR. NESP TWQ Hub research obtained multispectral light datasets at Cleveland Bay, including data collected during dredging operations and natural resuspension conditions (Jones *et al.*, 2020a). Overall, datasets showed a very high variability that was influenced by a range of factors such as waves, currents and bed type. The vertical light profiling with the hyperspectral sensor and the short-term deployment of the multispectral sensor provided new insights into the effects of suspended sediments on light quality, describing not only the well-known exponential decrease in light quantity and spectrum with depth, but also the recently reported changes in spectral quality in the presence of increased sediment concentrations. It was concluded that the loss of blue light is probably due to the iron content in the terrestrial sediment and to the increased absorption by 'chromophoric dissolved organic matter' (CDOM) (Jones *pers. comm*.). The resultant shift in colour spectrum to green light (550-600 nm) under increasing suspended sediment concentration, is outside the spectral region of the major photopigments and therefore implies not only a loss of light quantity but also light quality for photosynthetic organisms such as corals and seagrasses (Jones *et al.*, 2020a).

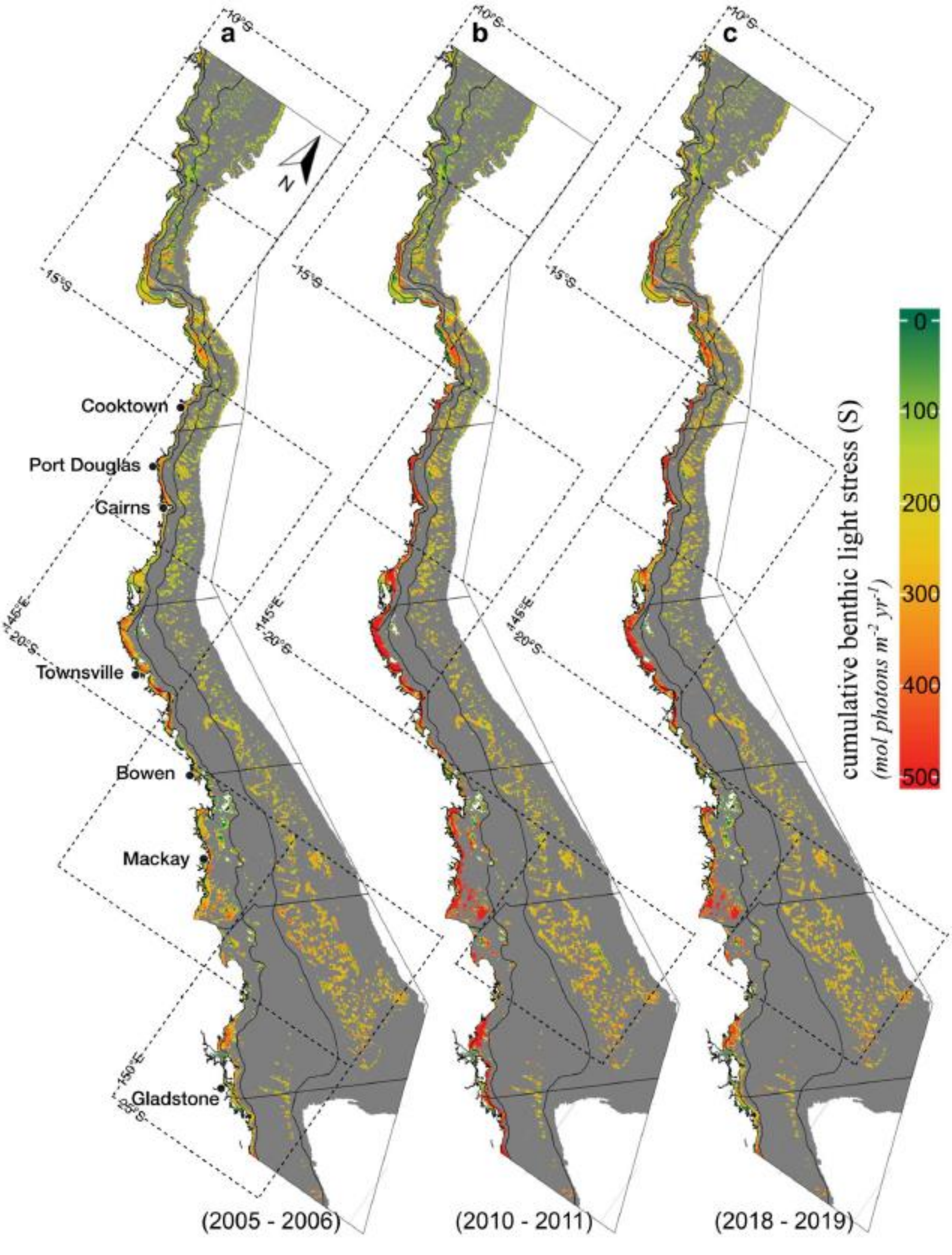


Figure 6. Cumulative (annual) benthic light stress (S) maps for some representative water years. Source: Robson *et al.,* (2020)

2.1.2 Site specific examples

Fine suspended sediments delivered from rivers into the GBR lagoon can reach coral reefs and seagrass meadows, reducing photic depth and water clarity and potentially affecting ecosystem health. Some additional site-specific case studies within the NESP TWQ Hub addressed the ecological impacts of fine sediment on GBR ecosystems and are summarised below.

Light requirements and thresholds for healthy corals in experimental conditions and along water quality gradients in the Burdekin River and Whitsunday region

NESP TWQ Hub research assessed ecological light limitations in benthic habitats, and specifically tested the effects of low light on different light history stages of corals at the National Sea Simulator (Robson *et al.*, 2019). Responses in adult corals were species-specific, but overall reduced growth rates were associated with low (6 mol photons m^{-2} d^{-1}) and variable light conditions (DiPerna *et al.*, 2018). Additional results suggested that it is the cumulative amount of light that corals receive which affects their physiology and growth, which means that even short-term reductions in light over coral reefs (e.g. due to flood plumes) could affect growth rates and therefore impair recovery potential from disturbances. A field study investigated the physiological responses of the coral *Acropora tenuis* along a water quality gradient in the Burdekin River and Whitsunday region. Overall, photosynthesis (both by coral and symbionts) and coral calcification were substantially reduced in the field at I_{bPAR} < 10 mol photons m^{-2} d^{-1} (Rocker *et al.*, 2017). This new data is important for informing the definition of thresholds for GBR communities in the development of water quality guidelines and targets.

Impacts of sediment discharge on seagrass communities in Cleveland Bay

Comparison of the condition of seagrass (area and biomass) in Cleveland Bay (NE Australia) to river discharge and associated sediment loads was undertaken by Collier and colleagues to inform the development of reliable ecologically relevant load targets for seagrass communities. The project fitted linear models to 12 years of monitoring data (Lambert *et al.*, 2020), and demonstrated that the Burdekin basin dominated sediment delivery to Cleveland Bay, and that TSS loads from the Burdekin River were significantly correlated with annual changes in the area and biomass of shallow subtidal seagrasses. Seagrass responses, however, were not directly linked to annual TSS loads, but the 4-year antecedent TSS and fine sediment loads were found to be significantly correlated, suggesting that seagrass state is affected by conditions accumulating over longer time periods. Sediment load thresholds (above which seagrass were predicted to decline or fail to meet desired state) were subsequently estimated, and were equivalent to a 38-49% reduction of the Burdekin River anthropogenic end of catchment fine sediment load (Lambert *et al.*, 2019; Lambert *et al.*, 2020). Seagrass data for the GBR was subsequently compiled, and the unique seagrass community types identified at the scale of the GBR. This provides data that can be used for further assessment of the risk of fine sediment to GBR ecosystems and the improved definition of end of catchment load targets, including sediment load thresholds (Carter *et al.*, 2021).

2.1.3 Other activities influencing sediment impacts

Marine dredging is often required to create and maintain navigable shipping channels and allow safe ship access in coastal areas, however it is usually associated with increased suspended sediments that could impact upon nearby marine communities (Erftemeijer *et al.*, 2012; Foster *et al.*, 2010). Researchers investigated potential risks associated with dredging in inshore coastal areas near reefs in Cleveland Bay (central GBR), an area already exposed to natural high turbidity events (Jones *et al.*, 2020a). The 3-year dataset (including 6 dredging events) provided by the Port of Townsville Ltd., is the longest description to date of benthic light availability in this environment, and the only one collected using reliable and calibrated light sensors (with known quantum responses and cosine corrections). The light data was examined over different running mean time periods (hours to weeks) to characterise the extent of light reduction that can actually occur on reefs, both naturally through sediment resuspension events, as well as through multiple bouts of maintenance dredging near the reef. Data showed a very clear turbidity gradient across Cleveland Bay, with mean daily turbidity ranging from <0.5 to >50 Nephelometric Turbidity Unit (NTU), with averages of ~2-7 NTU depending on the monitoring sites (Jones *et al.*, 2020a). Researchers highlighted the importance of such a matrix of data for risk assessments and to justify any subsequent manipulative experiments examining the effects of light (Jones *et al.*, 2020a). This range of turbidity is also known to cause changes to fish behaviour including habitat use and foraging success, and larval development (Wenger *et al.*, 2014; Wenger & McCormick, 2013).

Within the same project, the use of multi-spectral and hyper-spectral light sensors revealed marked changes in the spectrum (colour) of the underwater light caused by suspended sediments, with a preferential loss of blue light and the creation of a green hue underwater (as discussed in section 2.1.1). This event was described for the first time and has ecological implications as green light is less photosynthetically useful (i.e. loss of light quantity and quality). As cloudy days caused a loss of underwater light but no changes in colour, a simple ratio of blue (λ455 nm) to green (λ555 nm) light wavelengths was developed to identify the cause of any periods of low light (i.e. suspended sediments versus cloud cover). From those studies, an empirical spectral solar irradiance model was constructed for Cleveland Bay, using wavelength specific light attenuation coefficients to accurately describe the likely light levels using only information on sediment concentration, depth and solar elevation angle (Jones *et al.*, 2020a) (Figure 7). The model was used to further describe the inshore turbid reef zone light environment for the first time, and to define environmentally relevant and scientifically justifiable exposure conditions to test the effects of suspended sediments and changes in light quality/quantity on corals and sponges in the AIMS Sea Simulator.

While these experiments resulted in survival for all corals and sponges, clear physiological responses were measured, including changes in pigmentation, lipid concentrations, the ratio of structural to storage lipids, and density of symbiotic dinoflagellates. Statistical techniques employed in ecotoxicology were used to derive light-based water quality thresholds for inshore coral reefs based on mol quanta of PAR light per m^{-2} per day^{-1} over a relevant running mean period.

This study was the first to relate light availability in terms of mol photons m^{-2} d^{-1} (a daily light integral) to coral health, hence it was the first attempt to integrate time and light reduction (and spectral changes in conjunction with sediments) into a parameter that can be used for monitoring and risk assessments for natural turbidity events and dredging. The pressure-response relationships identified within this project could be used with plume trajectory modelling before dredging and for *in situ* monitoring programs during dredging, and could also be incorporated into risk-response reactive management cascades to guide dredging operations once underway (Jones *et al.*, 2020a).

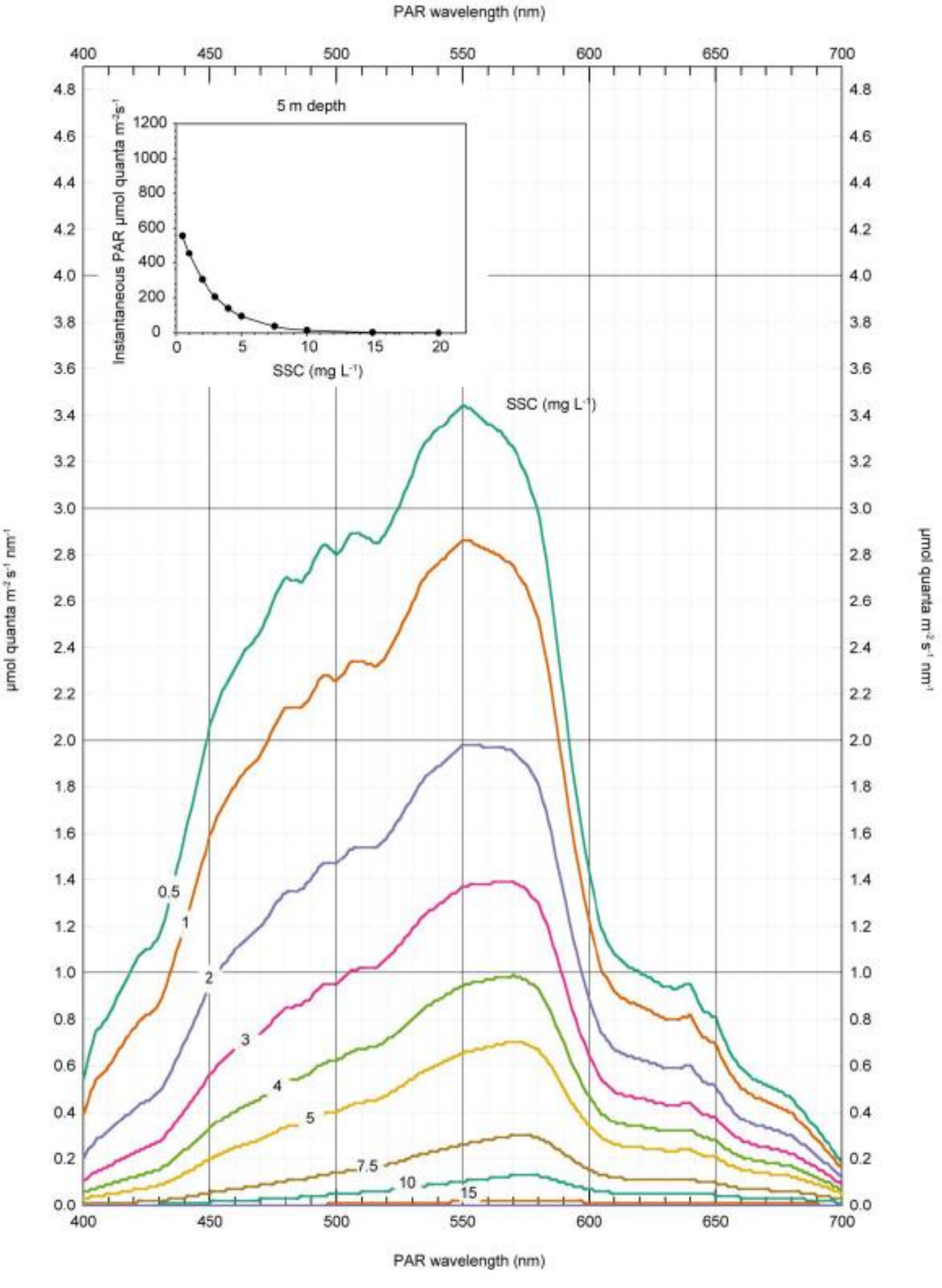


Figure 7. Modelled spectral profiles over the photosynthetically active radiation (PAR, 400-700 nm) range in µmol quanta m^{-2} s^{-1} nm at 5 m depth under a range of SSCs from 0.5-15 mg L^{-1} at a zenith angle of 0° (i.e. sun directly overhead), and a cloud-free day, based on the Cleveland Bay spectral solar model. Source: Jones *et al*., (2020a).

2.2 Sediment delivery to the end of catchment and GBR

2.2.1 Sediment transport, transformation and impact

The fine sediments that reduce photic depth and water clarity during both flood plumes and resuspension events at key locations within the GBR lagoon, including coral reefs and seagrass meadows, were traced back to their specific catchment sources by Lewis *et al.* (2020). Results showed that the composition of the newly delivered sediment to the GBR lagoon changes during transport, deposition and resuspension, with increasing importance of the organic component, and the preferential transport of fine-grained mineral particles in both Tully and Burdekin Rivers (Bainbridge *et al.*, *2021*).

Time-series data from seven marine instrumented logger sites demonstrated the influence of newly delivered terrigenous sediment (and particulate nutrients) in flood plumes at all sites where the highest sediment concentration coincided directly with the flood event and/or the highest accumulation rates (and highest total nutrient concentrations) in deployed sediment traps. These sites were strategically located at key coral reef and seagrass locations on the inshore central GBR. Key differences were evident at the sites that reflected the length of influence of the newly delivered fine sediment as well as local scale conditions. Three key mechanisms of impact were identified which included: 1) Increased suppression of light in shallow turbid water environments both during the flood plume and the months afterwards; 2) Pulsed delivery and deposition of flood plume sediment and associated nutrients to inshore coral reef sites which favour an increase in macroalgae cover and corresponding decrease in live coral cover and; 3) Development of chronic persistent turbidity (and reduced photic depth) for long periods as a result of wave and current disturbance (resuspension) of the sediment bed or new sediment delivery (Lewis *et al.*, 2020).

2.2.2 Importance of bioavailable nutrients and transformation during delivery

The importance of bioavailable nutrients and their transformation during delivery of sediments to the GBR lagoon (reviewed in Waterhouse *et al.*, 2018) was also addressed by Lewis *et al.*, (2020). Researchers quantified the quantity of dissolved inorganic nitrogen (DIN) that could potentially become bioavailable (i.e. released) from the terrigenous organic and particulate nitrogen pool via ammonium desorption and microbial processing in estuarine flood plumes. The estimated potential DIN load generated from the particulate nitrogen contained in the three Burdekin River plumes was equivalent to approximately 9 to 30% of the corresponding end-of-catchment DIN load in 4 to 5 days of plume travel time (Lewis *et al.*, 2020). Of the generated DIN load in the Burdekin plume, ammonium desorption was an important process in the early estuarine mixing reaches of the plume (< 10 PSU salinity) and accounted for between 25% and 100% of the total generated load. The remaining contribution was provided by microbial mineralisation of the organic nitrogen component, which has been determined to increase linearly towards the end of incubation experiments (7 days). This result indicated that the sediment and associated particulate nitrogen has the potential to continue to produce DIN once deposited on the marine floor and/or resuspended. Multivariate analysis indicated that the source of the organic matter in the plumes and the availability of DIN relative to the available organic matter for mineralisation are important determinants of mineralisation/immobilisation that occurs in marine sediment plumes (Lewis *et al.*, 2020).

Researchers also quantified changes in the chemical nature of organic carbon (using ^{13}C NMR spectroscopy) and microbial community composition to further assess shifts across the catchment-to-reef continuum and explore flood plume nitrogen and carbon biogeochemical cycling and availability within the GBR lagoon. A detailed understanding of the organic processes occurring to form sediment flocs in flood plumes provided critical information to help explain nutrient fluxes and the bioavailability of particulate nutrients. The data also help to describe the transformation of microbial communities from the catchment to reef continuum, including the transition from terrestrial to marine forms. The data collected could also be used as ‘biological fingerprints’, together with ^{13}C and ^{15}N isotopic signatures, to identify the terrestrial or marine origin of organic matter (Lewis *et al.*, 2020).

Organic carbon also plays a critical role in global biogeochemical cycles, including facilitating the availability of inorganic nitrogen, and is a key energy source in freshwater and marine food webs. However, it can also have negative impacts, particularly in coral reef ecosystems, where elevated organic carbon concentrations have been linked to increased coral mortality, coral bleaching, reduced rates of photosynthesis and slower calcification rates among other impacts. Anthropogenic activity is having an increasingly large impact on the source and flux of organic carbon from land to freshwater and marine environments, mainly through changes in riverine sediment flux. In fact, increasing concentrations of dissolved organic carbon (DOC) and particulate organic carbon (POC) have been lately reported from coastal waters in the GBR. Research results suggested that trends in DOC and POC were mostly driven by river discharge, although POC was also influenced by sediment resuspension and phytoplankton biomass, particularly further offshore. Thus, DOC was suggested as a useful measure of river influence in the GBR (Burrows *et al.*, 2018).

2.2.3 Time lags in delivery

A recent NESP co-funded publication evaluated the effect of variable grazing pressure on sediment and nutrient yields over a 15-year period in the Burdekin catchment (Koci *et al.*, 2020). This study identified that recovery of degraded savanna rangelands is slow and strongly influenced by local climate and hydrological conditions. It may take several decades before a clear sediment and nutrient load response to reduced grazing pressure becomes detectable in ephemeral catchment waterways. Due to the highly variable climate and multiple sources of sediment, measuring recovery in water quality requires nested spatial monitoring over long-time scales. To detect a change requires information on the water quality response (e.g., runoff and pollutant concentration), as well as factors that will influence the change (e.g., soil condition, vegetation cover, land use and climate), and the category of erosional processes affecting sediment and nutrient mobilisation and transport (e.g., hillslope, gully and stream bank erosion) (Koci *et al.*, 2020). Very few studies in the GBR have collated all of these data at a single location over a sufficiently long-time scale.

2.3 Catchment sources of sediment

2.3.1 Catchment scale sources and priorities

According to the 2017 Scientific Consensus Statement, the TSS load estimated to be delivered to the GBR lagoon (i.e. based on the 2015 Catchments modelling for the 1986-2014 period) was ~9,900 kt, with 80% of it considered to be due to land-use change (Bartley *et al.*, 2017). The delivery of sediment varies across different regions, basins and management units in the

GBR, with the Burdekin region delivering more than double the TSS loads of any other region. The models predict that there has been a 3-8 fold increase in TSS export across the GBR, depending on the region. The main processes responsible for the increased sediment losses are erosion from hillslopes or paddocks (i.e. surface erosion) and erosion from deep rills, gullies or riverbanks (i.e. sub-surface erosion). Based on the 2015 Source Catchments modelling, sub-surface erosion is the major source of sediment delivered from the Burdekin, Fitzroy, Mackay Whitsunday and Burnett Mary regions to the GBR. Hillslope erosion is the primary sediment source in the Wet Tropics region and Cape York, although sub surface erosion sources dominate the loads from the Normanby and Stewart basins accounting for a large proportion of the overall regional load (Bartley *et al.*, 2017; McCloskey *et al.*, *2021*).

The main factors affecting erosion rates include catchment geology and soil type, landscape gradient, climate, land use and land condition. The land uses that deliver most of the sediments to the GBR are grazing in the large dry catchments, and to a much lesser extent, sugarcane in the coastal areas (Bartley *et al.*, 2017). Ground cover and soil surface condition play a significant role in controlling the rates of run-off and sediment loss in savannah landscapes, with soil loss from grazed hillslopes increasing as vegetation cover decreases. Stock tracks and patchy vegetation on erodible soils within riparian zones can also lead to the initiation of alluvial gullies and scalded features (see Brooks *et al.*, 2019 for a full gully characterisation). Thus, adequate ground cover on both hillslopes and riparian zones needs to be maintained to reduce the potential for gully formation (Bartley *et al.*, 2017).

Insights into the delivery of sediment from catchment to reef have recently increased with the use of geochemical fingerprinting techniques which link the chemical signature of the marine sediment to soil and sediment within the basin (Bainbridge *et al.*, 2018).

2.3.2 Site specific considerations

Sediment sources in the Johnstone River catchment

A novel approach to combining isotopic geochemical signatures was developed to differentiate the sources of sediments and particulate nutrients from different land uses (Bahadori *et al.*, 2019; Lewis *et al.*, 2018). The sources of sediments and nutrients to the GBR were traced using organic fingerprint methods which allowed the allocation of different land uses in the Johnstone River catchment. Preliminary results suggested that the rainforest land use contributed a significant proportion of sediment (33.1 ± 14.5%) and particulate nitrogen (53.5 ± 7.3%) at the end of catchment; however, when the proportional area of rainforest was considered (i.e. 52% of the catchment area), the relative sediment contribution from this land use was much lower compared to the agricultural land uses examined (i.e. grazing, sugarcane, bananas) (Figure 8). In particular, the banana land use (~4% of the catchment area) contributed a much higher contribution per unit area. However, as only one snapshot sampling was carried out in this preliminary study, further sampling of the Johnstone River catchment and plume is recommended to improve reliability of this model prediction (Bahadori *et al.*, 2019; Lewis *et al.*, 2018).

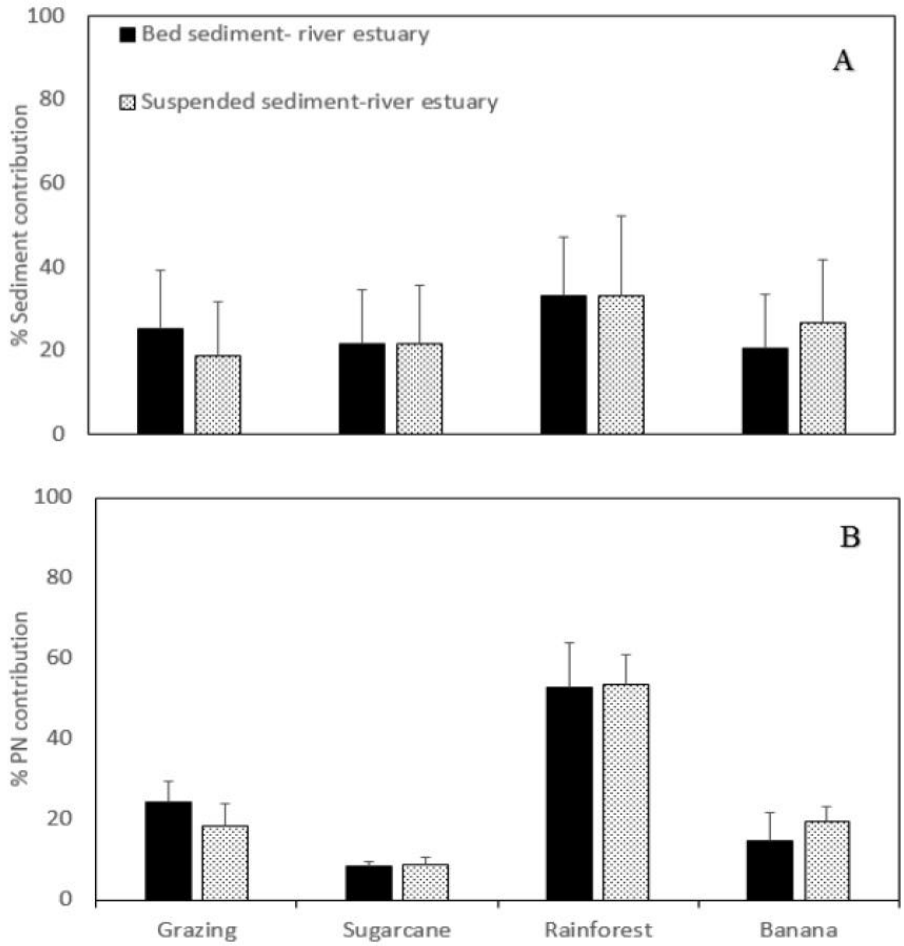


Figure 8. Contributions of different sources (grazing, sugarcane, rainforest and banana) to exported suspended sediments (A) and particulate nitrogen (B) associated with the Johnston River estuary. Source: Lewis *et al*., (2018).

Surface and sub-surface erosion and bioavailable nutrients in the Normanby catchment

Researchers additionally assessed recent trends in erosion sources in the upper Normanby and Laura Rivers (Far North Queensland) (2009-2015 data) (Brooks *et al.*, 2016a). Total erosion rates varied considerably among source areas and sampling years from a 5,536 ha sample of the catchment, with higher erosion rates occurring in alluvial gullies, and channel banks and beds (~2,000-2,500 t yr^{-1} per 100 mm incident rainfall). Gully erosion rates were linked to annual rainfall, while channel erosion rates responded more to the magnitude and frequency of local flood events.

Research confirmed that gullies are important sources of fine sediments to the GBR, but they can also be a significant source of bioavailable nutrients (i.e. nitrogen and phosphorous), even more than intensive agricultural land per unit area (Brooks *et al.*, 2016a). The upper 10-20cm of alluvial terrace soil appear to be an important long-term store of bioavailable nutrients and organics, whilst gully floors may act as a temporary store depending on gully evolution stage. The terrace surface soils were from 54-77 and 5-10 times richer in total organic carbon and total nitrogen, respectively, than the bank subsurface soil in alluvial gullies. However, the sources of organics and nutrient export from alluvial gullies would vary depending on the type of erosional process occurring (i.e. headscarp retreat vs. secondary incision vs. surface erosion from exposed sub-surface side walls) and their stage of development (e.g. gully depth and age). Despite the elevated concentrations of carbon and nitrogen in surface soils, the dominance of sub-surface sources associated with gully and streambank erosion means that these are the dominant inputs to the catchment nutrient budget (Brooks *et al.*, 2016a; Garzon-Garcia *et al.*, 2016).

The majority of the nitrogen in alluvial gully soils is in organic form, which makes it potentially bioavailable and easily mineralised into dissolved inorganic nitrogen during stream transport, once it reaches the estuarine or marine environment, or is used directly by algae in dissolved organic form (Bainbridge *et al.*, 2018; Lewis *et al.*, 2020). As these terrace soil organic and nutrient pools can be of large importance once in the aquatic environment, it should be a priority to protect terrace deposits from fast headscarp retreat. Developing optimal approaches for stabilising gully headscarps and associated gully side walls is critical if the sediment and nutrient inputs from gullies are to be reduced in any meaningful way within appropriate management timeframes (i.e. one to two decades) (Brooks *et al.*, 2016a).

Bioavailable nutrients and gully erosion control – a Burdekin River example

Bioavailable nutrient monitoring was performed within the Strathalbyn Station as part of an ongoing investigation conducted by the Queensland Department of Environment and Science and was reported within Brooks *et al.* (2020a). Comparison of bioavailable nutrient sample concentration data collected from the remediated and control gullies indicated that remediation activities significantly lowered particulate nutrient concentrations. However, dissolved nutrient sample data collected from the remediated gullies was in some cases higher than that from the control site. The increased dissolved nutrient concentrations appeared to be a by-product of the erosion control measures applied as part of the gully remediation works (i.e. mixing and compaction of soil and addition of soil enhancements such as mulch, compost and gypsum) and require further investigation. Treatments that did not involve the addition of organic matter, but instead relied more on rock surface capping, showed significant reductions in both particulate and dissolved nutrient loads (Brooks *et al.*, 2021).

2.4 Managing and reducing sediment inputs to the GBR

2.4.1 Advances in knowledge about management responses

As discussed above, sediment inputs to the GBR are mostly caused by sub-surface erosion (80-90%) from deep rills, gullies or riverbanks (Olley *et al.*, 2013; Wilkinson *et al.*, 2013) and to a lesser extent surface erosion from hillslopes or paddocks (i.e. ~ 10- 20%) . To achieve the target 25% reduction in sediment loss from catchment to the GBR lagoon by 2025 (Australian Government and Queensland Government, 2018; Commonwealth of Australia, 2018b), numerous projects within the NESP TWQ Hub focused in addressing different aspects of streambank and gully restoration from measuring erosion baseline data, to undertaking trials using different restoration methods, characterisation of different erosion systems, improvements in monitoring techniques, and evaluation of the most cost-effective methods in order to upscale the restoration practices.

Stream banks

Remediation of riparian vegetation is considered an important mechanism for reducing streambank erosion, improving water quality, and subsequently GBR health outcomes. Hence, in an initial phase, research was focused on reducing erosion from stream channels using riparian zone management in the GBR catchments (Bartley *et al.*, 2016a; Bartley *et al.*, 2016b). The effects of riparian vegetation in reducing erosion rates were also assessed in the Fitzroy and Mackay Whitsunday catchments as case studies, through analysis of historical air photos (~1950-2012). However, the results were not conclusive in detection of differences in channel change between sites with good and poor riparian vegetation. The historical aerial photographs were not of sufficient resolution and quality to detect changes over time as the error associated with the aerial photos was generally greater than the bank retreat rates). This result helps justify the increasing use of LiDAR (airborne Light Detection And Ranging) and other more recent high precision terrain analysis approaches for evaluating channel change following rehabilitation. The project made a significant contribution towards monitoring method development and highlighted the importance of assigning an adequate budget to evaluating the effectiveness of on-ground remediation works on improving water quality.

Subsequently, additional research analysed best practices for riparian zone management, including both social and biophysical factors (Paul *et al.*, 2018). The study found that the widespread uptake of riparian remediation will require landholders aligning environmental and production goals, and adequate financial incentives are needed to engage landholders. The field site assessments found that even after 35 years of revegetation, riparian condition (as measured using a the Riparian Condition Score) has only partially recovered in some areas (mainly due to issues related to plant cover, erosion and weeds) (Paul *et al.*, 2018). This means that full recovery of some ecological function may take longer than expected. The work also highlighted that riparian areas play a disproportionately large role in providing benefits to biodiversity and carbon mitigation due to their relatively fertile alluvial soils and increased moisture levels. Rates of carbon sequestration were 2-7 times higher than anticipated based on similar stands in non-riparian areas (Paul *et al.*, 2018).

Gullies

It is now understood that gully erosion contributes ~40% of the fine sediment load to the GBR from less than 1% of the catchment area (Bartley *et al.*, 2020a). This knowledge has led to growing interest in gully remediation in recent years with an investment of over $65M (~$40M from Reef Trust, ~$10M from Qld Govt, ~$15M from the Great Barrier Reef Foundation with further investment pending) in water quality improvements focused on reducing sediment losses from gully erosion. However, the methods and approaches for reducing this erosion source were not well understood in the region until NESP-funded research began addressing the gap. In collaboration with NQ Dry Tropics and the Queensland Government Landholders Driving Change Program, NESP research led by Bartley assessed the effectiveness of a range of gully rehabilitation treatments across different soil types and remediation approaches, analysing water quality data from 7 gully sites on commercial grazing properties in the Burdekin catchment (Table 1) (derived from Bartley *et al.*, 2020a). Overall, the project found high spatial variability of erosion and water quality data among sites, with catchment area being the strongest predictor of sediment yield.

The rehabilitation options implemented on the treatment gullies included fencing, livestock management, small sediment trapping check dams within the gullies, diversion banks upslope of gully heads, and larger engineered approaches such as re-shaping and rock grade control structures. All techniques trialled resulted in some improvements in percentage of vegetation cover or biomass and on sediment trapping, although effectiveness values (i.e. the % reduction in sediment loss) could only be calculated in two cases (0.95 effectiveness value after hillslope runoff diversion above the gully at Strathbogie; and 0.85 effectiveness value after gully reshaping, structural control and revegetation at Mt Wickham) (Table 1) (Bartley *et al.*, 2020a). Based on a comprehensive review, the authors proposed that combining engineering and vegetation measures were often the most successful for erosion management, with engineering measures such as check dams being important for stabilizing in the early phases, and vegetation being the key to the long-term success of gully rehabilitation. Researchers also highlighted the importance of preventing gullies from forming in the first place, through reducing livestock grazing pressure and properly managing vegetation cover (Bartley *et al.*, 2020a; Bartley *et al.*, 2020b; Brooks *et al.*, 2016a).

A parallel line of projects directed by Brooks focused on testing and evaluating the cost-effectiveness of different gully rehabilitation approaches within the larger alluvial gully complexes (Brooks *et al.*, 2021; Brooks *et al.*, 2016a). Based on initial gully regrading and bioengineering treatment plots within the Normanby catchment (i.e. Crocodile Station works initiated through Reef Rescue R&D; Shellberg & Brooks, 2013), the largest sediment loss reductions were obtained in sites treated with hydromulch (seed, mulch, gypsum and fertiliser), although the most sustainable results were obtained in sites treated with compost, gypsum and grasses (Brooks *et al.*, 2016a). In addition, grazing exclusion trials resulted in some vegetation improvements in un-eroded high terrace surfaces, although little to no improvement was detected inside gullies with exposed sodic sub-soils (Brooks *et al.*, 2016a). Thus, researchers suggested that additional management interventions beyond just cattle exclusion are required to hasten the recovery of those large gully structures. These include supplementary grass seeding from the air or ground, organic mulching of sodic soils, fire and weed management, and slope stabilisation through bioengineering. Subsequently, the adaptation and application of mine site rehabilitation techniques was proposed, as some hard engineering interventions involving terrain reforming of the whole gully system might be required in some cases (Brooks *et al.*, 2016b).

Drawing on these findings, the key principles of gully rehabilitation proposed included: i) stock exclusion, ii) short term erosion mitigation measures during construction phase (e.g. sediment traps), iii) determining optimal slope for soil when reforming vertical surfaces, iv) hardening of key slope components, v) hydrological reconfiguration and associated drainage management, vi) capping of unstable subsoils by covering with new soil and/or rock, and vii) revegetation and ongoing maintenance (Brooks *et al.*, 2016b).

Additional optimal approaches for treating alluvial gully erosion were proposed based on the outcomes of two cases study sites located at Crocodile Station in the Normanby catchment, and Strathalbyn in the Burdekin (Table 1) (Brooks *et al.*, 2021). Results showed that alluvial gullies can be cost-effectively remediated to achieve >95% effectiveness factor (i.e. reducing the sediment yield from the gully by more than 95%), with the highest effectiveness at sites that had full reshaping and rock capping, and lower effectiveness at sites treated with organic mulch and other non-rock surface treatments. Those gullies treated with rock capping and soil ameliorants were resilient to major events such as floods, although net increases in dissolved nutrients were also observed in some treatments as a result of the organic ameliorants used, which would require additional monitoring. The net end of system fine sediment abatement achieved at the Crocodile and Strathalbyn sites respectively by May 2020 was 0.165 and 4.43 kt $year^{-1}$, (Table 1) (Brooks *et al.*, 2021).

Table 1. Synthesis of the treatment history and monitoring results for all sites within Project 5.9 and 3.1.7 (Bartley *et al.*, 2020a; Brooks *et al.*, 2021).

	NESP TWQ Hub Projects 2.1.4 and 5.9							NESP TWQ Hub Project 3.1.7	
	Virginia Park	**Meadowvale**	**Strathbogie**	**Minnievale**	**Mt Wickham**	**Glen Bowen**	**Mt Pleasant**	**Crocodile Station**	**Strathalbyn Station**
Basin	Upper Burdekin	Upper Burdekin	Bogie (Burdekin)	Don (Burdekin)	Bowen (Burdekin)	Bowen (Burdekin)	Bogie (Burdekin)	Normanby	Burdekin
Gully type	Linear hillslope gullies	Linear hillslope gullies	Linear hillslope gullies	Linear hillslope gullies	Major alluvial gullies	Major alluvial gullies	Linear hillslope gullies	Large alluvial gully system	Large alluvial gully system
Catchment area[a]	1.3 ha	5.0 ha	41 ha	25 ha	14 ha	2.7 ha	259 ha	37.4 ha	122 ha
Treatment area-active/passive[b]	0.13 ha / 1.17 ha	NA / 3 ha	~1 ha /40 ha (proposed)	3 ha / 23 ha	~8 ha / 9 ha (proposed)	~2.4 ha / 0.3 ha	0.5 ha / 258 ha	0.9 ha / 36.5 ha	19.8 ha /102 ha
Treatment	-Disc plough above gully -Fencing -Porous check dams in gully	-Fencing -30% gully catchment has cattle exclusion	-Hillslope flow diversion banks with drains -Fencing -Small rock revetment neat headcut	-Hillslope ripped and seeded -Fencing -Porous check dams	-Major earth works, soil treatment, rock chute structures -Fencing -Re-vegetation	-Major earth works, soil treatment, rock chute structures, earth bund, water points -Fencing (pending) -Re-vegetation	-Landscape rehydration -V-notch log rock sill structures and earth bank to divert flows -Fencing (pending)	-Gullies 2.234: Fully reshaping, soil treatment, rock capping, rock check dams -Gullies 0.1, 0.2 and 1.1: rock chutes, reshaping, soil treat.	10 gully treatments including: -Catchment treatments (e.g., fencing, diversion and rock chutes to control flows) -Gully Scarp treatments (e.g., earthworks to reshape gully, soil treatment, rock capping) -Gully bed and other soil enhancement treatments
Total cost ($)	$3,500	$3,800	$44,000	$27,000	$595,000	$840,000	$95,000	$182,000	$2,510,000
Monitoring	3-4 yrs	3-4 yrs	4 yrs	4 yrs	3 yrs	1 yr	1 yr	4 yrs	4 yrs
Land condition	Improved	Improved	Declined	Improved	Improved	Not significant	Not significant	Improved	Improved
Vegetation	Improved	Improved	Not significant	Improved	Improved	NA	NA	Improved	Improved
Erosion rate	Improved	Improved	Improved	Improved	NA	NA	NA	Improved	Improved
Sediment concentrations	Improved	Not significant	Improved	Improved	Improved	Improved	Not significant	Improved (overall)	Improved (overall)
Sediment load reductions	Not significant	Not significant	Improved	Not significant	Improved	NA	Not significant	Improved	Improved
Treatment effectiveness	NA	NA	0.952[c]	NA	0.85[b]	NA	NA	0.62-1.002	0.51-1.00 (average 0.98)

	NESP TWQ Hub Projects 2.1.4 and 5.9							NESP TWQ Hub Project 3.1.7	
	Virginia Park	**Meadowvale**	**Strathbogie**	**Minnievale**	**Mt Wickham**	**Glen Bowen**	**Mt Pleasant**	**Crocodile Station**	**Strathalbyn Station**
Sediment delivery Ratio for EOS[e] calcs	0.5	0.5	0.85	0.96	0.87	0.87	0.85	0.45	0.96
Cost-effectiveness at EOS[f]	Estimated >$1500/t	Estimated >$1500/t	~$70/t[d]	Estimated >$1500/t	$300-$600/t	Insufficient data	Insufficient data	$58-$128/t or $673 - $1490/t/yr[g]	$43-$85/t or $282 - $680/t/yr[g]
Comment	Low baseline erosion rates and fine sediment trapping efficiency <20%	Baseline erosion rates relatively low, but good improvement in cover and biomass	Only has 1 year of post-treatment data, so this is a preliminary estimate	Low baseline erosion rates	Cost-effectiveness varies with the baseline erosion rates applied	Baseline erosion rates very high, further data pending.	Baseline erosion rates relatively low, so cost-effectiveness for erosion likely to be poor	Based on cost effectiveness method 3 yrs post treatment data	1 – 3 yrs post treatment data

NA = new site with insufficient data [a]Catchment area above monitoring station at treatment site; [b]Treatment area: active (e.g. earth works, porous check dams), passive (e.g. fencing, grazing management); [c] Estimated as a change in measured (flow derived) sediment loads between a control and treatment gully, both before and after rehabilitation; [d]Additional data needed in subsequent wet seasons to improve certainty on this result; [e]End of System (EOS) (*sensu* Kentula et al., 1992). [f]Calculated using Gully Toolbox method / equivalent; [g]Calculated over 25-year period with a discount rate of 7% per annum, the figures expressed in $/t/yr are based on the full treatment cost at the time of implementation for the mean annual baseline erosion rate.

2.4.2 Key factors affecting management responses

NESP TWQ Hub research has highlighted several key factors that potentially affect the assessment of the effectiveness (efficacy, timing and cost) of management responses and provide guidance for selecting options for future investment.

The assessments of erosion management techniques highlighted the need to incorporate a 'lag effect' in the models used to evaluate investments in GBR catchment remediation (i.e., Source Catchments models), as improvements in water quality usually take 2-18 years following remediation. This specially affects the 'remediation' approaches which do not directly influence the amount and extent of riparian vegetation (e.g., fencing, off-site stock watering point) due to the long lag times between these and the establishment of riparian vegetation from natural seeding. This has major implications for the Source Catchments modelling as it assigns the water quality benefit from a management practice change to the year that the intervention occurred. Additionally, a comprehensive review of the international literature on the magnitude and response times for sediment yield reductions following the rehabilitation of gullied landscapes found that timeframes could vary from 2 up to 80 years. However, applying a variety of rehabilitation measures which generally included treating both the hillslope above the gully (e.g. with vegetated soil bunds, infiltration ditches, revegetation or terraces) and trapping sediments within the gully (e.g. via check dams), resulted in shorter timescales for sediment yield reduction (median value ~19 years), as compared to remediating the catchment only (median ~28 years) or using only within-gully treatments (median ~25 years) (Bartley *et al.*, 2020b). Consideration of a lag term that realistically accounts for the time it takes for water quality improvements following remediation to be realised would allow for more realistic estimates of the potential benefit of remediation to the GBR (Bartley *et al.*, 2016b). It is worth noting, however, that despite the long timescales described by the international literature to influence sediments yields from gully erosion, evidence from initial experiments shows that 95% reductions in sediment yields from remediation of large alluvial gullies (e.g. using intensive engineering techniques) are achievable within 1 – 2 years (Table 1) (Bartley *et al.*, 2020a; Brooks *et al.*, 2021).

Another important factor affecting management responses in reducing sediment yields is the selection and targeting of sites for rehabilitation. The initial identification of different types of gullies in the landscape is essential to prioritise management effort and resources such that the appropriate treatments are applied to different gullies in the most cost-effective manner, as described within Brooks *et al.* (2019). With additional information about different types of gullies in different parts of the landscape, resources can be much more efficiently targeted to the areas where they are most needed for water quality improvement. When coupled with detailed mapping of gullies using LiDAR data, there is also potential for significantly improving catchment models, highlighting the value of the development and application of automated tools for high-resolution gully mapping and classification (Stout *et al.*, 2020).

To demonstrate the value of these tools, Stout *et al*., (2020) mapped gullies at 1m resolution from 529,000 ha of LiDAR data in three catchments. This highlighted that the gully population is highly skewed, with a small number of gullies contributing a large proportion of the total sediment load. In the Bowen, Broken and Bogie catchments of the Burdekin basin, 2% of gullies (~450 of 22,300 mapped gullies) were estimated to contribute 30% of the sediment load, while 50% of the gully sediment load comes from 6% of mapped gullies. In the Fitzroy basin, 1.5% of gullies contributed 30% of the gully sediment load (27 of 1,785 mapped gullies) and in the

Laura/Normanby basins 3.5% of gullies contribute 30% of the of the sediment load (64 of 1,820 mapped gullies). With access to data like these, the task of achieving a 25% overall reduction in sediment load becomes a much more tractable problem, particularly as research has demonstrated that individual gully sediment yields can be affectively reduced to very low levels within a timeframe of one to two years using the appropriate remediation techniques (Brooks *et al.*, 2021). The critical issue then becomes one of identifying and accessing the relatively small cohort of the gullies that are contributing the largest proportion of the sediment load for remediation activities (Stout *et al*., 2020). Thus, through these studies, NESP TWQ Hub research enable accurate mapping of gullies at high resolution to quantify their key attributes as the critical first step in the process of prioritising and designing rehabilitation solutions, as well as improving catchment modelling and management strategies (Brooks *et al.*, 2019; Stout *et al.*, 2020). The identification of properties where the landholder is willing to participate in these relatively new initiatives is also a priority consideration.

A final key factor to consider in any rehabilitation process is the cost and benefits associated with it, including the budget required for the initial remediation works and associated monitoring, the budget required for the long-term maintenance, and the study of effectiveness in sediment yield reduction at each site. Project activities should therefore focus on strategies that deliver the greatest reduction in sediment yield for the lowest cost per tonne of sediment and nutrient export avoided or reduced. For instance, remediation on-ground works performed within Bartley *et al.* (2020a) ranged from $3,500 (i.e. fence off-gully and porous check dams within the gully, at Virginia Park) up to $595-840,000 (i.e. projects involving major earth works, soil treatment, rock structure and revegetation, such as those at Mt Wickham and Glen Bowen, respectively) (Table 1). Based on estimates of treatment effectiveness, this equated to >$1,500/t and $600-800/t respectively. Similar results were reported by Wilkinson *et al.* (2019), with lower cost projects associated with grazing management and fence control activities (although those had usually low erosion control effectiveness, ~0.1-0.2), up to the more resource-intensive projects involving engineering works, rock capping and revegetation, with usually higher effectiveness values associated (estimated at ~0.4-0.6) (Wilkinson *et al.*, 2019).

Using a slightly different approach, Brooks *et al.* (2020) reported a total cost of $182,000 for the Crocodile Station project (Normanby catchment), which using a 7% discount rate over 25 years, resulted in End of System (EOS) cost effectiveness of $58-$128/tonne, while the total cost at Strathalbyn Station (Burdekin) was $2,510,000 and a cost-effectiveness range of $43-$85/tonne, depending on the specific treatments applied (Table 1). Average remediation effectiveness across all 10 treatments at Strathalbyn was 0.98 (98% sediment reduction) after 2 years, while at Crocodile Station it was 0.87 after 2 years. The 7% discount rate and 25-year lifetime enable the upfront cost to be converted to its annualised equivalent cost so that it can be compared with annual sediment reduction. However, researchers recognised that further work is needed to determine the most appropriate approach for calculating cost-effectiveness of gully remediation, and recommended that a consistent guideline for calculating cost-effectiveness of all water quality improvements in the GBR (including cross-comparison between different approaches) be established as a matter of urgency (Brooks *et al.*, 2021). Typically, however, the most cost-effective treatments observed thus far have been the larger sites that have a significant upfront capital cost because they achieve large sediment reductions in a short period of time (Brooks *et al.*, 2021). Other opportunities for efficiencies include the remediation of a large number of densely situated gully features which may prove to be more viable through ‘clustering’ of efforts.

2.4.3 Site specific examples

Mt Wickham Case Study

Mt Wickham is a ~7,790 ha property in the Bowen management unit (Burdekin catchment), with all treatment and control sites draining into the Sandalwood Creek which connects with the Bowen River. It is characterised by linear hillslope gullies, scalds and major alluvial gullies on highly sodic soils (including tunnel erosion).

Monitoring started in 2018 in the property and treatment was initiated in early 2019, hence treatment had been in place for 2.5 years at the time of preparing this report. The catchment area above the treatment monitoring station was 14 ha, and the treatment consisted of:

- Major earth works, soil treatment and rock chute structures installed.
- Permanent 4 barb fences.
- Significant re-vegetation using mixed exotic species.
- Additionally, cattle were excluded from the beginning of the works (although future grazing was proposed).

The total cost of the remediation on-ground cost was $595,000.

Figure 9. Selection of photographs showing the Mt Wickham site before (top), during (bottom left) and after (bottom right) treatment: Source: Bartley et al., (2020a). Photo credits: Verterra/NQDT.

Two years after the treatment works, results showed statistically significant outcomes that demonstrate the success of the treatment:

- The amount of vegetation cover and biomass on the hillslope and gully walls had significantly improved.
- The water quality data (particularly suspended sediments loads) also improved.

Overall, the relative effectiveness of the Mt Wickham rehabilitation works was calculated as 0.85.

However, the land condition in the site remained fragile and researchers remarked that it could take several more years for additional perennial native plans to take hold of this site. Until then, it was proposed that grazing had to be carefully managed.

NESP TWQ Hub Projects 2.1.4 and 5.9 (Bartley et al., 2020a)

Strathalbyn Station Case Study

Strathalbyn Station is 45Km northwest of Collinsville and 60Km south of Ayr, located in the Burdekin-below-dam catchment on the eastern bank of the Burdekin River. The study gullies were a set of large alluvial gully systems along the Bonnie Doon Creek, a right bank tributary of the Burdekin River. The area is characterised by extensive alluvial sediments of considerable depth interspersed with 'blacksoil' cracking clay alluvia and local basalt origins. In total, the gullies in the study area contributed approximately 450,000 tonnes of sediment since 1945, with 37% of this amount eroded in the last 20 years and gullies currently eroding at a constant/increasing rate. Prior to remediation, these gullies were contributing, on average, 6300 tonnes of fine sediment to the GBR lagoon each year.

Ten different treatments were applied, consisting on a combination of the following actions:

- Catchment treatments: fencing, diversion and rock chutes to divert flows.
- Gully Scarp treatments: earthworks to reshape gully, soil treatment, rock capping.
- Gully bed treatments: rock bed, porous check dams, soil treatment
- Regraded batter treatments: coir mesh, blanket mulching (hay, bagasse), seeding, etc.

The total cost of the remediation on-ground cost was $2,510,000.

Figure 10. Selection of photographs showing the Strathalbyn gullies in various stages of construction: before (top left), during (top right) and after (bottom). Source: Brooks et al., (2020). Photo credits: top, D. Telfer; bottom, A. Brooks.

Two years after the treatment works, overall results showed that the gully remediation measures applied significantly reduced suspended sediments by 1-2 orders of magnitude (especially of the coarser sediment ranges) and erosion rates in these gully systems. Average remediation effectiveness ratios for the whole site were calculated at 97-98%, with end of system cost-effectiveness at $43-$85 per tonne of sediment removed from the system. Hence, this study demonstrated that large alluvial gullies can be cost-effectively remediated to the point where they achieve an effectiveness factor of ~100% after two years.

NESP TWQ Hub Project 3.1.7 (Brooks et al., 2021)

2.5 Innovations in methodology and delivery

NESP TWQ Hub research has developed and applied a wide range of innovations both in research methods, and also in project delivery. At a higher level, one of the most significant innovations of NESP was the development of quantitative **analytical tools and interactive online platforms** for data delivery, which allowed not only more objective and reliable systems for decision-making, but also open accessibility to all stakeholders and interested parties. More specifically, the new quantitative models and dynamic maps, delivered through online platforms such as eAtlas or eReefs, allow open access and easy interactions by end-users, including the use of data for statistical analyses, comparisons of complex environmental scenarios and risk assessments among others. Regular and meaningful communication between researchers and relevant stakeholders has also enabled the integration of some of those analytical tools within monitoring programs and reporting processes, such as the GBRMPA Outlook Report, RIMReP, etc.

Some specific examples for the suite of projects described in this report include (information summarised in Table A1):

- New dynamic mechanistic models enabled predictions of cumulative risks in space and time for complex environmental scenarios (Uthicke *et al.*, 2016) (more information in NESP Synthesis report on managing for reef resilience Pineda *et al.*, 2020).
- Exposure maps were developed combining 25 environmental pressures and were made accessible through eAtlas (Uthicke *et al.*, 2020) (more information in NESP Synthesis report on managing for reef resilience, Pineda *et al.* 2020).
- A new method to measure benthic PAR from remote sensing (satellite) ocean colour data was developed (Magno-Canto *et al.*, 2019, 2020) and daily data derived using this method has been provided in netCDF format via eAtlas.
- A new method to calculate the chronic light stress experienced by benthic ecosystems was developed, and used to produce a new index of water quality in the GBR (Robson *et al.*, 2020).
- Additional water quality data was collected and analysed for model validation (Source Catchments, eReefs) and improvement (Lewis *et al.*, 2020).
- A gully database was developed and made available on eAtlas to facilitate systematic collection of data on gullies along with purpose-built-Excel-based data entry forms to allow for easy data upload to the centralised database (Brooks *et al.*, 2019).
- Semi-automated gully mapping approaches were refined and new tools developed in order to automate the attribute extraction and assignment of types to the mapped gullies from high-resolution LiDAR Digital Elevation Models (DEMs) data, which should aid prioritisation, management and catchment modelling (Stout *et al.*, 2020).
- Real-time water quality sampling can be monitored via web-based portals for land holders and regional delivery providers at the gully rehabilitation monitoring sites (Bartley *et al.*, 2020a)

NESP research has also enabled the development of new tools and methods for monitoring of water quality and for streambank and gully management, such as:

- Equipment development (e.g. sediment traps: SediSampler® and SediPump®) to collect and characterise terrigenous sediment in river plume and other marine settings and new protocols for sediment sample collection and grain size analysis across the catchment to reef continuum (Bainbridge *et al.*, *2021*.; Lewis *et al.*, 2018, 2020).

- New multi- and hyper-spectral light sensors revealed spectral (colour) changes caused by elevated sediment concentrations and allowed development of an innovative empirical underwater light model to characterize the light field for the turbid zone communities of the inshore GBR (Jones *et al.*, 2020a). The model was also used to create environmentally realistic exposure conditions which were replicated at the AIMS Sea Simulator, using an innovative and highly sophisticated fully automated, computer-controlled sediment dosing system with custom made LED lights that could replicate light quality and quantity (Jones *et al.*, 2020a).
- Development and/or validation of different methods for streambank and gully remediation (Bartley *et al.*, 2018; Bartley *et al.*, 2020a; Brooks *et al.*, 2016a; Brooks *et al.*, 2016b; Brooks *et al.*, 2021). These included:
    - Comparison of different tools for monitoring and evaluating channel change (i.e. 2 terrestrial laser scanning instruments RIEGL VZ400 and Zebedee, and an airborne LiDAR), showing that the RIEGL was more accurate than the Zebedee, although the LiDAR could be useful to cover large areas rapidly (Bartley *et al.*, 2016a).
    - The application of High Resolution Airborne LiDAR (100-500 pts m^{-2}) from an ultralight plane as a significant innovation for cost-effective monitoring (Brooks *et al.*, 2021).
    - Results showed that the PASS sampler (a new time integrated suspended sediment sampler was ideally suited for the cost-effective and rigorous collection of pre- and post- treatment sediment concentration data (Doriean *et al.* 2019, 2020a, 2020b).
    - Characterisation of different type of gullies (Brooks *et al.*, 2019).
    - Automatisation of LiDAR data to enable easily access to models (Stout *et al.*, 2020).
    - Development of a new method for identifying Potentially Active Erosion from gullies from a single LiDAR image (Stout *et al.*, 2020).
    - In conjunction with the automated gully mapping methodology, a new method was developed for reconstructing the pre-existing land surface (or Prior Land Surfaces) before gully erosion as a means of accurately determining the whole of life sediment yield from gully erosion. When coupled with analysis of the average commencement dates of gullies, calculation of the total sediment yield delivered to the GBR from gullies in the areas mapped since European settlement can be undertaken (Stout *et al.*, 2020).

Finally, several projects contributed to an improvement in **water quality monitoring** through the development of new indicators for measuring ecosystem health. These included:

- A new water quality indicator (I_{bPAR}) based on the amount of light that penetrates to the seafloor, using satellite data validated by *in-situ* data loggers (DiPerna *et al.*, 2018; Magno-Canto *et al.*, 2019; Robson *et al.*, 2019; Robson *et al.*, 2020).
- Sea-bed light availability was also proposed as a very suitable parameter to monitor and assess risks when dredging close to turbid-zone coral communities by Jones *et al.*, (2020a).
- The relationship between meadow condition and seagrass storage reserve could be used to assess meadow trajectory, through the use of TNSC (i.e. Total non-structural carbohydrates) as an early-warning indicator (Collier *et al.*, 2016c).

3.0 RESEARCH INFORMING MANAGEMENT

NESP TWQ Hub research has generated valuable findings for further understanding sediment generation and transport, fate and impact in the GBR and its catchments which are relevant to many stakeholders and can be applied at a range of scales. With the emphasis on providing management solutions, a key feature of all NESP TWQ Hub projects has been the delivery of highly applied science, coupled with close collaboration with stakeholders in project implementation, thereby enhancing the likelihood of research uptake.

One of the main impacts of NESP TWQ Hub research related to the sediment provenience and management was the direct reduction in end of catchment fine sediment loads associated with proposed management practices such as streambank and gully remediation projects (estimated at >4,500 tonnes/year by only one of the projects (Brooks *et al.*, 2021). A potential reduction in ecosystem impacts could also be expected from the i) improved understanding of nutrient bioavailability and light limitations in coastal ecosystems (particularly from gullies) ii) improved water quality monitoring tools and protocols, and iii) the application of the new indicators of ecosystem health within monitoring programs. Additionally, this synthesis is expected to contribute towards key policy documents and the next Scientific Consensus Statement, of which sediment management and reduction is a key component. It will also help inform investments in improved water quality under the Reef Trust Partnership and the Major Integrated Project (MIP) conducted in the Burdekin catchment by NQ Dry Tropics. Additionally, NESP TWQ Hub research has allowed numerous improvements in management strategies, monitoring programs and reporting processes. Several examples of how the suite of projects highlighted in this report already have, and potentially could, inform management are summarised below.

3.1 Policy applications

The most recent policy application of NESP TWQ Hub science includes the current review of the Reef 2050 Long Term Sustainability Plan (Commonwealth of Australia, 2020). For example, the review of the Plan incorporated NESP TWQ Hub research related to the improvement in water quality (e.g. nutrients, pesticides and sediments run-off, marine debris), reduction in cumulative impacts, and increased biodiversity protection, among others. NESP TWQ Hub science results have also informed other key government planning and management documents such as the Reef 2050 Water Quality Improvement Plan (Australian Government and Queensland Government, 2018) and other regional water quality improvement plans such as the Burdekin Water Quality Improvement Plan 2015 (NQ Dry Tropics, 2016) and the Wet Tropics Water Quality Improvement Plan 2015-2020 (Terrain NRM, 2015). All these peer-reviewed publicly available results are also expected to contribute to the scientific evidence base, which is synthesised as part of the process for developing the next Scientific Consensus Statement and review of the Reef 2050 Water Quality Improvement Plan. Finally, numerous projects additionally contributed to the improvement of the Reef 2050 Integrated Monitoring and Reporting Program Strategy (GBRMPA, 2015), including: a) Identification of additional indicators for monitoring programs required to populate cumulative risk maps (Uthicke *et al.*, 2016), b) A new cost-effective indicator was proposed based on benthic light (I_{bPAR}) (Robson *et al.*, 2020), and c) The use of seagrasses storage reserves was proposed as an early warning indicator and to assess meadow trajectory (Collier *et al.*, 2016c), among other examples.

3.2 Management applications

Most of the management applications resulting from NESP TWQ Hub research could be classified into 2 categories, 1) More accurate and reliable knowledge and systems for decision-making and 2) Improved approaches to monitoring and evaluation.

3.2.1 More accurate and reliable knowledge and systems for decision-making

The effectiveness of investment in riparian management and other streambank and gully remediation works to reduce end of catchment sediment loads were addressed by several projects within the NESP TWQ Hub, with valuable outcomes for management. Bartley *et al.*, (2016b), for instance, highlighted the need to incorporate a 'lag effect' in the models used to evaluate GBR remediation investments (i.e. Source Catchment models), as the physical water quality benefits are only noticeable 2-18 years after remediation has taken place. The importance of maintaining vegetation upstream and to apply a holistic catchment scale approach to tackling sediment sources was recommended within various projects (Bartley *et al.*, 2016b; Brooks *et al.*, 2016a). NESP TWQ Hub-funded research also highlighted the need to prevent the initiation of additional gullies through appropriate grazing management and promoting passive recovery where possible (Bartley *et al.*, 2020a; Brooks *et al.*, 2016a).

Estimation of cost-effectiveness was another management outcome, and included optimal strategies to calculate it in order to capture realistic costs of on-ground projects and their effectiveness over the long term (Bartley *et al.*, 2020a; Brooks *et al.*, 2021). For instance, the use of 'End of System' cost effectiveness (calculated using a 7% discount rate and a 25-year lifetime to enable the upfront cost to be converted to its annualised equivalent cost so that it can be compared with annual sediment reduction) was suggested as a metric to inform investments in gully remediation across different GBR catchments (Brooks *et al.*, 2021). Scenario analyses using the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef) (including the Source Catchment models) could also be refined with data coming from those projects, allowing for improved accuracy to support decision-making. However, the most important message for management from gully remediation science was that cost-effective remediation seems to be possible, reaching levels of >95% sediment yield reductions within two years, and it was also estimated that, for instance, 130 sites (i.e. alluvial gullies) would have to be remediated in order to meet the 2025 water quality targets in the Bowen catchment (Brooks *et al.*, 2021).

The development of cumulative impact risk maps, as well as the spatial and temporal assessment of ecological risks was identified to guide management decisions around a range of activities in the coastal zone and inshore GBR waters (Uthicke *et al.*, 2016, 2020)[8].

Finally, reporting by stakeholders (e.g. GBRMPA, Australian Government through its Reef Trust program) could be facilitated by tools such as eAtlas, eReefs or Source Catchment

[8] https://eatlas.org.au/gbr/nesp-twq-5-2-cumulative-impacts

models, which offer open-access data, ecosystem models and predictions that enable the integration of information to provide potential future scenarios for the reef, as was presented in the Great Barrier Reef Outlook Report 2019 (GBRMPA, 2019).

3.2.2 Improved approaches to monitoring and evaluation

Estimation of water quality trends and prediction of ecological consequences of human activities such as run-off, dredging or on-ground management strategies, was enhanced by the development of a new water quality indicator based on the amount of light that penetrates to the seafloor (Robson *et al.*, 2020). The benthic irradiance product was thus derived from satellite data and further validated against *in-situ* light loggers, and was proposed as a cost-effective, responsive, ecologically-relevant water quality indicator that describes the light environment at local and GBR-wide scales. The new benthic light water quality index (I_{bPAR} WQI), along with maps of benthic PAR and light stress, can be made available for incorporation into the Reef water quality Report Cards (Robson *et al.*, 2019; Robson *et al.*, 2020).

Guidelines for light quantity were also recommended as a management trigger for seagrass meadows at risk from declining water quality (Collier *et al.*, 2016b). Specifically, acute management thresholds (suited to compliance guidelines for managing short-term impacts) were proposed, from 2 to 6 mol m^{-2} d^{-1} depending on species. Similarly, long-term thresholds (suited to the setting of water quality guidelines for catchment management) were also suggested for seagrasses: 10-13 mol m^{-2} d^{-1} on average, although researchers highlighted the need to determine the desired state for seagrasses at a regional scale beforehand (Collier *et al.*, 2016b; Robson *et al.*, 2020).

The use of seabed light availability was also supported by Jones *et al.*, (2020a) as the most suitable parameter to monitor and assess risks associated with dredge activities close to turbid-zone coral communities. Pressure-response relationships were also identified and could be used with plume trajectory modelling before dredging and *in situ* monitoring programs during dredging activities, and could also be incorporated into risk-response reactive management cascades to guide dredging operations once underway.

Lewis *et al.*, (2018) identified which GBR sites are mostly influenced by newly delivered riverine sediment and hence where management in the catchment for sediment erosion would improve water quality and likely ecosystem health at those coral reef and seagrass meadows. The project also provided some of the first empirical data to support the finding of the satellite photic depth modelling (Fabricius *et al.*, 2014, 2016), where the delivery of new terrigenous sediment has a significant influence on water clarity on the inshore Great Barrier Reef. Finally, new research tools were identified to determine thresholds of SPM exposure, allowing for an improved appreciation of marine risk. These tools can be used to determine ecologically-relevant end-of-basin load targets and reliable marine water quality guidelines, thereby enabling enhanced prioritisation and management of SPM export from ridge-to-reef.

A range of methods to capture changes to the gully area and surrounding landscape before, during and after rehabilitation were tested and applied in the NESP TWQ Hub research, adopting a 'multiple lines of evidence' approach. This approach provides for redundancy or failure of any one method, allows independent validation of results and generates more defensible conclusions. The research also identified where which methods are most likely to deliver the greatest confidence in the results (e.g. Bartley *et al*., 2021).

One of the additional outcomes from the experimental remediation projects undertaken through the NESP TWQ Hub program, came from the need to develop innovative and cost-effective monitoring techniques. Gullies are difficult landscape features to monitor accurately, and it has been assumed that to do it properly is extremely expensive. As such it was assumed that only a few gullies could be fully monitored, and the remainder would only be able to be monitored qualitatively. Through this program, however, methods have been developed that can be deployed at scale, significantly reducing the monitoring costs per gully. Cost effectiveness, and objectivity, could be optimised if a standard strategy was deployed by an expert group.

4.0 FUTURE DIRECTIONS

4.1 Investment priorities for on-ground activities to address the problem

NESP TWQ Hub projects evaluating the effectiveness of streambank and gully remediation highlighted the need to continue investment in the evaluation of restoration projects. There is now considerable understanding of the effectiveness of a range of rehabilitation treatments on some gully types (e.g. large alluvial gullies). However, there are other erosion processes and approaches for which there is little measured empirical data (e.g. streambanks and hillslopes in vulnerable soil types). These data are needed to provide support to the Paddock to Reef models and make investment decisions in order to achieve the desired water quality targets by 2025 (Australian Government and Queensland Government, 2018). The research highlighted the need to (Bartley *et al.*, 2020a; Brooks *et al.*, 2021):

- Carefully prioritise remediation sites.
- Priority sites should have (a) high fine sediment baseline erosion rates; (b) high sediment delivery or connectivity to the coast; and (c) be most cost effective to manage (large alluvial gullies are relatively cost-effective to treat, but other smaller gullies can also be cost-effective to manage.
- Carefully design field monitoring studies. Treatment effectiveness can be accurately assessed within 2-3 years with a good design (Before-After-Control-Treatment). It will take longer if adequate baseline data is not captured.
- Apply a multiple-lines of evidence approach to monitoring. Each technique has strengths and weaknesses, and no one technique can provide all the answers.
- Carefully manage grazing within the remediation areas. For most gully remediation sites, stock reduction/exclusion is needed to maintain the integrity of the engineering structures and allow vegetation re-establishment. Re-introducing cattle into remediation sites poses a significant risk to the project if grazing is poorly timed with the rainfall season.
- Improve understanding of the role of sediments in delivering particulate nutrients that may affect water clarity beyond the immediate zone of influence of river plumes in nearshore waters and have direct effects from remobilisation of bioavailable nutrients (see also Waterhouse & Pineda, 2021).

NESP TWQ Hub research has also highlighted that although the effects of acute stressors (e.g. climate, cyclones, COTS) can overwhelm the influence of poor water quality, the effects of reef state and performance can also be influenced by land runoff, suggesting that improvement of water quality will assist reef condition (Uthicke *et al*., 2020). Additionally, exposure maps of multiple pressures and information on water quality on reefs and certain locations are limited, and information is often not available over long temporal scales needed to understand their influences on the reef. Better water quality data from within the GBR (beyond the river mouth and inshore reefs) are necessary to attribute spatial and temporal changes in reef and seagrass communities to episodic and chronic changes in water quality. Improved water quality monitoring and development of new proxies for water quality should be a priority for future monitoring projects (Uthicke *et al*., 2020).

4.2 Investment priorities for research to address knowledge gaps

Gaps were identified regarding knowledge of the impacts of sediments delivered to the inshore GBR to seagrass meadows. Additional data about understudied species, location and population-specific thresholds (particularly for the most at-risk species), the effect of spectral quality on light thresholds for seagrasses and on the effect of cumulative impacts (i.e. temperature, nutrients, sediment concentrations) on acute and long-term light thresholds is required (Carter *et al.*, 2021; Collier *et al.*, 2016b). Seagrass habitats naturally undergo cycles of decline and recovery. Resilience and capacity to recover from these events is key to their long-term survival. A greater understanding of the ecology of estuarine seagrasses including community connectivity and the way fauna utilise seagrass and distribute propagules and how cumulative pressures may disrupt these processes is required given the critical role of seagrass in connecting sea to source, and filtering water and stabilising sediments (Carter *et al.* 2021).

Further development of the remote sensing algorithm behind the I_{bPAR} WQI to improve its accuracy including incorporation of regional and seasonal variations in cloud cover in the algorithm was also identified as a priority. Further work is required to ensure its use is embedded in stakeholder workflows, including the evaluation of GeoScience Australia's DataCube as an additional means of distribution and automation of the I_{bPAR} and WQI products. Development and comparison of the utility of an additional I_{bPAR} product based on eReefs model output to allow the index to be used in evaluation of future land-management and climate change scenarios would also be valuable (Robson *et al.*, 2019; Robson *et al.*, 2020).

A project studying the sources, transformations and fate of dissolved organic carbon additionally recommended that the existing water quality monitoring data could be used in conjunction with catchment scale environmental and river-discharge data to assess the spatial and temporal variation in the main drivers of change in the water column dissolved and particulate organic carbon concentrations in coastal regions of the GBR. This combined assessment would provide a more certain understanding of what is driving altered organic carbon dynamics in the GBR and could help prioritise future research and management actions to minimise future increases in organic carbon concentrations and any potential adverse ecological effects (Burrows *et al.*, 2018).

4.3 Integrated research and on-ground actions

A project on biological indicators for seagrass condition assessment, identified additional knowledge gaps to address, such as: 1) to adopt biomass calibrations where applicable and to continue to refine them for additional species and habitats, 2) to continue exploring existing storage reserve data for effects of other environmental pressures such as other light indicators, water type and nutrients in relation to plant dynamics such as reproduction and meadow expansion, 3) to consider adoption of carbohydrates as a complimentary indicator of decline or recovery, and 4) to examine fine temporal scales of change for application in assessment of acute disturbances, among others (Collier *et al.*, 2016c). Still within the seagrass space, future works were also proposed to explore whether feedbacks in the system are likely to create possible tipping points beyond which recovery would become difficult or impossible for seagrasses. The project additionally highlighted the need for comprehensive spatial data sets across a range of spatial and temporal scales and across gradients of pressures, in order to track ecological health and for setting and assessing progress in meeting management targets. Existing data sets should also continue to be built upon, with greater resolution, and even further capacity so that monitoring data can continue to answer increasingly specific management questions (Lambert *et al.*, 2020). Finally, Carter *et al.*, (2021) identified some additional opportunities for further research, including: 1) Expanding the spatial extent of models to incorporate connected areas to the GBR such as Torres Strait and Fraser Island and other regions in Australia (i.e. Gulf of Carpentaria), 2) Evaluating indirect risks and benefits of different level of protection on seagrass communities, and 3) assessing additional challenges for the future of seagrass communities (e.g. cumulative risks and vulnerability, appropriateness to intervene with restoration techniques when required, and a better understanding of desired states in terms of resilience) (Carter *et al.*, 2021).

5.0 CONCLUSIONS

Improved understanding of sediment sources, interactions and impacts on GBR ecosystems is essential to guide management responses, and research outcomes of the NESP TWQ Hub provide a valuable contribution to the knowledge required to facilitate reduced losses of fine sediment to the GBR. NESP TWQ Hub research has determined that:

- Pulsed delivery of flood plume sediment and particulate nutrients to inshore coral reef sites results in an increase in macroalgae cover (and potential deposition of marine snow).
- Chronic persistent turbidity (and reduced photic depth) occurs for long periods as a result of considerable disturbance and resuspension or new sediment delivery in areas of poor flushing.
- Increased suppression of light occurs in shallow (~ 5 m) turbid environments within flood plumes and this continues for extended timeframes (months) following flooding.
- For considerable (environmental) impact to occur in seagrass meadows, large consecutive flooding events are typically required, over 2-3 years.

In terms of specific management applications in the GBR marine environment, the research has:

- Provided quantitative temporal data on the light reduction that can be caused by cloud cover and turbidity caused by natural and dredging-related process.
- Identified changes in the ratio of subsurface blue light to green light as a diagnostic tool to identify the cause of aquatic light reduction.
- Linked light availability in terms of mol photons m^{-2} d^{-1} to coral health.
- Developed a new Water Quality Index (I_{bPAR}) related directly to ecological impacts that can be considered for application in the GBR and considered chronic effects of light stress.
- Established ecologically important indicators (seagrass and light thresholds) and defined ‘desired state’ – relevant to target setting.
- Determined that the primary drivers in relation to sediment loads and seagrass health are inter-annual changes, and multiannual loads.
- Provided assurance for existing sediment load targets (when annualised) by comparing scenarios with proposed thresholds.
- Assessed cumulative impacts of multiple stressors.

The research has also defined the most important sediment characteristics for ecosystems and identified that understanding of how and when sediments are transported helps to target catchment management efforts. For example:

- The most ‘damaging’ sediment sources are the fine (<20 µm), organic-rich (bacteria) sediment which travels furthest in the GBR and has the capacity to release dissolved nutrients and influence turbidity (and macroalgae) regimes in the inshore GBR.
- River plume sediment is sourced predominantly from subsurface erosion.
- The release of dissolved inorganic nitrogen from sediment laden plumes has confirmed that bioavailable particulate nitrogen is an important source of nutrients.

Several erosion management trials have demonstrated that the most cost-effective management options for sediment reduction will vary between catchments and landscapes and intervention prioritisation must be supported by high quality evidence. The research successfully generated foundational knowledge to accelerate sediment reductions in high priority areas. This was supported by:

- A gully characterisation framework which allows prioritisation of effort in the landscape in a cost-effective way.
- Identification that the rate of fine sediment erosion is dependent on soil type, and that black soils (vertosol) are a major sediment and particulate nutrient source.
- Assessment of the diversity of gully forms and confirmation that a range of management interventions will be required for their effective treatment.

An important consideration in gully remediation is the choice of management options which is driven by effectiveness in reducing sediment losses, and costs at various scales. The trials showed that:

- Porous check dams constructed from sticks and logs, in combination with stock exclusion fencing, appear to have a major impact on the amount of vegetation that stabilises gullies floors and is linked with an improvement in water quality. This is most relevant at small scale activities involving landholders as part of whole of farm management strategies.
- Treatment of the gully area itself can yield large benefits, but management of the surrounding catchment area is also important.
- The reduction of livestock grazing pressures within and around gullies in hillslope drainage lines is a primary component of an integrated gully management strategy.
- Total erosion rates varied considerably among source areas and sampling years, with higher rates amongst alluvial gullies, channels banks and beds.
- Large scale engineering solutions have proven to be successful and, in many cases, highly effective in reducing sediment losses cost effectively from active alluvial gullies.
- Treating the small number of high yielding gullies using intensive remediation techniques is central to any strategy to achieve catchment water quality targets by 2025 and beyond. However, the targets will not be achieved by treating these high yielding (typically alluvial gullies) alone. Some lower yielding gullies need to be treated as well, and the most cost-effective approach is to treat gullies that are close to high yielding gullies at the same time that the high yielding gullies are being treated to maximise efficiencies.
- Remediation costs vary between locations and methods. There is an urgent need for the application of a standard cost- effective metric across investment programs.

This NESP TWQ Hub research has been conducted in collaboration with a wide range of stakeholder groups and is of interest to an even larger audience. The research findings are significant to the future management of the GBR and its catchments. Future programs should ensure that these results are built on and continue to be communicated in a way that can be fully understood and utilised by a range of interested people. This will ensure that the legacy of the program will continue well into the future.

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APPENDIX 1: RELEVANT NESP TWQ HUB PROJECTS

Table A1.1. List of NESP TWQ Hub projects and relevant information relevant to the synthesis topic (6.4 *Reducing end-of-catchment fine sediment loads and ecosystem impacts*). Summary of research outcomes, innovations in methodology and delivery and implications for policy and management.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Sediment Fate and Impact in the GBR				
Dr C Collier (JCU) - Light thresholds for seagrasses of the GBR: a synthesis and guiding document for managing seagrass *(Project 3.3)*	(Collier *et al.*, 2016b)	• Synthesis of light thresholds for seagrass species in the GBRWHA, to ensure protection of seagrasses from activities that impact water quality and the light environment, such as coastal and port development (acute management thresholds). Colonising species are the most sensitive to light reduction and have the lowest light thresholds (2 to 6 mol m^{-2} d^{-1}) and shortest time to impact (14-28 days). Opportunistic and Persistent species have higher light thresholds (5-6 mol m^{-2} d^{-1}) and longer times to impact (28-50, and 50 days, respectively). • Thresholds for long-term maintenance of seagrasses were also proposed: 10-13 mol m^{-2} d^{-1} is likely to prevent light limitation for the long-bladed species, although deepwater species require less light.		Guidelines for light are recommended as a management trigger for seagrass meadows at risk from declining water quality. • Acute management thresholds (suited to compliance guidelines for managing short-term impacts): from 2 to 6 mol m^{-2} d^{-1} depending on species. • Long-term thresholds (suited to the setting of water quality guidelines for catchment management): 10-13 mol m^{-2} d^{-1} on average. However, it is essential to determine the desired state at a regional scale beforehand.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr C Collier (JCU) - Developing and refining biological indicators for seagrass condition assessments in an integrated monitoring program *(Project 3.4)*	(Collier *et al.*, 2016c)	• The potential bioindicator 'total non-structural carbohydrates' (TNSC) in seagrasses (i.e. storage reserves) responded to cumulative stress and was correlated to seagrass abundance and condition, although specific pressures could not be identified. • TNSC did not respond to changes in light conditions as expected and therefore the study could not support its inclusion as an indicator in monitoring programs such as the MMP. • Above ground biomass was highly correlated to % cover, although canopy height had a strong effect on the calibration values, highlighting the importance of habitat/morphology-specific calibration formulae.	The newly discovered relationship between meadow condition and storage reserve could be used to assess meadow trajectory, through the use of TNSC as an early-warning indicator. However, additional data and validation for other regions and species is still required.	• The inclusion of TNSC as an indicator in monitoring programs such as the MMP was not supported by this study. Additional research is required to address the effects of other pressures and other biological processes and to obtain further data on other species. • Additional work is required to refine calibration formulae to convert %cover to biomass, facilitating integration among seagrass monitoring programs including Queensland Ports Seagrass Monitoring Program and GBR historical baseline data.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr C Collier (JCU) - Deriving ecologically relevant load targets to meet desired ecosystem condition for the GBR: a case study for seagrass meadows in the Burdekin region *(Project 3.2.1/5.4)*	(Carter *et al.*, 2021; Carter *et al.*, 2018; Collier *et al.*, 2020; Lambert *et al.*, 2019; Lambert *et al.*, 2020)	• A 'desired state' for seagrass meadows in Cleveland Bay (3.2.1) and the whole GBRWHA (5.4) was stablished as ecological benchmarks. • Catchment inputs of sediments were linked to seagrass desired state based on long-term monitoring data and eReefs. However, seagrass responded over many years, suggesting the use of multi-annual load targets. • A range of estimates for sediment load reduction targets (~30-50%) was proposed by considering multiple indicators of ecological response and stressors over multiple timescales. • Long-term seagrass light requirements were determined at ca. I_{bPAR} > 4-7 mol m^2 d^{-1}. • The models found stronger correlations between seagrass variables and river flow than sediment load, suggesting that the riverine discharge has other properties that could affect seagrass area and biomass (e.g. organic matter, nutrients).	The project could not use eReefs predictions to quantity ERT, but identified that finer-scale information and improved understanding of sediment-water column interactions are needed to use eReefs RECOM for predicting benthic light and associated variables in localized areas.	• The seagrass ERTs derived in this study found a 38-49% reduction in anthropogenic sediment load from the Burdekin River had the greatest likelihood of enabling seagrass to achieve minimum desired state or achieve net zero loss. This ERTs were comparable to the existing 2018 WQIP ERT of 30% for the Burdekin River. • Light levels in shallow coastal waters should be thoroughly and accurately characterised, as I_{bPAR} over-predicted compared to measured light levels. • Long-term data sets on seagrass species, abundance and area should continue to be collected so that management targets can be assessed using ecological data in the future. • The study highlighted the critical role of historical data in understanding spatial complexity and for making informed management decisions on the current state of seagrass in the GBRWHA. • Results can guide conservation planning through prioritisation of at-risk communities that are continuing to fail to attain desired state.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr K Fabricius & B Robson (AIMS) - Benthic light as ecologically-validated GBR-wide indicator for water quality: drivers, thresholds and cumulative risks *(Project 2.3.1/5.3)*	(DiPerna *et al.*, 2018; Magno-Canto *et al.*, 2019, 2020; Robson *et al.*, 2019; Robson *et al.*, 2020)	• Water Quality indicators were developed based on the amount of light that penetrates to the seafloor (I_{bPAR}), using satellite data validated through in-situ light loggers. In a second stage, an additional I_{bPAR} product was based on eReefs model outputs. • Minimum light requirements and thresholds for healthy corals were also determined using experimental and field data. • Reduced growth rates were observed under low-light conditions (6 mol photons m^{-2} d^{-1}) in several species of corals. Results also showed that it's the cumulative amount of light that corals receive which affects their physiology and growth. • Seagrasses were also at risk of light limitation when I_{bPAR} declined below 5-6 mol photons m^{-2} d^{-1}.	The new water quality indicator will allow estimating trends and predicting ecological consequences of human activities (e.g. run-off, dredging). The new I_{bPAR} based on eReefs model outputs allows its use in evaluation of future land management and climate change scenarios.	• The new indicator could become a cost-effective means to directly inform Reef Integrated Monitoring Plans and Report Cards • Changes in I_{bPAR} can be related back to its drivers and contribute to (i) set ecologically relevant targets and inform future WQ Improvement plans, (ii) assess effectiveness of region-specific river load reductions, (iii) predict ecological consequences, (iv) compare risks from river loads vs. dredging, (v) inform scenario models, estimating effects of land management scenarios on I_{bPAR}.

Dr R Jones (AIMS) - Risk assessing dredging activities *(Project 2.1.9)*	(Jones *et al.*, 2020a; Jones, *et al.*, 2020b; Whinney *et al.*, 2017)	• The study focused on underwater light and the implications of light reduction for corals caused by increase turbidity. The 3-year dataset is the longest description to date of benthic light availability in this environment and the only one collected using reliable and calibrated light sensors (with known quantum responses and cosine corrections). • The light data was examined over different running mean time periods (hours to weeks) to characterise what levels of light reduction can occur on reefs naturally through sediment resuspension events and through nearby maintenance dredging. • Multispectral and hyperspectral light sensors showed marked changes in the spectrum (colour) of the underwater light caused by suspended sediments, which caused a loss of blue light to create a green hue underwater (less photosynthetically useful light). Cloudy days caused loss of underwater light but without changes in colour, hence a ratio of blue to green light wavelengths was developed to identify the cause of any periods of low light. • An empirical spectral solar irradiance model was constructed for Cleveland Bay using wavelength specific light attenuation coefficients under different turbidity levels, and using a turbidity to SSC conversion factor from samples collected *in situ*. The model was used to further describe the inshore turbid reef zone light environment for the first time • The model was also used to define environmentally relevant exposure conditions to test the effects of suspended sediments and changes in light quality/quantity on corals and a sponge in the AIMS Sea Simulator. All corals and sponges survived the exposures but clear physiological responses were measured,	3-yr time series of underwater light in the turbid inshore GBR to contextualise the risk of light reduction by sediments over different time periods. Use of new multi- and hyper-spectral light sensors to identify spectral changes caused by elevated sediment concentrations and allowed development of an innovative empirical underwater light model. Experimentation at the AIMS Sea Simulator, using an innovative automated, computer-controlled sediment dosing system with custom made LED lights that replicate light quality and quality.	• Results suggest that seabed light availability is the most suitable parameter to monitor and assess risks when dredging close to turbid-zone coral communities. • Underwater PAR levels, as mol photons m^{-2} d^{-1} (a daily light integral) measured over different running mean time intervals (14 d or 28 d) were derived that can be used: (1) with plume trajectory modelling before dredging to assess the risk of light reduction from suspended sediments when dredging close to coral communities, or (2) with *in situ* monitoring programs once dredging is underway. • These values can be incorporated into reactive management cascades and to guide dredging operations once underway i.e. for deciding when, or if, to move a dredge to a different location or even stopping dredging. • These thresholds are specific to inshore turbid zone reef communities and to a shallow depth that encompasses where the majority of the corals are found. • Changes in the ratio of blue light to green light (underwater) can be used as a diagnostic tool to identify if any reduction of underwater light is caused by turbidity or cloud cover (or both).

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		including changes in pigmentation, lipid concentrations, the ratio of structural to storage lipids, and density of symbiotic dinoflagellates.	First study to relate light availability to coral health. Development of light-based water quality thresholds.	
Dr S Lewis (JCU) - A validation of coral geochemical records to reconstruct suspended sediment loads to the Great Barrier Reef *(Project 1.3)*	(Lewis *et al.*, 2016)	• To assess the link between trace element ratios (Ba/Ca, Y/Ca and Mn/Ca) in corals and measured sediment and particulate nutrient loads from the Burdekin River. • Only the coral Ba/Ca ratio showed trends consistent with river floods. However, the coral Ba/Ca ratios on the GBR may in fact be recording changes in salinity/terrestrial freshwater input rather than sediment load.		• The results showed no clear link between trace element ratios (specifically, the coral Ba/Ca ratio) and changes in sediment loads. Hence, the authors suggest that a critical review of literature from other locations around the World would have to be conducted.
Sediment Delivery to the End of Catchment and GBR				
Prof M Burford (GU) - Sources, transformations and fate of dissolved organic carbon – implications for the reef *(Project 4.11)*	(Burrows *et al.*, 2018)	• Concentrations of dissolved organic carbon (DOC) were mostly influenced by variables related to river discharge. Thus, DOC provides a useful measure of river influence in the GBR. • Concentrations of particulate organic carbon (POC) were not only influenced by river discharge but also by sediment resuspension and phytoplankton biomass, particularly further away from the coast. • Results suggested that trends in DOC and POC are mostly driven by river discharge.		• A more certain understanding of what is mediating altered organic carbon dynamics in the GBR will help prioritise future research and management actions that aim to minimise (1) future increases in organic carbon concentrations, and (2) adverse ecological effects.

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Dr S Lewis (JCU) - What's really damaging the reef? Tracing the origin and fate of the environmentally detrimental sediment *(Project 2.1.5)*	(Bahadori *et al.*, 2019; Bainbridge *et al.*, 2018; Lewis *et al.*, 2018)	• The project delivered *in situ* continuous turbidity and light loggers and sediment trap accumulation datasets. Newly delivered sediment from the Tully River influenced turbidity regimes surrounding Dunk Is for ~5 months following flood events in 2017 and 2018. • Development of novel sampling techniques to characterise and trace the origin and fate of environmentally detrimental sediment within the GBR delivered from the Burdekin, Tully and Johnstone Basins. • Considerable contribution of DIN in the Burdekin flood plume that has desorbed from sediment. • Mineral particles <20 µm associated with terrestrial organic matter were found to travel furthest in the marine environment. • Sediment dynamics at marine sites in the inshore GBR lagoon region likely fall into three separate categories including sites where: 1. Input of new terrigenous sediments have by far the greatest influence on sediment exposure and subsequent resuspension (e.g. Dunk Is, Orpheus Is, Havannah Is, Cleveland Bay). 2. Input of new terrigenous sediments are at least equivalent to resuspension events which likely increases upon larger river discharge events (e.g. Cleveland Bay, Orchard Rocks). 3. Input of new terrigenous sediments are less than or equal to common resuspension events (e.g. Middle Reef, Geoffrey Bay).	A core part of the project was to develop equipment (e.g. sediment traps: SediSampler® and SediPump®) and protocols for sample collection to undertake the diverse array of analyses and laboratory experiments required. Relationship between turbidity and TSS was stablished for 7 inshore marine sites. Other new analytical techniques included the analysis of ^{13}C NMR and bacterial/fungal communities, and the measurement of DIN generation in flood plumes.	• Due to the differences in sediment dynamics, the study revealed which sites are most influenced by newly delivered riverine sediment and hence where management in the catchment for sediment erosion would improve water quality and likely ecosystem health at those coral reef and seagrass meadows sites. • The project also provided some of the first empirical data to support the finding of the satellite photic depth modelling by (Fabricius *et al.*, 2014, 2016), where the delivery of new terrigenous sediment considerably influences water clarity on the inshore Great Barrier Reef. • The latest research tools were identified to determine thresholds of suspended particulate matter (SPM) exposure, allowing for an improved appreciation of marine risk. These tools can be used to determine ecologically-relevant end-of-basin load targets and reliable marine water quality guidelines, thereby enabling enhanced prioritisation and management of SPM export from ride-to-reef.

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Dr S Lewis (JCU) - What’s really damaging the reef? Tracing the origin and fate of the environmentally detrimental sediment and associated bioavailable nutrients *(Project 5.8)*	(Lewis *et al.*, 2020)	• The project characterised the physical, biogeochemical and isotopic composition of suspended sediment samples from flood plumes and resuspension events in order to trace the within-catchment source of the sediments and understand the transformations that occur as fine clay-sized sediment moves from ‘catchment to reef’. • The organic component of floc aggregates in flood plumes and sediment traps was characterised using 13C-NMR spectroscopy and microbial composition analyses to determine the liability (i.e. bioavailability) of organic matter and to further quantify contributions of terrestrial and marine sources. • Results showed that the composition of the newly delivered sediment to the GBR lagoon changes during transport, deposition and resuspension, with increasing importance of the biological component. • A pilot study was also conducted to characterise the sediment causing persistent turbidity issues in the Whitsundays Islands, using the SediPump™ developed in Project 2.1.5 and the techniques derived from this research.	Additional data for model (Source Catchments, eReefs) validation and improvement.	• Sediment tracing across the catchment to marine continuum should allow a more targeted investment of on-ground remediation activities in main sources. • Results of this study can also be applied to port management and dredging as it also examines the changing behaviour of sediments in resuspension events. • Additional outcomes include contributions to (1) OGBR Bioavailable Nutrients workshop/concept paper, (2) the creation of a ‘fluffy’ sediment layer within eReefs model, (3) the Burdekin Landholders Driving Change Major Integrated Project, (4) Scientific Consensus Statement and additional presentations to (4) GBRMPA staff, (5) Port of Townsville Community Liaison Group, (6) Canegrowers Policy Council Meeting, (7) attendance at Qld Gov OGBR stall at Beefweek 2018, and (8) Sediment Working Group.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Managing and reducing catchment sources of sediment to the GBR				
Dr R Bartley (CSIRO) - Developing an approach to evaluate the effectiveness of investments in riparian management in the GBR catchments *(Project 1.2)*	(Bartley *et al.*, 2016a; Bartley *et al.*, 2016b)	• Stream-bank erosion rates (or channel change) for the GBR catchments can vary from 0.01 m to 5 m yr^{-1}, with higher erosion rates following flood events, but overall low rates otherwise (0.01- 0.1 yr^{-1}). • The effectiveness of riparian vegetation in reducing erosion rates was assessed in the Fitzroy and Mackay Whitsunday catchments as case studies. • Changes in channel width were mostly measured through historical air photos (~1950-2012), showing no statistically significant differences in channel change between sites with good and poor riparian vegetation. However, this could be an artefact of the technique used and does not prove that riparian vegetation is not effective.	A comparison of tools for monitoring and evaluating channel change (2 terrestrial laser scanning instruments RIEGL VZ400 and Zebedee, and airborne LiDAR) showed that the RIEGL was more accurate than the Zebedee, although the airborne LiDAR could be useful to cover large areas rapidly.	• The need to incorporate a 'lag effect' in the models used to evaluate GBR remediation investment (i.e. Source Catchments models), as the physical water quality benefits 2-18 years after remediation has taken place. • Riparian vegetation is important for stabilising banks, intercepting run-off and ecological function, but it is also important to maintain vegetation upstream. Multiple vegetation metrics should be considered for a given site. • A specific budget should be given to evaluating the effectiveness of on-ground remediation works, including riparian management, on water quality.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr R Bartley (CSIRO) - Demonstration and evaluation of gully remediation on downstream water quality and agricultural production in GBR rangelands *(Project 2.1.4)*	(Bartley *et al.*, 2017, 2018; Bartley *et al.*, 2018; Wilkinson *et al.*, 2018)	• The Bowen catchment was found to be the major contributor of sediments compared to any other catchment within the GBR area. • Porous check dams constructed from sticks and logs, in combination with stock exclusion fencing, appear to have an impact on the amount of vegetation that stabilises gullies floors, which in turn was linked with an improvement in water quality (i.e. reduced total suspended sediment concentrations and total nitrogen). • Gullies located on black soils (vertosol) were a major sediment and particulate nutrient source and thus require further attention. • The reduction on livestock grazing pressures within and around gullies in hillslope drainage lines could be a primary method of gully erosion control, which could deliver substantial reductions in sediment yield.		• The high variability in estimating sediment supply and cost-effectiveness. Hence, cost-effectiveness is best calculated at the project or program scale (across multiple gullies) to account for inherent spatial and temporal variability at individual sites. • Sites with the following attributes are more cost-effective to treat, when (i) more efficient sediment delivery to the coast; (ii) high proportion of silt and clay; (iii) higher nutrient content. • The reduction on livestock grazing pressures within and around gullies could be a primary method of gully erosion control, which could deliver substantial reductions in sediment yield.

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Dr R Bartley (CSIRO) - Gully remediation effectiveness *(Project 5.9)*	(Bartley *et al.*, 2020a; Bartley *et al.*, 2020b)	• High variability of erosion and WQ among gullies, with catchment area being the strongest predictor of sediment yield for linear gullies. TSS concentrations in control sites varied from 60 m/L (Mt Pleasant) to 53,000 m/L (Glen Bowen). Total Nitrogen was not as responsive as sediments to rehabilitation treatment. • Livestock management and revegetation: some improvements in % cover or biomass were observed after treatment, but sites remained in poor condition. • Porous Check Dams (plus fencing) (sites at Virginia Park and Minnievale) resulted in high (>90%) coarse sediment trapping (>63µm). • Hillslope runoff diversion above the gully (Strathbogie) statistically improved the runoff and WQ metrics (~0.95 effectiveness value), but further monitoring is required to assess if the treatment is causing gully initiation elsewhere. • Runoff management within gully (Mt Pleasant) had some success although the property already had good vegetation metrics and in-active gully systems. • Gully reshaping, structural control and revegetation (Mt Wickham) resulted in statistically improved vegetation metrics, TSS and declined sediment loads (effectiveness value of ~0.85).		• Data from this project will be critical for scenario analysis using the P2R modelling. • This is a long-term research field, and sites will continue to produce data as sites are exposed to different weather/climate conditions, succession in vegetation, etc. • The qualitative information such as terrain monitoring of gully erosion, photographs of event runoff, vegetation responses and treatment intactness, provides early information to support gully rehabilitation, the appropriateness of the techniques being tested, and the types of responses which can be expected to continue to develop.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Prof A Brooks (GU) - Achieving maximum reductions of sediment loads to the GBR on the shortest possible timescales: the application and adaptation of mine site rehabilitation approaches to alluvial gully rehabilitation in the Bowen catchment *(Project 2.1.10)*	(Brooks *et al.*, 2016b)	• Large alluvial gully systems are a significant contributor to the sediment load of the GBR catchment rivers and require of rehabilitation efforts in order to significantly reduce sediment and nutrient loads to the GBR and meet reduction targets. • Given the diversity of gully forms, a diverse array of management interventions will be required for their effective treatment, such as hard engineering interventions involving terrain reforming of the whole gully system, or less interventionist measures. • Mine site landscape rehabilitation approaches could be adapted and applied to alluvial gully rehabilitation, cost-effectively. • A stable soil surface needs to be reconstructed. • General principles were proposed as a requirement for successful alluvial gully rehabilitation.	As a result of this project significant progress has been made towards the development of a major collaborative project (with Glencore) that will take this forward into large field trials of the application of mine site rehabilitation strategies for alluvial gully rehabilitation.	Key principles of gully rehabilitation include: • Stock exclusion. • Short term erosion mitigation measures during construction phase (e.g. sediment traps). • When reforming vertical surfaces, determine first appropriate slope for soil. • Hardening of key slope components. • Hydrological reconfiguration and associated drainage management. • Cap unstable subsoils by covering with new soil (imported or built on-site). • Revegetation and ongoing maintenance.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Prof A Brooks (GU) - Reducing sediment loads to the Great Barrier Reef – developing optimal approaches for treating alluvial gully erosion *(Project 3.1.7)*	(Brooks *et al.*, 2021)	• Main focus of the project was testing and evaluating cost-effectiveness of different gully rehabilitation approaches within the larger alluvial gully complexes (i.e. Crocodile Station and Strathalbyn). • Results showed that alluvial gullies can be cost-effectively remediated to achieve >95% effectiveness factor, with highest effectiveness at sites that had full reshaping and rock capping, and lower effectiveness at sites treated with organic mulch and other non-rock surface treatments. • Gullies treated with rock capping and soil ameliorants are resilient to major events (e.g. large floods.) • Net increases in dissolved nutrient yields were observed in sites treated with organic ameliorants, which requires ongoing monitoring. • The net end of system fine sediment abatement achieved at the Crocodile and Strathalbyn sites respectively by May 2020 was 0.165 and 4.43 kt/yr, equivalent to reductions of 1.7% and 0.8% of the water quality targets for the Normanby and Bowen catchments, respectively.	The PASS sampler is ideally suited for the cost-effective and rigorous collection of pre- and post- treatment sediment concentration data.	• In order to calculate cost effectiveness of gully remediation, using a 7% discount rate and a 25-year lifetime enables the upfront cost to be converted to its annualised equivalent cost so that it can be compared with annual sediment reduction. • End of system (EOS) cost effectiveness could be used as a metric to inform investments in gully remediation across different GBR catchments. • More efforts and resources need to be directed towards baseline sediment and nutrient yield determination to ensure the integrity of estimates of GBR water quality improvement. • In order to meet the 2025 WQ targets for the Normanby and Bowen catchments respectively, 61 and 129 equivalent sites would need to be remediated in each catchment.

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Prof A Brooks (GU) - Gully characterisation framework to underpin GBR catchment water quality management *(Project 4.9)*	(Brooks *et al.*, 2019)	In brief, gullies could be classified based on: 1. Climate Zone 2. Gully scale / Gully System Complexity (i.e. simple, composed, complex). 3. Landscape domain: Hillslope (colluvial vs. residual), composite (alluvium to Hillslope, alluvium slopes), and alluvial (Floodplain/terrace, Bank/Slopes, Valley bottom). 4. Gully form: Linear, Dendritic, Open, Amphitheatre, Scarp-front, Variant forms. 5. Gully Catchment: Contributing Catchment Area (CCA) / Distance to Divide (DtD): i) Minimal, ii) Moderate, iii) Extensive 6. Vegetation Cover (In gully / Around gully): i) bare, ii) sparse, iii) dense. 7. Soil materials 8. Erosion Activity	A gully database was developed to facilitate systematic collection of data on gullies, along with purpose-built-Excel-based data entry forms to allow for easy data upload to the centralised database. Available through the NESP TWQ Hub website and eAtlas.	• The identification of different types of gullies in the landscape allows to prioritise management effort and resources so that the appropriate treatments can be applied to different gullies in the most cost-effective manner.

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Prof A Brooks (GU) - Development and application of automated tools for high-resolution gully mapping and classification from LiDAR data *(Project 5.10)*	(Stout *et al.* 2020)	• Airborne Light Detection And Ranging (LiDAR) is widely recognised as being the best way to accurately map gullies at a landscape scale at a suitable resolution for management planning. Given the large volume of LiDAR data now becoming available, this project developed and applied automated tools to enable the location of gullies to be extracted from LiDAR Digital Elevation Models (DEMs), along with key attributes of the gullies enabling them to be grouped into classes of similar gully types to aid prioritisation, management and catchment modelling. • Results showed that both alluvial and hillslope gullies can be mapped with a high degree of precision using these approaches and thereby provide the basis for quantifying a range of gully metrics such as: width, depth, area, length, volume, slope, planform shape and cross-sectional shape.	This project refined automated gully mapping approaches currently under development and developed new tools in order to automate the attribute extraction and assignment of types to the mapped gullies from high-resolution LiDAR DEM data.	• Accurately mapping gullies at high resolution and quantifying their key attributes is the critical first step in the process of prioritising and designing rehabilitation solutions. • Mapping gullies from LiDAR, particularly where coupled with high resolution multi-spectral imagery, provides a far superior product to that which can be obtained via manual and visual mapping from satellite imagery
Dr K Paul (CSIRO) - Optimizing the management of riparian zones to improve the health of the Great Barrier Reef *(Project 3.1.4)*	(Paul *et al.*, 2018)	• Sub-optimal rehabilitation: Improved WQ outcomes increased with project age, although remediation projects may not result in full rehabilitation to 'natural' stage (due to persistent erosion, weeds…). • Importance of financial incentives to engage landholders. • Overcoming normalising behaviour and perceived risks by landholders is important to ensure widespread participation in riparian remediation. • Need to prioritise resources to maximise impacts. • Riparian areas play a large role in providing benefits to biodiversity and biosequestration due to their fertile alluvial soils and increased moisture levels.		Recommendations: • To facilitate landholder groups to engage and build local knowledge, including to develop guidelines for recommended management practices that are practical and also provide benefits to agricultural production. • To facilitate alternative incentive schemes (i.e. landholder payments that are directly linked to outcomes of improved water quality, biodiversity and carbon mitigation). • Underpinning research to support riparian remediation.

This project is supported through funding from the Australian Government's National Environmental Science Program