2022 Scientific Consensus Statement

Question 3.1 What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef

Question 3.1.1 What is the variability of turbidity and photic depth in coastal and marine areas of the Great Barrier Reef?

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

These explanatory notes were produced by the SCS Coordination Team and apply to all evidence syntheses in the 2022 SCS.

What is the Scientific Consensus Statement?

The Scientific Consensus Statement (SCS) on land use impacts on Great Barrier Reef (GBR) water quality and ecosystem condition brings together scientific evidence to understand how land-based activities can influence water quality in the GBR, and how these influences can be managed. The SCS is used as a key evidence-based document by policymakers when they are making decisions about managing GBR water quality. In particular, the SCS provides supporting information for the design, delivery and implementation of the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) which is a joint commitment of the Australian and Queensland governments. The Reef 2050 WQIP describes actions for improving the quality of the water that enters the GBR from the adjacent catchments. The SCS is updated periodically with the latest peer reviewed science.

C_2O Consulting was contracted by the Australian and Queensland governments to coordinate and deliver the 2022 SCS. The team at C_2O Consulting has many years of experience working on the water quality of the GBR and its catchment area and has been involved in the coordination and production of multiple iterations of the SCS since 2008.

The 2022 SCS addresses 30 priority questions that examine the influence of land-based runoff on the water quality of the GBR. The questions were developed in consultation with scientific experts, policy and management teams and other key stakeholders (e.g., representatives from agricultural, tourism, conservation, research and Traditional Owner groups). Authors were then appointed to each question via a formal Expression of Interest and a rigorous selection process. The 30 questions are organised into eight themes: values and threats, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions, and future directions, that cover topics ranging from ecological processes, delivery and source, through to management options. Some questions are closely related, and as such Readers are directed to Section 1.3 (Links to other questions) in this synthesis of evidence which identifies other 2022 SCS questions that might be of interest.

The geographic scope of interest is the GBR and its adjacent catchment area which contains 35 major river basins and six Natural Resource Management regions. The GBR ecosystems included in the scope of the reviews include coral reefs, seagrass meadows, pelagic, benthic and plankton communities, estuaries, mangroves, saltmarshes, freshwater wetlands and floodplain wetlands. In terms of marine extent, while the greatest areas of influence of land-based runoff are largely in the inshore and to a lesser extent, the midshelf areas of the GBR, the reviews have not been spatially constrained and scientific evidence from anywhere in the GBR is included where relevant for answering the question.

Method used to address the 2022 SCS Questions

Formal evidence review and synthesis methodologies are increasingly being used where science is needed to inform decision making, and have become a recognised international standard for accessing, appraising and synthesising scientific information. More specifically, ’evidence synthesis’ is the process of identifying, compiling and combining relevant knowledge from multiple sources so it is readily available for decision makers[1]. The world’s highest standard of evidence synthesis is a Systematic Review, which uses a highly prescriptive methodology to define the question and

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[1] Pullin A, Frampton G, Jongman R, Kohl C, Livoreil B, Lux A, ... & Wittmer, H. (2016). Selecting appropriate methods of knowledge synthesis to inform biodiversity policy. *Biodiversity and Conservation*, 25: 1285-1300. https://doi.org/10.1007/s10531-016-1131-9

evidence needs, search for and appraise the quality of the evidence, and draw conclusions from the synthesis of this evidence.

In recent years there has been an emergence of evidence synthesis methods that involve some modifications of Systematic Reviews so that they can be conducted in a more timely and cost-effective manner. This suite of evidence synthesis products are referred to as **'Rapid Reviews'**[2]. These methods typically involve a reduced number of steps such as constraining the search effort, adjusting the extent of the quality assessment, and/or modifying the detail for data extraction, while still applying methods to minimise author bias in the searches, evidence appraisal and synthesis methods.

To accommodate the needs of GBR water quality policy and management, tailormade methods based on Rapid Review approaches were developed for the 2022 SCS by an independent expert in evidence-based syntheses for decision-making. The methods were initially reviewed by a small expert group with experience in GBR water quality science, then externally peer reviewed by three independent evidence synthesis experts.

Two methods were developed for the 2022 SCS:

- The **SCS Evidence Review** was used for questions that policy and management indicated were high priority and needed the highest confidence in the conclusions drawn from the evidence. The method includes an assessment of the reliability of all individual evidence items as an additional quality assurance step.
- The **SCS Evidence Summary** was used for all other questions, and while still providing a high level of confidence in the conclusions drawn, the method involves a less comprehensive quality assessment of individual evidence items.

Authors were asked to follow the methods, complete a standard template (this 'Synthesis of Evidence'), and extract data from literature in a standardised way to maximise transparency and ensure that a consistent approach was applied to all questions. Authors were provided with a Methods document, *'2022 Scientific Consensus Statement: Methods for the synthesis of evidence'*[3], containing detailed guidance and requirements for every step of the synthesis process. This was complemented by support from the SCS Coordination Team (led by C_2O Consulting) and the evidence synthesis expert to provide guidance throughout the drafting process including provision of step-by-step online training sessions for Authors, regular meetings to coordinate Authors within the Themes, and fortnightly or monthly question and answer sessions to clarify methods, discuss and address common issues.

The major steps of the Method are described below to assist Readers in understanding the process used, structure and outputs of the synthesis of evidence:

1. **Describe the final interpretation of the question.** A description of the interpretation of the scope and intent of the question, including consultation with policy and management representatives where necessary, to ensure alignment with policy intentions. The description is supported by a conceptual diagram representing the major relationships relevant to the question, and definitions.
2. **Develop a search strategy**. The Method recommended that Authors used a S/PICO framework (Subject/Population, Exposure/Intervention, Comparator, Outcome), which could be used to break down the different elements of the question and helps to define and refine

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[2] Collins A, Coughlin D, Miller J, & Kirk S (2015) The production of quick scoping reviews and rapid evidence assessments: A how to guide. UK Government. https://www.gov.uk/government/publications/the-production-of-quick-scoping-reviews-and-rapid-evidence-assessments

[3] Richards R, Pineda MC, Sambrook K, Waterhouse J (2023) 2022 Scientific Consensus Statement: Methods for the synthesis of evidence. C_2O Consulting, Townsville, pp. 59.

the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[4].

3. **Define the criteria for the eligibility of evidence for the synthesis and conduct searches.** Authors were asked to establish **inclusion and exclusion criteria to define the eligibility of evidence** prior to starting the literature search. The Method recommended conducting a **systematic literature search** in at least **two online academic databases**. Searches were typically restricted to 1990 onwards (unless specified otherwise) following a review of the evidence for the previous (2017) SCS which indicated that this would encompass the majority of the evidence base, and due to available resources. In addition, the geographic **scope of the search for evidence** depended on the nature of the question. For some questions, it was more appropriate only to focus on studies derived from the GBR region (e.g., the GBR context was essential to answer the question); for other questions, it was important to search for studies outside of the GBR (e.g., the question related to a research theme where there was little information available from the GBR). Authors were asked to provide a rationale for that decision in the synthesis. Results from the literature searches were screened against **inclusion and exclusion** criteria at the title and abstract review stage (**initial screening**). Literature that passed this initial screening was then read in full to determine the eligibility for use in the synthesis of evidence (**second screening**). Importantly, all literature had to be **peer reviewed and publicly available.** As well as journal articles, this meant that grey literature (e.g., technical reports) that had been externally peer reviewed (e.g., outside of organisation) and was publicly available, could be assessed as part of the synthesis of evidence.
4. **Extract data and information from the literature**. To compile the data and information that were used to address the question, **Authors were asked to complete a standard data extraction and appraisal spreadsheet**. Authors were assisted in tailoring this spreadsheet to meet the needs of their specific question.
5. **Undertake systematic appraisal of the evidence base**. Appraisal of the evidence is an important aspect of the synthesis of evidence as it provides the reader and/or decision-makers with valuable insights about the underlying evidence base. Each evidence item was assessed for its spatial, temporal and overall relevance to the question being addressed, and allocated a relative score. The body of evidence was then evaluated for overall relevance, the size of the evidence base (i.e., is it a well-researched topic or not), the diversity of studies (e.g., does it contain a mix of experimental, observational, reviews and modelling studies), and consistency of the findings (e.g., is there agreement or debate within the scientific literature). Collectively, these assessments were used to obtain an overall measure of the level of confidence of the evidence base, specifically using the overall relevance and consistency ratings. For example, a high confidence rating was allocated where there was high overall relevance and high consistency in the findings across a range of study types (e.g., modelling, observational and experimental). Questions using the **SCS Evidence Review Method** had an **additional quality assurance step**, through the assessment of reliability of all individual studies. This allowed Authors to identify where potential biases in the study design or the process used to draw conclusions might exist and offer insight into how reliable the scientific findings are for answering the priority SCS questions. This assessment considered the reliability of the study itself and enabled authors to place more or less emphasis on selected studies.
6. **Undertake a synthesis of the evidence and complete the evidence synthesis template** to address the question. Based on the previous steps, a narrative synthesis approach was used by authors to derive and summarise findings from the evidence.

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[4] https://libguides.jcu.edu.au/systematic-review/define

Guidance for using the synthesis of evidence

Each synthesis of evidence contains three different levels of detail to present the process used and the findings of the evidence:

1. **Executive Summary**: This section brings together the evidence and findings reported in the main body of the document to provide a high-level overview of the question.
2. **Synthesis of Evidence:** This section contains the detailed identification, extraction and examination of evidence used to address the question.
    - ***Background***: Provides the context about why this question is important and explains how the Lead Author interpreted the question.
    - ***Method:*** Outlines the search terms used by Authors to find relevant literature (evidence items), which databases were used, and the inclusion and exclusion criteria.
    - ***Search Results:*** Contains details about the number of evidence items identified, sources, screening and the final number of evidence items used in the synthesis of evidence.
    - ***Key Findings:*** The **main body of the synthesis**. It includes a summary of the study characteristics (e.g., how many, when, where, how), a deep dive into the body of evidence covering key findings, trends or patterns, consistency of findings among studies, uncertainties and limitations of the evidence, significance of the findings to policy, practice and research, knowledge gaps, Indigenous engagement, conclusions and the evidence appraisal.
3. **Evidence Statement:** Provides a succinct, high-level overview of the main findings for the question with supporting points. The Evidence Statement for each Question was provided as input to the 2022 Scientific Consensus Statement Summary and Conclusions.

While the Executive Summary and Evidence Statement provide a high-level overview of the question, it is **critical that any policy or management decisions are based on consideration of the full synthesis of evidence.** The GBR and its catchment area is large, with many different land uses, climates and habitats which result in considerable heterogeneity across its extent. Regional differences can be significant, and from a management perspective will therefore often need to be treated as separate entities to make the most effective decisions to support and protect GBR ecosystems. Evidence from this spatial variability is captured in the reviews as much as possible to enable this level of management decision to occur. Areas where there is high agreement or disagreement of findings in the body of evidence are also highlighted by authors in describing the consistency of the evidence. In many cases authors also offer an explanation for this consistency.

Peer Review and Quality Assurance

Each synthesis of evidence was peer reviewed, following a similar process to indexed scientific journals. An Editorial Board, endorsed by the Australian Chief Scientist, managed the process. The Australian Chief Scientist also provided oversight and assurance about the design of the peer review process. The Editorial Board consisted of an Editor-in-Chief and six Editors with editorial expertise in indexed scientific journals. Each question had a Lead and Second Editor. Reviewers were approached based on skills and knowledge relevant to each question and appointed following a strict conflict of interest process. Each question had a minimum of two reviewers, one with GBR-relevant expertise, and a second 'external' reviewer (i.e., international or from elsewhere in Australia). Reviewers completed a peer review template which included a series of standard questions about the quality, rigour and content of the synthesis, and provided a recommendation (i.e., accept, minor revisions, major revisions). Authors were required to respond to all comments made by reviewers and Editors, revise the synthesis and provide evidence of changes. The Lead and Second Editors had the authority to endorse the synthesis following peer review or request further review/iterations.

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Executive Summary

Questions

Primary Question 3.1 What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the GBR?

Secondary Question 3.1.1 What is the variability of turbidity and photic depth in coastal and marine areas of the GBR?

Background

It has long been perceived that the ecosystems of the Great Barrier Reef (GBR) are threatened by increased loads of suspended sediment and particulate nutrients due to land use changes following the arrival of Europeans. In order to understand potential impacts of suspended sediments and particulate nutrients, it is important to understand the fundamental components and processes which shape the sedimentology of the GBR lagoon. This background helps to explain the spatial and temporal variability of suspended terrigenous (i.e., sediment eroded from the land) sediment and particulate nutrients across the GBR lagoon so that relevant management interventions can be devised. This synthesis of evidence will also serve as key background for several questions in the 2022 Scientific Consensus Statement (SCS).

This question covers the key spatial distributions of terrigenous sediment in both the water column and seafloor of the GBR and how these may change over time. In the context of this question, the GBR is interpreted to represent the estuarine and marine environment and does not include coastal freshwater wetlands. The spatial distribution of terrigenous sediment on the seafloor is considered over two specific temporal periods which include the longer-term geological scale (glacial-interglacial periods over the past 300,000 years) and the 'modern period' that covers the past 8,000 years when sea level was within 5 m of its present position. For the spatial distribution of terrigenous sediment in the water column, the synthesis predominantly focuses on the contemporary period (i.e., last two to three decades). The 'associated indicators' are interpreted to represent not just the influence of sediments on water quality such as turbidity and photic depth but also other terrestrial materials that have been measured in the GBR. These may include terrestrial organic matter and organic biomarkers. The synthesis primarily focuses on the fine (<20 µm) terrigenous sediment as this fraction is of most concern in the GBR due to its ability to travel long distances in flood plumes and its impact on photic depth[5]. The composition (i.e., particulate nutrient concentrations) of the benthic deposited sediment is also examined. The synthesis covers the spatial distribution of terrigenous sediment in river flood plumes as well as the spatial distribution of deposited (benthic) terrigenous sediment in the GBR.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[6]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations included Web of Science, Scopus and Google Scholar.

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[5] Bainbridge, Z., Lewis, S., Bartley, R., Fabricius, K., Collier, C., Waterhouse, J., Garzon-Garcia, A., Robson, B., Burton, J., Wenger, A., Wenger, A., & Brodie, J. (2018). Fine sediment and particulate organic matter: A review and case study on ridge-to-reef transport, transformations, fates, and impacts on marine ecosystems. *Marine Pollution Bulletin*, *135*, 1205–1220. https://doi.org/10.1016/j.marpolbul.2018.08.002

[6] Cook CN, Nichols SJ, Webb JA, Fuller RA, Richards RM (2017) Simplifying the selection of evidence synthesis methods to inform environmental decisions: A guide for decision makers and scientists. *Biological Conservation* 213: 135-145 https://doi.org/10.1016/j.biocon.2017.07.004

- Main source of evidence was exclusively studies derived from the Great Barrier Reef lagoon.
- A total of 1,709 potential studies were retrieved from the literature searches of which 235 studies were shortlisted for secondary screening. Four of these studies were unobtainable and could not be screened. A further 19 studies were identified manually through expert contact and personal collection. Following the secondary screening, 150 studies were eligible for inclusion in the synthesis of evidence.

Method limitations and caveats to using this Evidence Summary

For this Evidence Summary, the following caveats or limitations should be noted when applying the findings for policy or management purposes:

- Only studies written in English were included.
- Only GBR derived studies were included.
- Only studies published after 1990 were considered (only seminal studies prior to 1990 were included).
- Only peer reviewed studies were included.
- Studies exclusively on carbonate material such as shell and coral fragments produced in the marine environment were excluded (i.e., not terrigenous sediment).
- Indicators not associated with suspended sediment (or terrigenous materials) were excluded.
- Fragmented data, data limited to small number of samples and covering limited sites/area were excluded.
- Effect-based studies of sediments and/or nutrients were excluded.
- Catchment-based studies about sediment inputs to the GBR are covered in Question 2.3 (changes in delivery over time, Lewis et al., this SCS), Question 3.3 (sediment sources and loads, Prosser and Wilkinson, this SCS) and Question 3.4 (sediment transport and delivery to end-of-catchment, Prosser et al., this SCS).
- Review papers were excluded (i.e., not the primary source of information).

Key Findings

Summary of evidence to 2022

- On geological timescales (i.e., the last 300,000 years covering multiple glacial (ice ages) and inter-glacial periods), the highest terrigenous sediment (i.e., sediment originally eroded from the land) flux to the continental shelf occured during the periods of sea level transgression (between ~16,000 and 8,000 years ago or ka) (i.e., rise from a lowstand when sea levels were at their lowest). Sediment cores reveal that there is modern (defined here as the past 8,000 years when sea level was within 5 m of its present position) terrigenous sediment flux to the continental shelf (up to 13% of the riverine inputs) but the mechanism for such transport is unclear.
- All relevant literature clearly documents three distinct changes in the sediment composition on the seafloor of the GBR lagoon which coincides with water depth and have been classified as the inner, middle and outer shelf zones. This includes the dominance of land-derived ‘terrigenous’ sediment on the inner shelf (0 to 20 m water depth); mixed carbonate/terrigenous sediment (i.e., combined marine sediment such as shell fragments with land-derived sediment) on the middle shelf (20 to 40 m) which are relict deposits that are continually reworked and; carbonate-dominated (i.e., marine sediment from coral and shells) on the outer shelf (>40 m) of the GBR lagoon. The physical (colour, grain size) and chemical (organic markers, major and trace element geochemistry and bioavailability of phosphorus) composition of the sediments also follow this clear shelf zonation. The mechanisms that drive this strong zonation is through a combination of cyclones that promote strong shore-parallel currents and a product of the dominant south-east trade winds and the water depth limit of wave resuspension (up to 22 m).
- The literature also shows that most river-exported terrigenous sediment is deposited within river floodplains, river estuaries, close to river mouths and within the eastern sections of north-facing embayments. In addition, nearshore and inshore fringing coral reefs host considerable

amounts of terrigenous sediments within their internal structures and contain decreasing terrigenous to carbonate sediment proportions across inshore-offshore gradients.

- There is strong evidence for cross-shelf movement of terrigenous sediment (i.e., from the inner shelf to the middle and outer shelfs or, conversely, from the middle shelf to the inner shelf) which likely occurs during riverine flood plumes, nepheloid layers (i.e., highly concentrated suspended sediments on or near the seabed that are transported in currents), tidal currents, cyclones and mushroom jets (i.e., large scale water movements likely triggered by differences in water temperatures coupled with opposing tidal and wind currents), although the dominant transport mechanism is unresolved.
- A wealth of literature exists that considers the dominant influences on turbidity (i.e., water clarity) and photic depth (i.e., the depth in the water column that photosynthetically usable light can reach) in the inner shelf of the GBR lagoon, showing that wave-driven resuspension is the dominant driver, with tidal resuspension acting as a secondary influence. Resuspension of sediments on the inner shelf in conjunction with tidal and wave currents can transport sediments to other sediment respositories such as mangroves, beaches, sheltered embayments.
- Studies on particulate nutrients in flood plumes and river estuaries highlight the potential for rapid transformation of particulate nutrients to bioavailable forms (dissolved nutrient forms that are readily consumed by algae) within coastal areas. Frequent resuspension of sediments within estuaries and the coastal zone helps promote rapid cycling of particulate nutrients which are largely mineralised through microbial communities.
- Several studies show that terrigenous sediments in flood plumes are highest at river mouths, with a rapid decline in concentrations within the 0 to 10 practical salinity units (PSU; i.e., a unitless scale that measures salinity of the water where 0 PSU = freshwater and ~35 PSU = seawater) salinity zone due to flocculation processes (i.e., when sediment particles stick together as a result of salinity changes or biological production). While most flood plumes are constrained within the inner shelf of the GBR lagoon, appreciable terrigenous sediment loads can be carried to the middle shelf and even the outer shelf during periods of large riverine discharge events (noting the size of the event is difficult to quantify which also relates to the distance to the middle and outer shelf from the river mouth), especially those that coincide with periods of slack winds. Turbidity logger data from the inner shelf of the GBR lagoon show a clear spatial gradient where decreasing turbidity levels are observed with increasing distance from river mouths. This spatial gradient is likely related to the depth of the water column (i.e., ability for wave resuspension) and the availability of sediment on the seafloor to be readily resuspended.
- Statistically accounting for the turbidity generated by wave and tidal resuspension reveals a significant contribution of riverine discharge and associated sediment and particulate nutrient loads on the turbidity regime in sections of the inner and middle shelfs of the GBR lagoon. Seasons of above average discharge and loads coincide with increased and prolonged (up to 6 months) turbidity and corresponding low light in these sections of the GBR compared to below average discharge years.
- The quality of the most usable light spectrum that reaches the seafloor is rapidly diminished predominantly by the amount of suspended particulate matter in the water column. The finer ‘dust/fluff’ grain size fractions of the suspended particulate matter can be transported much greater distances in flood plumes, take longer to compact on the seafloor and hence are more easily resuspended and contribute to longer periods of diminished light. Turbidity as low as <5 nephelometric turbidity units (NTU) can greatly attenuate light reaching the seafloor. Logger readings of turbidity within this lower range have higher uncertainty in terms of the ‘instrument zero point’ (i.e., the variability in background turbidity readings when the instrument is placed in filtered water) as well as for the conversion of turbidity to a concentration of suspended particulate matter.

- Remote sensing and modelling analyses support the findings that river discharge and associated loads significantly influence turbidity and photic depth regimes along areas of the inner and middle shelfs of the GBR lagoon.

Recent findings 2016-2022

31 of the 150 studies reviewed were published between 2016 and 2022, comprising 21% of the studies. Key findings from these studies are:

- Remote sensing outputs highlight the subtle yet significant contribution of riverine discharge and associated loads on photic depth variability along areas of the inner and middle shelf of the GBR lagoon. Model outputs with improved parameterisation (i.e., finer sediment grain size) and validation with continuous turbidity loggers provide similar findings. Collectively these new data support an earlier study that applied turbidity logger data to show the influence of river discharge and associated loads on turbidity regimes.
- Remote sensing of flood plumes show that suspended particulate matter (SPM) and coloured dissolved organic matter (CDOM) are the dominant parameters that cause attenuation of light. A study using satellite images from the 2019 Burdekin flood plume showed that plume waters with SPM concentrations >20 milligrams per litre (mg L^{-1}) reached the middle shelf.
- Field measurements of flood plumes continue to show that SPM declines rapidly as the plume waters extend out from the coastline and the composition of the sediments become finer in mineral particle size (<20 microns (µm)), more organic rich and relatively enriched in expandable clays as the plume moves further offshore.
- Studies of the bioavailable nutrients (i.e., dissolved nutrient forms that are readily consumed by algae) within flood plumes and river estuaries also continue to highlight the potential for rapid desorption (i.e., previously attached to and released from mineral particles) and mineralisation of particulate nutrients (i.e., organic matter transformed by bacteria and fungal microbes) in the GBR lagoon.
- New data from turbidity loggers continue to highlight the distinct spatial inshore-offshore turbidity gradient with increasing distance offshore from the river mouth.
- The recent focus on the quality of light shows that the most ‘usable light spectrum’ is rapidly diminished under relatively low SPM concentrations and that this particulate matter is the key contributor to this light attentuation (i.e., reduced photic depth).
- Modelling of the dispersal of suspended sediments and particulate nutrients through ‘plume loading maps’ also highlights the extent of exposure within the GBR lagoon and how this has likely changed under increased loads following the arrival of Europeans. Importantly these areas of increased exposure broadly match those identified in the remote sensing and modelling outputs.
- Sediment transport and fate modelling also confirmed the results of previous field studies to show that the Fly River sediment loads have little influence on the islands of the Torres Strait and are largely constrained to the coastal areas of Papua New Guinea.
- Recent studies of inshore fringing coral reefs continue to show the relatively high amounts of terrigenous sediment incorporated within their internal structures and with a declining inshore-offshore trend in the proportion of terrigenous sediment relative to carbonate sediment.
- There have also been considerable research outputs on the spatial variability and composition of terrigenous sediment trapped within algal turfs (i.e., a form a macroalgae present on coral reefs) on inshore coral reefs.

Significance for policy, practice, and research

Multiple lines of evidence highlight the influence of increased sediment and particulate nutrient loads on increased turbidity regimes and reduced and prolonged photic depth on certain sections of the inner and middle shelf of the GBR lagoon. The evidence has been gleaned from statistical analysis of long-term (>3 years) turbidity logger data, remote sensing analysis of spatial and temporal variability of photic depth and modelling outputs of suspended sediments, secchi disc depth and benthic light. Collectively, the evidence provides a powerful base to demonstrate the need to reduce riverine sediment and particulate nutrient loads in efforts to improve the benthic light conditions in the GBR lagoon, which would greatly benefit the health of marine life.

The latest eReefs modelling can better simulate the riverine sediment inputs as well as its transport and fate in the GBR lagoon and hence the model can be used with improved confidence to develop end-of-basin ecologically-relevant load targets.

While there is still scope for improvement to further develop the knowledge (and quantification) of the complex catchment to reef processes that will further refine the outputs of the eReefs marine model (and as such improve catchment prioritisation), the current level of conceptual and process-based understanding is sufficient to deploy the model for informing catchment-based load targets.

Key uncertainties and/or limitations

- While terrigenous sediments continue to be delivered from rivers and the resuspension of seafloor sediments on the inner and middle shelfs to outer shelf of the GBR, the dominant mechanism and the specific sediment budget contributed from the inner and middle shelfs to the outer shelf have largely not been quantified.
- The evidence for the spatial and temporal influence of riverine discharge and associated loads on turbidity and photic depth in the GBR lagoon has strengthened over the past decade through a multiple lines of evidence based understanding. There is a wealth of new long-term turbidity logger data from several sites from the inner shelf of the GBR lagoon that could be analysed in a similar way to previous reviews[7]. Indeed many are from the same sites analysed in the previous dataset, although instead of the 3 years of data analysed in that study these sites now have up to 16 years of continuous data. The detailed analysis of these datasets would further strengthen the evidence base.
- There are limited turbidity logger data from the middle shelf of the GBR lagoon. The establishment of continuous turbidity and light logger sites on the middle shelf (informed by remote sensing and modelling outputs) would enhance the understanding of the level of influence of riverine discharge and associated loads in this monitoring-poor area of the GBR lagoon.
- Given the potential uncertainties of the low level turbidity readings, it would be instructive to transition to loggers that measure the light regime (and preferably the quality of light) in the GBR lagoon. Despite light being the critical parameter of interest, turbidity has been the traditional unit of measure (almost as a proxy for light) and comparatively light loggers have been used less in the GBR lagoon.
- Basin-specific suspended particulate matter loads that transit past the initial deposition zone including the organic component that forms *in situ* need to be better quantified and linked to areas where prolonged reductions in photic depth in the GBR lagoon have been reported.

Evidence appraisal

The relevance of each individual indicator was Moderate to High for overall relevance to the question, Moderate-High for spatial relevance, and Moderate for temporal relevance. The overall confidence in the body of evidence used to answer the primary question is considered High. This is based on High ratings for the overall consistency, relevance of the body of evidence used and the diversity of methods applied to address the question. A high sample size (i.e., quantity of literature = 149 relevant studies) of the available peer-reviewed evidence across multiple fields was used to address this question. The scientific literature on the cross-shelf distribution, transport processes, deposition, composition, nutrient processing and repositories/budgets of terrigenous sediment on the seafloor is well developed for the GBR lagoon. The spatial and temporal distribution of sediment and particulate nutrients in the water column and the key drivers have also been well established in the literature. There are now

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[7] Fabricius, K. E., De'ath, G., Humphrey, C., Zagorskis, I., & Schaffelke, B. (2013). Intra-annual variation in turbidity in response to terrestrial runoff on near-shore coral reefs of the Great Barrier Reef. *Estuarine Coastal and Shelf Science*, *116*, 57–65.

multiple lines of evidence to highlight the influence of inter-annual variability in river discharge and associated loads on the turbidity and light regimes at certain areas of the inner and middle shelfs of the GBR.

1. Background

It has long been perceived that the ecosystems of the Great Barrier Reef (GBR) are threatened by increased loads of suspended sediment and particulate nutrients due to land use changes following the arrival of Europeans (Brodie et al., 2012a; Lewis et al., 2021; McCloskey et al., 2021). In order to understand potential impacts of suspended sediments and particulate nutrients, it is important to understand the fundamental components and processes which shape the sedimentology of the Great Barrier Reef lagoon. This fundamental understanding allows the explanation of the spatial and temporal variability of suspended terrigenous sediment and particulate nutrients across the Great Barrier Reef lagoon so that relevant management interventions can be devised. This synthesis also serves as key background for several questions in the 2022 Scientific Consensus Statement (SCS).

Over the past 50 years, there has been a considerable amount of research carried out in the GBR lagoon examining the distribution and composition of the terrigenous sediment on the seafloor and in the water column, as well as the processes that shape this spatial and temporal distribution. The Atlas of the Great Barrier Reef book by W. 'Graham' H. Maxwell (1968) deserves special mention as this landmark publication laid the foundation for subsequent studies to build on those observations and test hypotheses that have ultimately led to a comprehensive understanding of terrigenous sediment in the GBR.

This Evidence Summary provides an audit of the key sedimentology literature on the GBR lagoon which has been divided into three key sections including: 1) the spatial distribution, composition and temporal processes that shape the terrigenous sediment on the seafloor of the GBR lagoon (relevant areas of knowledge explored included: terrigenous sediment flux on a geological timescale; the modern spatial terrigenous sediment distribution; sediment composition and; sediment processes); 2) the spatial and temporal distribution of terrigenous sediment within the water column and the main processes that drive this variability (relevant areas of knowledge explored included: flood plume measurements; turbidity/light logger measurements; remote sensing measurements and modelling) and; 3) the spatial and temporal variability of turbidity and photic depth in the GBR lagoon and the relationship with inter-annual river discharge and associated loads. The difference between the geological and modern timescales is defined as when sea level reached and remained within 5 m of its present position which occurred approximately 8,000 years ago (ka) (Lewis et al., 2013).

1.1 Questions

Primary question	**Q3.1** What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef?
Secondary question	**Q3.1.1** What is the variability of turbidity and photic depth in coastal and marine areas of the Great Barrier Reef?

Question 3.1 What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef?

This question covers the key spatial distributions of terrigenous sediment in both the water column and seafloor of the GBR and how these may change over time. In the context of this question, the GBR is interpreted to represent the estuarine and marine environment and does not include coastal freshwater wetlands. The spatial distribution of terrigenous sediment on the seafloor was considered over two specific temporal periods which included the longer-term geological scales (glacial-interglacial periods over the past 300,000 years) and the 'modern period' that covers the past 8,000 years when sea level was within 5 m of its present position. This modern distribution of sediments on the seafloor covers the sediment composition and the key processes that have shaped this distinct zonation (Figure 1). For the spatial distribution of terrigenous sediment in the water column, the synthesis predominantly focused on the contemporary period (i.e., last two to three decades) provided from direct measurements, remote sensing studies and model simulations (Figure 2). The 'associated indicators' were interpreted to represent not just the influence of sediments on water quality such as turbidity and photic depth but also other terrestrial materials that have been measured in the GBR. These may have included terrestrial organic matter and organic biomarkers. The synthesis primarily focused on the fine (<20 µm) terrigenous sediment as this fraction is of most concern in the GBR. The composition (i.e., particulate nutrient concentrations) of the benthic deposited sediment was examined where data were available. The synthesis covered the spatial distribution of terrigenous sediment in river flood plumes as well as the spatial distribution of deposited (benthic) terrigenous sediment in the GBR.

Question 3.1.1 What is the variability of turbidity and photic depth in coastal and marine areas of the Great Barrier Reef?

The synthesis considered spatial and temporal trends in turbidity measurements and satellite photic depth analysis across the Great Barrier Reef since 1990, with emphasis on trends observed since the Inshore Water Quality program began consistent nearshore water quality monitoring as part of the Marine Monitoring Program (MMP) in 2006. The synthesis considered factors that influence turbidity and photic depth including river inputs and wind/current/tidal-driven resuspension.

1.2 Conceptual diagram and map

The two conceptual figures are designed to capture the spatial distribution and composition of terrigenous sediment on the seafloor of the GBR lagoon and the processes that shape this distribution (Figure 1) as well as the spatial and temporal distribution of suspended particulate matter, turbidity and photic depth of the water column across the GBR lagoon (Figure 2). Figure 1 highlights that the spatial distribution and composition of the terrigenous sediments on the seafloor can be explained by riverine inputs (river flood plumes), the prevailing southeast trade winds and from strong shelf-parallel currents that develop during tropical cyclones. Figure 2 illustrates the spatial and temporal variability in photic depth and its correlations with river discharge and associated loads. The key message in the collection of images in Figure 2 is that: 1) mean photic depth increases from inshore to offshore (top left panel); 2) the correlations between temporal variability in photic depth and river discharge are stronger closer to the river mouths and become progressively weaker with increasing distance from river mouths (top right and bottom left panels); 3) the correlation between photic depth and river discharge is generally weaker offshore from the Cape York region relative to the other regions (top right panel) and; 4) there is inter-annual variability in photic depth where it is greater during the years of below average discharge (i.e., 2003 and 2004) and diminished during years of above average discharge (i.e., 2008 and 2009) (bottom right panel).

1.3 Links to other questions

This synthesis of evidence addresses one of 30 questions that are being addressed as part of the 2022 SCS. The questions are organised into eight themes: values and threats, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions, and future directions, that cover topics ranging from ecological processes, delivery and source, through to management options. As a result, many questions are closely linked, and the evidence presented may be directly relevant to parts of other questions. The relevant linkages for this question are identified in the text where applicable. The primary linkages for this question are listed below.

Links to other related questions	**Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?

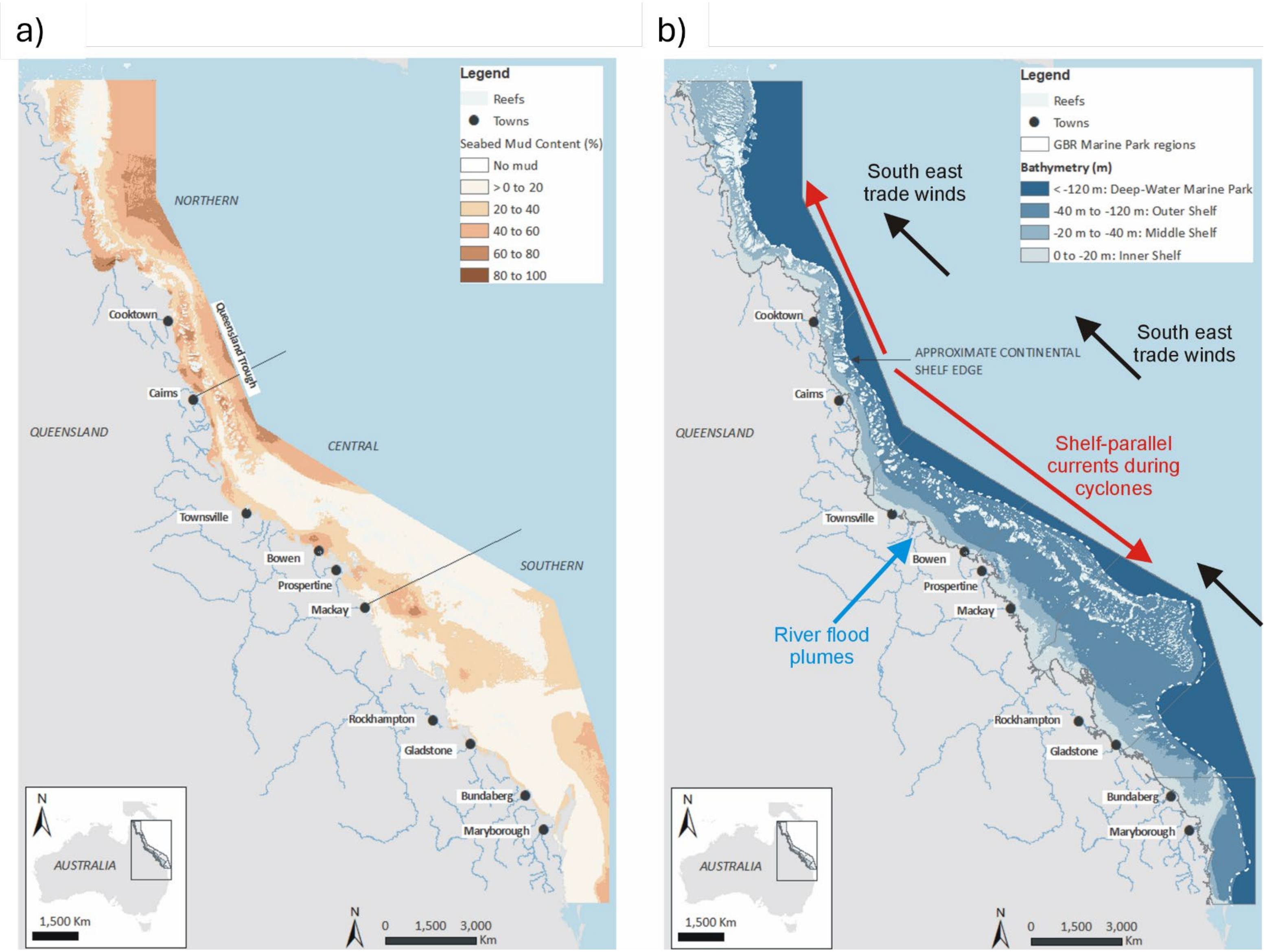

Figure 1. a) the mapped distribution of mud grain size particles (modified from Mathews et al., 2007) across the GBR lagoon. b) Map of the inner, middle and outer shelf of the GBR lagoon on the continental shelf with the key sedimentary processes that shape the partitioning of the shelf.

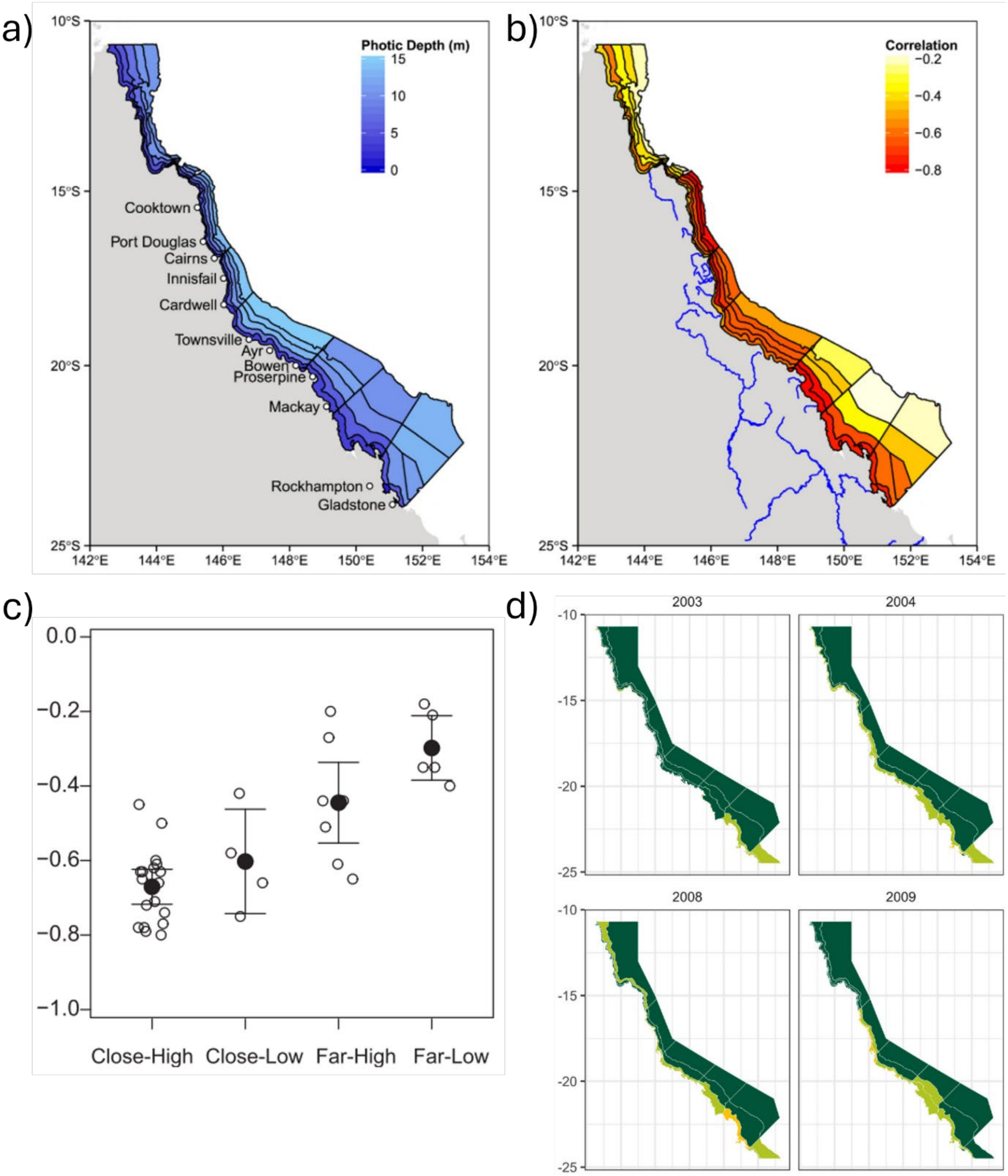

Figure 2. Variability in photic depth/benthic light across the GBR. The marine boundaries of the marine Natural Resource Management (NRM) regions are shown in a, b and c – showing (north to south) Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary. a) Average satellite photic depth across the GBR and, b) its correlations to river discharge and, c) distance to river mouth (close to far) and catchment modification (high to low) (From Fabricius et al., 2016), d) Temporal variability in benthic light for selected years for the GBR with colours signifying a grade for photic depth (Dark green = no stress/very good; light green = good; yellow = moderate; orange = poor) (From Canto et al., 2021).

2. Method

A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[8]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.

2.1 Primary question elements and description

The primary question is: ***What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the GBR?***

The secondary question is: **What is the variability of turbidity and photic depth in coastal and marine areas of the GBR?**

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[9] but other variations are also available.

- **Subject/Population:** Who or what is being studied or what is the problem?
- **Intervention/exposure:** Proposed management regime, policy, action or the environmental variable to which the subject populations are exposed.
- **Comparator**: What is the intervention/exposure compared to (e.g., other interventions, no intervention, etc.)? This could also include a time comparator as in 'before or after' treatment or exposure. If no comparison was applicable, this component did not need to be addressed.
- **Outcome:** What are the outcomes relevant to the question resulting from the intervention or exposure?

Table 1. Description of question elements for Questions 3.1 and 3.1.1.

Question S/PICO element	Question term	Description
Subject/Population	Terrigenous sediment	The synthesis primarily focuses on the fine (<20 µm) terrigenous sediment as this fraction is of most concern in the GBR.
	Associated indicators	Water quality indicators as reported in the Marine Monitoring Program (MMP) Annual Reports for Inshore Water Quality modelling (https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3826, i.e., water quality indices that are influenced by suspended sediment such as secchi disc depth, turbidity and light. Other indicators may include terrestrial organic matter, organic biomarkers and terrestrial markers in coral skeletons. The synthesis does not include dissolved and particulate nutrients in the water column, which are covered in Q4.1,

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[8] Cook CN, Nichols SJ, Webb JA, Fuller RA, Richards RM (2017) Simplifying the selection of evidence synthesis methods to inform environmental decisions: A guide for decision makers and scientists. *Biological Conservation* 213: 135-145. https://doi.org/10.1016/j.biocon.2017.07.004

[9] https://libguides.jcu.edu.au/systematic-review/define and https://guides.library.cornell.edu/evidence-synthesis/research-question

Question S/PICO element	Question term	Description
		although the composition of the deposited sediment is considered.
	The GBR	The GBR is interpreted as referring to the Great Barrier Reef World Heritage Area (GBRWHA). The boundaries of the area to be considered includes the area encompassed by the boundary of the Great Barrier Reef World Heritage Area. For completeness some studies in the Torres Strait are also considered.
Intervention, exposure qualifiers	Spatial distribution	Large-scale spatial patterns in water-column suspended sediment concentrations and turbidity/photic depth across the whole GBR, including latitudinal variations organised by Natural Resource Management region, variations with distance from coast organised by waterbody (inner, middle, outer shelfs), and variations associated with the spatial extent of flood plumes. Polygons defining the boundaries of management areas are available from the Great Barrier Reef Marine Park Authority (GBRMPA) geoportal: (http://www.gbrmpa.gov.au/agssdc/rest/services). This synthesis considers all sources of evidence reported in the relevant peer-reviewed literature, including *in situ* water sampling, loggers, remote sensing evidence and modelling. The spatial distribution of terrigenous sediments along the GBR seafloor are also considered in this question.
	Temporal distribution	Patterns observed over seasonal and multi-year timescales over the past two to three decades, with emphasis on trends observed since the installation of turbidity loggers coinciding with the commencement of the Inshore Water Quality Marine Monitoring Program (MMP) in 2006 and satellite remote sensing of photic depth variability since 2002.
	Coastal and marine areas of the GBR	Areas within the GBR, as defined above. “Coastal areas” are as defined in GBRMPA spatial polygons, and include both “enclosed coastal” and “open coastal” areas. “Marine areas” includes any part of the GBR World Heritage Area outside these coastal areas.
	Variability	Variability due to seasonal variations, and variations in weather, over the past two to three decades. This does not include long-term change associated with human influences, change over geological timescales, or change due to climate change, which are addressed in other questions (Q2.2 and Q2.3).
Comparator	N/A	
Outcome	The measures of spatial and temporal patterns within the GBR and variability in coastal and marine areas.	

Table 2. Definitions for terms used in Questions 3.1 and 3.1.1.

Definitions	
Terrigenous sediment	Mineral sediment that is <20 µm in diameter derived from a primary rock source (i.e., does not include sediment generated in the marine environment such as coral or shell carbonate material).
Associated indicators	A physical or compositional indicator that may be related to land derived particulate materials that have been transported in a flood plume or resuspended from the seafloor. These may include turbidity levels in the water column, photic depth measurements and terrestrial markers in benthic sediments.
GBR	The boundaries of the area to be considered includes the area encompassed by the boundary of the Great Barrier Reef World Heritage Area with some consideration of the Torres Strait area.
Coastal and marine areas of the GBR	Areas within the GBR, as defined above. “Coastal areas” are as defined in GBRMPA spatial polygons, and include both “enclosed coastal” and “open coastal” areas. “Marine areas” includes any part of the GBR World Heritage Area outside these coastal areas.

2.2 Search and eligibility

The Method includes a systematic literature search with well-defined inclusion and exclusion criteria.

Identifying eligible literature for use in the synthesis was a two-step process:

1. Results from the literature searches were screened against strict inclusion and exclusion criteria at the title and abstract review stage (initial screening). Literature that passed this initial screening step were then read in full to determine their eligibility for use in the synthesis of evidence.
2. Information was extracted from each of the eligible papers using a data extraction spreadsheet template. This included information that would enable the relevance (including spatial and temporal), consistency, quantity, and diversity of the studies to be assessed.

a) Search locations

Searches were performed on:

- Web of Science
- Scopus
- Google Scholar

b) Search terms

Table 3 shows a list of the search terms used to conduct the online searches.

Table 3. Search terms for S/PICO elements of Questions 3.1 and 3.1.1.

Question element	Search terms
Subject/Population	sediment, terrigenous, photic depth, turbidity, secchi, TSS, GBR “Great Barrier Reef”, Queensland, marine, coast, coastal, ocean, shore, inshore, offshelf, shelf, estuary, estuarine, Bay
Exposure/Intervention	N/A
Comparator (if relevant)	N/A
Outcome	A description of the spatial and temporal variability in terrigenous sediment in the water column and on the seafloor of the Great Barrier Reef lagoon.

c) Search strings

Table 4 shows a list of the search strings used to conduct the online searches.

Table 4. Search strings used for electronic searches for Questions 3.1 and 3.1.1.

Search strings
Web of Science: "ALL=(sediment OR terrigenous OR photic depth OR turbidity OR secchi OR TSS) AND (GBR OR "Great Barrier Reef" OR Queensland) AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshelf OR shelf OR estuary OR estuarine OR Bay)"
Scopus: "ABS-TI-KEY(sediment OR terrigenous OR photic depth OR turbidity OR secchi OR TSS) AND (GBR OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshelf OR shelf OR estuary OR estuarine OR Bay)"

d) Inclusion and exclusion criteria

Table 5 shows a list of the inclusion and exclusion criteria used for accepting or rejecting evidence items.

Table 5. Inclusion and exclusion criteria for Questions 3.1 and 3.1.1 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Terrigenous sediment Associated indicators The GBR	1. Carbonate material such as shell and coral fragments produced in the marine environment. 2. Indicators not associated with suspended sediment (or terrigenous materials). 3. Studies outside of the GBR.
Exposure or Intervention	Spatial and temporal data	4. Fragmented data, data limited to small number of samples and covering limited sites/area.
Comparator	N/A	N/A
Outcome	Distribution of suspended sediment in the water column of the GBR and how it varies under different environmental and climate conditions. Distribution of terrigenous sediment on the seafloor of the GBR.	
Language	English	5. Non-English written
Study type	Peer reviewed studies that cover a relatively long temporal period (i.e., >6 months) or a large study area (i.e., coverage of areas across different NRM regions).	6. Studies which have not been peer reviewed or cover a limited time period or spatial area. 7. Effect-based studies of sediments and/or nutrients. 8. Catchment-based studies. 9. Not a primary source of information (i.e., review study).

3. Search Results

A total of 1,709 studies were returned from the online searches for peer reviewed and published literature, of which 235 studies were identified for secondary screening. Nineteen (19) studies were identified manually through expert contact and personal collection, which represented 7.6% of the total evidence. Following second screening, a total of 150 studies were eligible for inclusion in the synthesis of evidence (Table 6, Figure 3). Four (4) of the 235 studies identified through the online searches were unobtainable.

Table 6. Search results table, separated by A) Academic databases, B) Search engines (i.e., Google Scholar) and C) Manual searches.

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
_14/12/2022_	_Search string 1: ((TI=(((sediment OR terrigenous OR "photic depth" OR turbidity OR secchi OR tss) AND (gbr OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshell OR shelf OR estuary OR estuarine OR bay)))) OR AB=(((sediment OR terrigenous OR "photic depth" OR turbidity OR secchi OR tss) AND (gbr OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshell OR shelf OR estuary OR estuarine OR bay)))) OR KP=(((sediment OR terrigenous OR "photic depth" OR turbidity OR secchi OR tss) AND (gbr OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshell OR shelf OR estuary OR estuarine OR bay)))_ _OR_ _TITLE-ABS-KEY ((sediment OR terrigenous OR "photic depth" OR turbidity OR secchi OR tss) AND (gbr OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshelf OR shelf OR estuary OR estuarine OR bay))_	_637_	_750_
_24/01/2023_	_ABS-KEY (((distrib* W/4 sediment OR terrigenous OR "photic depth" OR turbidity OR secchi OR tss) AND (gbr OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshelf OR shelf OR estuary OR estuarine OR bay)))_		_22_
B) Search engine (Google Scholar)			
_16/12/2022_	_((sediment OR terrigenous OR "photic depth" OR turbidity OR secchi OR tss) AND (gbr OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshelf OR shelf OR estuary OR estuarine OR bay))_	_26,700 (first 300)_	
	Total items online searches	***231 out of 1,709 (92.8%)*** _(Excludes four studies that were unobtainable)_	

C) Manual search		
Date	Source	Number of items added
07/11/2022	*Literature submitted by stakeholders (i.e., industry)*	*6*
24/01/2023	*Author personal collections*	*13*
	Total items manual searches	***19 (7.6%)***

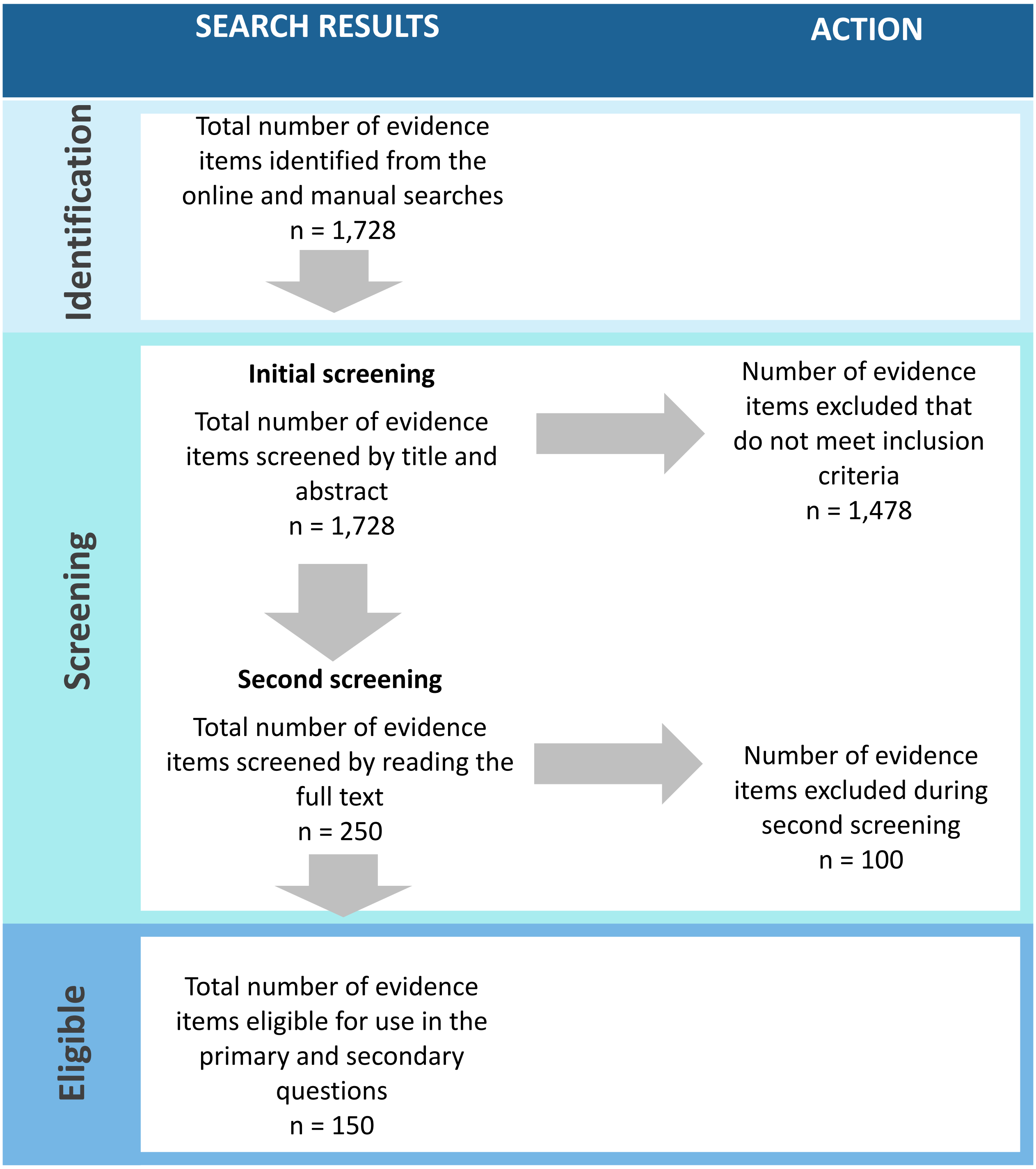


Figure 3. Flow chart of results of screening and assessing all search results.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

A total of 150 eligible studies were identified for this question. The characteristics are summarised in Table 7. Studies were considerd that examined the past 8,000-year time period to cover the 'modern sediment distribution' as this coincides with when sea level approached and remained within ~5 m of its present position. Overall, the studies can be broadly separated into eight areas of knowledge:

1) Geological timescale variability (i.e., studies covering periods greater than 8,000 years ago);
2) Modern sediment distribution (i.e., seafloor sediment and key areas of terrigenous sediment retention);
3) Sediment composition (i.e., related to organics, biomarkers, grain size, nutrient and trace metal contents);
4) Sediment processes (i.e., conceptual and evidence-based studies that help describe the partitioning of the shelf, produce sediment budgets, provide insights on sediment transport and bioavailable nutrients);
5) Flood plume measurements (i.e., direct measurements of sediment concentration and composition suspended within the plume);
6) Turbidity/light logger measurements (i.e., direct logger measurements of sediment concentration and light levels within the water column);
7) Remote sensing (i.e., satellite measurements of water colour coupled with developed algorithms to describe spatial and temporal variability in suspended sediment and benthic photosynthetic available radiation (PAR)); and
8) Modelling (i.e., covers sediment distribution on the seafloor, sediment transport processes and spatial and temporal variability of water column suspended sediment and light).

Some of these studies overlap across multiple areas of knowledge and while the most appropriate area has been allocated to each study in Table 7, studies which overlap with other areas of knowledge are still considered in those other areas.

Overall, the eligible studies represent a solid coverage of geological (12 studies: 8.0%), modern sediment distibution (43 studies: 28.7%), sediment composition (27 studies: 18.0%), sediment processes (21 studies: 14.0%), flood plume measurements (9 studies: 6.0%), turbidity/light measurements (21 studies: 14.0%), remote sensing (8 studies: 5.3%) and modelling studies (9 studies: 6.0%) (Table 7). Most studies were observational (108 studies: 72%) from direct measurements of the seafloor or from the water column, followed by a combination of observational/modelling studies (17 studies: 11%) where observations/measurements (satellite images, turbidity measurements) were combined with modelling (remote sensing, numerical modelling). The remaining studies combined observations (measurements/samples from the field) with experimental data (laboratory experiments/extractions) (5 studies: 3%) or modelling (hydrodynamics, sediment transport and fate) (10 studies: 7%), or were review/conceptual understanding-type studies (10 studies: 7%).

On a spatial scale, most eligible studies (95: 63.3%) were focused on the central section of the GBR (Cairns to Mackay), with more limited coverage on the northern section (Torres Stait to Cairns) with 13 studies (8.7%) and 11 studies (7.3%) on the southern section (Mackay to Maryborough). The eligible studies provide good coverage of the whole GBR, with 15 additional studies (10.0%) focused on the entire GBR and another 16 studies (10.7%) focused on at least two sections of the GBR.

On a temporal scale, there is very large variability in the timescales considered by the studies which range from <1 week up to the past 300,000 years (300 ka). Indeed, this variability is related to the type of study where the geological timescale studies range from 15 ka to 300 ka; the modern sediment distribution and sediment processes studies range from <1 month (i.e., event focused) to 8,000 ka (i.e., the period when sea level has been within 5 m of its present position); sediment composition studies range from samples collected across weeks to years; flood plume measurement studies focus on discrete river discharge events (which typically last <3 weeks), although most of these studies report data from either multiple events from the same river or from different rivers; similarly remote sensing studies range from a focus on a single flood plume event (<1 month) to longer periods of analysis (~16 years); turbidity/light logger studies range from <1 month to ~15 years; and modelling-based studies range from a single flood or hydrodynamic process (i.e., tidal change or island wake upwelling) up to ~13 years.

Table 7. Summary of the key types of studies and the location focus for each of the studies.

Study type/Area of knowledge	Northern	Central	Southern	Two sections	Whole GBR	Total
1. Geological time-scale variability	3	5	2	2		**12**
2. Modern sediment distribution	4	30	4	2	3	**43**
3. Sediment composition	1	16	3	7		**27**
4. Sediment processes	2	15	1		3	**21**
5. Flood plume measurements	2	6		1		**9**
6. Turbidity/light logger measurements		15		4	2	**21**
7. Remote sensing		4			4	**8**
8. Modelling	1	4	1		3	**9**
Total	**13**	**95**	**11**	**16**	**15**	**150**

Differences in the number of studies found across the eight knowledge areas are likely reflected by the proportionate search effect where search efforts were particularly focused on addressing the contemporary (i.e., past 30 years) terrigenous sediment distribution/variability of the seafloor and the water column of the GBR lagoon. There has been a particular focus to capture studies that report on high temporal resolution turbidity/light logger data and high spatial resolution data on suspended sediment/benthic light variability across the GBR that address both the primary and secondary questions. The geological-scale variability in terrigenous sediment transport and fate over sea level lowstands, transgressions and highstands has been captured for completeness, although should not be considered a definitive coverage of studies. Further, the synthesis has attempted to cover studies on key sedimentary processes in the GBR lagoon particularly on the distribution of the fine-grained (<63 µm) sediment fraction, although it is acknowledged this will not be a complete representation of studies. While the primary focus was to capture relevant literature published since 1990, some of the seminal/pioneering studies were also included, particularly related to sediment distribution across the GBR lagoon seafloor and observations of the sediment distribution and composition following Tropical Cyclone Winifred (1986).

For the secondary question (variability of turbidity and photic depth), there were 31 eligible studies which included all the turbidity/light measurements and remote sensing studies identified and 2 of the modelling-based studies (Baird et al., 2021; Waterhouse et al., 2017). The spatial and temporal coverage of these studies have been covered in the above section.

4.1.1 Summary of evidence to 2022

Over the past 50 years, there has been a considerable amount of research carried out in the GBR lagoon examining the distribution and composition of the terrigenous sediment on the seafloor and in the water column as well as the processes that shape this spatial and temporal distribution. The Atlas of the Great Barrier Reef book by W. 'Graham' H. Maxwell (1968) deserves special mention as this landmark publication laid the foundation for subsequent studies to build on those observations and test hypotheses that have ultimately led to a comprehensive understanding of terrigenous sediment in the GBR. This section highlights that there is a high level of agreement across much of the literature. The key findings show that on geological timescales, the highest terrigenous sediment flux to the continental shelf occurred during periods of sea level transgression (i.e., rise from a lowstand) (Bostock et al., 2009; Dunbar et al., 2000; Dunbar & Dickens, 2003; Harper et al., 2015; Page et al., 2003; Page & Dickens, 2005). Sediment cores reveal that there is modern (but much lower) terrigenous sediment flux to the continental shelf (up to 13% of the riverine inputs) but the mechanism for such transport is unclear (Francis et al., 2007).

All relevant literature clearly documents a strong partitioning of sediments on the inner (0 to 20 m water depth), middle (20 to 40 m) and outer shelf (>40 m) of the GBR lagoon where terrigenous sediments are mostly constrained within the inner shelf (Belperio, 1983; Mathews et al., 2007). The physical (colour, grain size) and chemical (organic markers, major and trace element geochemistry and bioavailability of phosphorus, P) composition of the sediments also follow this clear shelf partitioning (Alongi & McKinnon, 2005; Brunskill et al., 2002; Cooper et al., 2007; Currie & Johns, 1989; Hamilton, 2001; Johns et al., 1994; Monbet et al., 2007; Orpin et al., 2004b; Ward et al., 1995). The mechanisms that drive this strong partitioning are through cyclones that promote strong shore-parallel currents and a product of the dominant southeast trade winds and the water depth limit of wave resuspension (up to 22 m) (Larcombe & Carter, 2004; Orpin et al., 1999; Orpin & Woolfe, 1999; Woolfe et al., 2000). The literature also shows that most river-exported terrigenous sediment is deposited within river floodplains, river estuaries, close to river mouths and within the eastern sections of north-facing embayments (Bannister et al., 2012; Bostock et al., 2007; Lewis et al., 2014; Webster & Ford, 2010).

In addition, nearshore and inshore fringing coral reefs host considerable proportions of terrigenous sediments within their internal structures and contain decreasing terrigenous sediment composition across inshore-offshore gradients (e.g., Smithers et al., 2006). There is strong evidence for cross-shelf movement of terrigenous sediment (i.e., from the inner shelf to the middle and outer shelfs or, conversely, from the middle shelf to the inner shelf) which likely occurs during flood plumes, nepheloid layers, tidal currents, cyclones and mushroom jets, although the dominant transport mechanism is unresolved (Devlin et al., 2012; Francis et al., 2007; Gagan et al., 1990; Gruber et al., 2020; Larcombe & Carter, 2004; Lewis et al., 2020; Orpin et al., 1999; Patricio-Valerio et al., 2022; Perry et al., 2014; Wolanski et al., 2008).

A wealth of literature exists that considers the dominant control on turbidity and photic depth in the inner shelf of the GBR lagoon. The literature shows that wave-driven resuspension is the dominant driver with tidal resuspension acting as a secondary influence (Browne et al., 2013b; Larcombe et al., 1995; Larcombe & Woolfe, 1999b; Macdonald et al., 2013; Orpin et al., 1999; Orpin et al., 2004a; Orpin & Ridd, 2012). Resuspension of sediments on the inner shelf in conjunction with tidal and wave currents can transport sediments to other sediment respositories (i.e., mangroves, beaches, sheltered embayments, tidal flats, inshore coral reefs) as well as promote rapid cycling of particulate nutrients which are largely mineralised through microbial communities (Alongi et al., 2007; Alongi & McKinnon, 2005; Orpin & Woolfe, 1999; Radke et al., 2010).

Several studies show that terrigenous sediments in flood plumes are highest at the river mouths whereby concentrations rapidly decline due to flocculation processes within the 0 to 10 PSU salinity zone (Bainbridge et al., 2012; 2021; Devlin & Brodie, 2005; Howley et al., 2018; Livsey et al., 2022). While most flood plumes are constrained within the inner shelf of the GBR lagoon, appreciable terrigenous sediment loads can be carried to the middle shelf and even the outer shelf during periods of very large riverine discharge events that coincide with periods of slack winds (Devlin et al., 2012; Gruber et al., 2020; Lewis et al., 2020; Patricio-Valerio et al., 2022). Turbidity logger data from the inner shelf of the GBR lagoon show a clear spatial gradient where decreasing turbidity levels are observed with increasing distance from river mouths (Fabricius et al., 2013; Gruber et al., 2020; Lewis et al., 2020; Moran et al., 2022). This spatial gradient is likely related to the depth of the water column (i.e., ability for wave resuspension) and the availability of sediment on the seafloor to be readily resuspended.

Statistically accounting for the turbidity generated by wave and tidal resuspension processes reveals a significant contribution of riverine discharge and associated sediment and particulate nutrient loads on the turbidity regime in sections of the inner and middle shelfs of the GBR lagoon (Baird et al., 2021; Canto et al., 2021; Fabricius et al., 2014; 2016). Seasons of above average discharge and loads coincide with relatively increased and prolonged (up to 6 months) turbidity (and corresponding low light) in these sections of the GBR compared to below average discharge years (Canto et al., 2021; Fabricius et al., 2014, 2016).

The quality of the most usable light spectrum is rapidly diminished predominantly by the amount of suspended particulate matter in the water column (Anthony et al., 2004; Jones et al., 2020; Luter et al., 2021). The finer 'dust/fluff' grain size fractions of the suspended particulate matter can be transported much greater distances in flood plumes, take longer to compact on the seafloor and hence are more easily resuspended and contribute to the diminished light periods (Margvelashvili et al., 2018). Turbidity as low as <5 NTU can greatly attenuate light reaching the seafloor (Cooper et al., 2008). Logger readings of turbidity within this lower range have higher uncertainty in terms of the 'instrument zero point' as well as for the conversion of turbidity to a concentration of suspended particulate matter (Macdonald et al., 2013). Remote sensing and modelling analyses support the findings that river discharge and associated loads significantly influence turbidity and light regimes along sections of the inner and middle shelfs of the GBR lagoon (Baird et al., 2021; Canto et al., 2021; Fabricius et al., 2014, 2016; Margvelashvili et al., 2018).

1. Geological timescale variability

The contributions within the geological time-scale variability area of knowledge examined the flux of terrigenous sediment to the outer shelf (or over the continental shelf) either through riverine inputs or from landslides over several glacial and inter-glacial cycles. One of the key findings to emerge is that the highest fluxes of terrigenous sediment to the outer shelf occur during marine transgression periods (i.e., during sea level rise following glacial lowstand periods) which also coincide with the highest flux of carbonate sediments. This finding supports the coeval sedimentation model which has now been well-established across the northern, central and southern sections of the GBR (Bostock et al., 2009; Dunbar et al., 2000; Dunbar & Dickens, 2003; Harper et al., 2015; Page et al., 2003; Page & Dickens, 2005) and opposes the traditional reciprocal model which suggests that terrigenous fluxes should be highest during sea level lowstands and carbonate fluxes highest during sea level highstands (e.g., Harris et al., 1990). The higher fluxes during the transgression period (~16 to 8 ka) was postulated to be a result of either climate variability (i.e., higher rainfall in the catchment coupled with a transition from drier to wetter vegetation types) or the remobilisation and transport of terrigenous sediment stored on the shelf behind relict carbonate platforms during sea level lowstand periods (e.g., Bostock et al., 2009; Dunbar & Dickens, 2003; Harper et al., 2015; Page & Dickens, 2005).

A recent modelling study (Thran et al., 2020) supports the latter remobilisation hypothesis to explain the increased sediment flux during sea level transgression periods. Relatively elevated terrigenous sediment fluxes (compared to the sea level highstand period) also occur during glacial periods (i.e., sea level lowstands) (e.g., Bostock et al., 2009; Dunbar et al., 2000) which are linked to the observations of multiple relict river delta deposits expunging directly to the continental shelf (Daniell et al., 2020). Appreciable modern terrigenous sediment deposition off the continental shelf has also been documented during the recent sea level highstand period (i.e., past 8 ka) (e.g., Bostock et al., 2009; Dunbar et al., 2000; Francis et al., 2007), which suggests that modern cross shelf terrigenous sediment transport continues to occur, although the mechanisms for this cross-shelf sediment transport remain unclear (Francis et al., 2007).

A collection of studies has also examined the presence of turbidite deposits within sediment cores offshore from the continental shelf (Puga-Bernabeu et al., 2014; 2019; Webster et al., 2012). These deposits are common within the cores taken from the northern and central sections of the GBR (i.e., there are no studies from the southern GBR at this time) and consist of a mixture of coarse-grained siliciclastic and carbonate materials as a result of landslides on the continental slope likely due to sporadic earthquakes over the past 300,000 years (Puga-Bernabeu et al., 2014; 2019; Webster et al., 2012).

2. Modern sediment distribution

Maxwell (1968; see also Maxwell & Swinchatt, 1970) first recognised the strong cross-shelf (i.e., East to West) partitioning/zonation of sediments (and groups of distinctive sediment facies) and in particular the mixed siliciclastic-carbonate province of the GBR lagoon. Maxwell and Swinchatt (1970) separated the GBR into North-South regions including northern (Torres Strait to ~Cooktown), central (~Cooktown to ~Bowen) and southern (~Bowen to Gladstone) regional groupings. Belperio (1983) recognised the East to West cross-shelf sediment partitioning and proposed three key cross-shelf zones within the GBR lagoon which include: i) the inner shelf (0 to 20 m water depth) characterised by terrigenous sediment deposition, ii) the middle shelf (20 to 40 m water depth) composed of a mixture of palimpsest terrigenous and carbonate sediments (little deposition) and, iii) the outer shelf (>40 m water depth) dominated by carbonate-rich sediments; this terminology has been exclusively adopted in the subsequent literature. Geoscience Australia carried out a more detailed mapping exercise of the seafloor sediment composition of the GBR lagoon (Mathews et al., 2007) where the mud contents largely reflect the distribution of the terrigenous inputs (Figure 4). Finer spatial scale sedimentary studies have focused on sediment characterisation and distribution for areas such as Cape York (~12° S latitude) (Woolfe et al., 1998a), Rockingham-Halifax Bays (Brunskill et al., 2002; Woolfe et al., 2000), Cleveland Bay (Carter et al., 1993), Bowling Green-Upstart Bays (Belperio, 1983; Orpin et al., 2004b) and Keppel Bay (Bostock et al., 2007). All these mapping-based studies highlight that terrigenous sediments are mostly confined to the inner shelf of the GBR and indeed much of the sediment is deposited and retained within the river floodplain, estuaries or in the close vicinity of river mouths (Bannister et al., 2012; Bostock et al., 2007; Lewis et al., 2014; Webster & Ford, 2010).

However, areas on the middle shelf can also be storage grounds for considerable volumes of terrigenous sediment such as in the Whitsunday Island Group (Heap et al., 2002) and, as previously shown, there is continued modern terrigenous sediment flux to the GBR outer shelf (Bostock et al., 2009; Dunbar et al., 2000; Francis et al., 2007). It has been calculated that up to 13% of the late Holocene riverine sediment export is delivered to the Queensland Trough (Francis et al., 2007). In the case of the Whitsunday Island Group, this bank of sediment is interpreted to have been originally delivered to the middle shelf during the sea level transgression period (i.e., period of lower sea level) which has subsequently been reworked and trapped within the complex morphology that is the island archipelago (Heap et al., 2002). Heap et al. (2002) postulate that sediment is still being winnowed from the middle shelf and redeposited within this area where sediment cores from the Nara Inlet (Hook Island) show 3 m of sediment deposition over the past 3,000 years (Heap et al., 2001). As previously stated, the mechanisms for the modern terrigenous sediment delivery to the middle and outer shelfs are unresolved with possibilities including river plumes, nepheloid layers, tidal currents, cyclones and mushroom jets (Francis et al., 2007). Some of these mechanisms will be considered further in the sediment processes and flood plume sections.

The distinct distribution and layering of the Holocene sedimentary sequences within the GBR lagoon has been deciphered from sediment cores and seismic profiling (e.g., Bostock et al., 2007; Carter et al., 1993; Johnson & Searle, 1984; Larcombe & Carter, 1998; Lewis et al., 2014; Orpin et al., 2004b). Seismic profiling of the seafloor recognised a ‘reflector A’ surface that represents the hard Pleistocene substrate exposed during the sea level lowstand, and hence the sedimentary sequences above this reflector represent the most recent deposition during the Holocene transgression and highstand (Johnson & Searle, 1984). The terrigenous-dominated sequences include channel-fill deposits where old river palaeochannels have been infilled with fine-grained sediments; organic-rich mud deposits containing mangrove detritus which represent the period of sea level transgression and – for the inner shelf areas of the GBR lagoon – bay-fill deposits of various compositions laid down during the current sea level highstand (e.g., Bostock et al., 2007; Carter et al., 1993; Johnson & Searle, 1984; Larcombe & Carter, 1998; Lewis et al., 2014; Orpin et al., 2004b). We note that several different sediment facies of the bay-fill sediments have been identified based on grain size distribution measurements (e.g., Orpin et al., 2004b; Woolfe et al., 1998a; 2000) as well as for the coastal sedimentary deposits (e.g., Larcombe & Carter, 1998). The terrigenous sediment delivered from rivers is mostly captured at the coast and fuels progradation (e.g., Belperio, 1983; Bostock et al., 2007) while a large amount of the remaining portion is captured in the eastern sections of sheltered (from the southeast trade winds) north-facing embayments and, over the longer term, accreted back to the coast (e.g., Orpin et al., 2004b; Woolfe et al., 1998a). Sediment burial rates within inshore cores taken from Upstart, Bowling Green and Cleveland Bays reveal a more complex deposition history related to the changing coastal discharge points (i.e., channel avulsion history) of the Burdekin River (Lewis et al., 2014). With the exception of the relatively

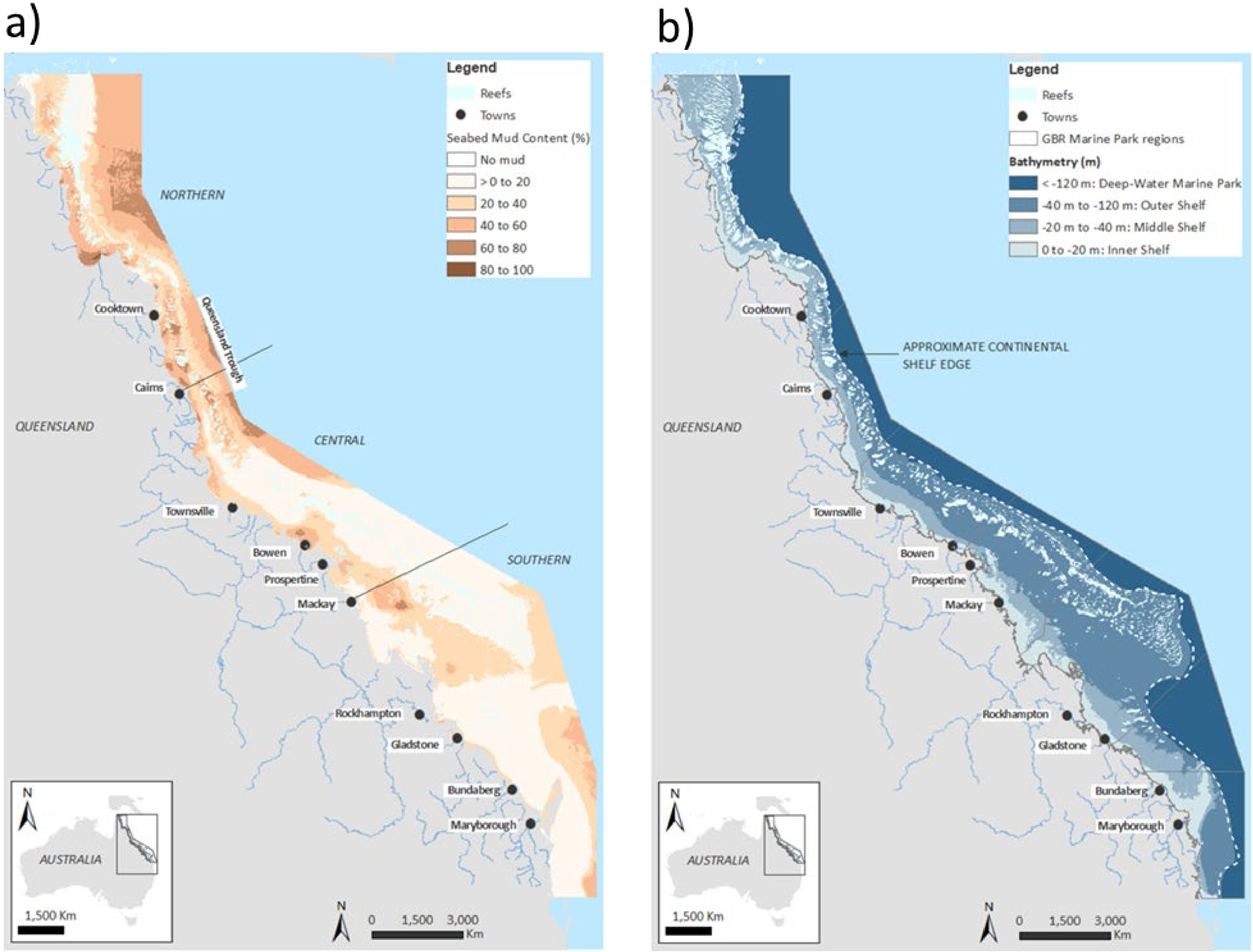


Figure 4. a) Distribution of mud grain size (<63 µm) in the GBR highlighting the northern, central and southern regions (modified from Mathews et al., 2007), b) Main geographical zonation of the GBR including the inner, middle and outer shelf sections on the continental shelf.

thicker sediment deposits within the north facing bays and trapped within island land masses, most ‘bay-fill’ sediment deposits are generally thin units (<2.5 m thick) (e.g., Johnson & Searle, 1984; Orpin et al., 2004b; Woolfe et al., 1998a). Indeed, the ‘reflector A’ surface crops out at the surface of the seafloor at several areas of the middle shelf and some areas of the inner shelf which shows that no deposition has occurred in these parts of the lagoon (Johnson & Searle, 1984; Orpin et al., 2004b).

The dredging of the seafloor to create channel access for shipping and the associated marine disposal of the spoil has the potential to modify sediment ‘bay-fill’ deposits. While considerable dredged sediment have been disposed at different locations within Cleveland Bay (i.e., for Townsville Port) over the years, aerial photograph analysis between 1941 and 1988 shows relatively little change in physical features over this time with the exception of some localised areas such as the Ross River delta (where considerable sand has been dredged from the river mouth), the intertidal and subtidal zones off Shelly Beach-Cape Pallarenda (influences on the seagrass meadows), the Sandfly Creek-Cape Cleveland area and the southwest coast of Magnetic Island (Pringle, 1989). Carter et al. (1993) showed that the main spoil disposal site has been considerably remobilised and redistributed within Cleveland Bay where the remnants of this spoil become well-mixed and incorporated within the upper sedimentary layers on the seafloor which are prone to natural wave-driven resuspension.

Sediment cores reveal that the internal structure of shore-attached, nearshore and inshore coral fringing reefs of the GBR lagoon contain considerable amounts (up to ~60%) of fine-grained terrigenous sediment, and most of these fringing reefs have developed on top of weakly consolidated terrigenous sediments (e.g., Smithers et al., 2006). This not only highlights that these reefs have grown in highly turbid conditions over millennia, but also that they provide a repository for terrigenous sediments. The reefs of the GBR inner shelf that have been studied using percussion cores that capture the internal reef stratigraphy (i.e., ability to recover fine-grained terrigenous sediment) include Pipon Reef (Perry et al., 2017), Lugger Shoal (Perry & Smithers, 2006; Perry et al., 2009); Fantome Island (Johnson & Risk, 1987); Pandora Reef (Roff et al., 2015); Havannah Island (Roff et al., 2015); Paluma Shoals (Browne et al., 2012; 2013a; Johnson et al., 2017; Palmer et al., 2010; Perry & Smithers, 2006; Perry et al., 2008; 2013; Smithers & Larcombe, 2003); Middle Reef (Browne et al., 2012; 2013a; Perry et al., 2012); Nelly Bay (Lewis et al., 2012); Bramston Reef (Ryan et al., 2016a; 2018); Stone Island (Ryan et al., 2016b, 2018); Middle Island (Ryan et al., 2016c, 2018); Keppel Islands (Leonard et al., 2020) and; Hervey Bay (Butler, 2015). Highest terrigenous sediment incorporation into the reef structure generally coincides with the temporal periods of highest vertical reef accretion and declines spatially with distance of the reef from the shore (e.g., Ryan et al., 2018). For example, the Ryan et al. (2018) study of a transect of reef sites in Edgecumbe Bay found the shore-attached reefs (Bramston Reef and Stone Island-South) had terrigenous sediment contents within the reef framework facies in the order of up to 50%, compared to up to 32% at Middle Island and up to 7% at Holbourne Island on the middle shelf. It was unclear whether the terrigenous sediment in the Holbourne Island site was derived from the mainland (riverine) or local sources (i.e., erosion of the high island). In that regard, localised sources of terrigenous sediment can be a more important contributor than regional sediment sources which need to be confirmed with sediment tracing exercises. For example, sediment tracing shows that the Fly River contributes negligible terrigenous sediment to the seafloor surrounding the islands of the Torres Strait (Heap & Sbaffi, 2008).

Studies on the sediment captured within the epilithic algal matrix (EAM: turf macroalgae) on coral reefs show that an appreciable amount of terrigenous sediment can be incorporated within these structures particularly within the shore-attached and inshore reefs. Studies have reported terrigenous contents in the EAM from shore-attached reefs such as Myall Beach, King Reef, Horseshoe Bay (Bowen), Hydeaway Bay, Cape Gloucester (Tebbett et al., 2018) and inshore fringing reefs of the Turtle Islands (Tebbett et al., 2017) and Orpheus Island (Gordon et al., 2016; Latrille et al., 2019; Schlaefer et al., 2021). The loads of sediment captured within the EAM vary spatially across different zones within an individual reef (Gordon et al., 2016), across inshore-offshore gradients (Tebbett et al., 2017; 2018), and even along the coastline of shore-attached reefs (Tebbett et al., 2018). While there is also variability in sediment grain size across these spatial areas, the particles are mostly in the fine to median sand range (i.e., 63 to 500 µm: Tebbett et al., 2017; 2018) and so this implies that the terrigenous sediment incorporated within the EAM is more likely derived from localised (i.e., within/surrounding reef) sources.

3. Sediment composition

The studies on the composition of sediments on the seafloor of the GBR lagoon have focused on various aspects such as physical composition including colour, grain size and mineralogy; sediment sources measured from geochemical tracing and organic biomarkers; nutrient contents and cycling; and trace metal composition. The majority of these parameters reveal distinct cross-shelf sediment partitioning/zonation similar to that described in knowledge area 2: 'Modern sediment distribution'.

The colour of the sediment on the seafloor generally becomes lighter across the inner, middle and outer shelfs due to the increasing contribution of carbonate material to the bottom sediments (Cooper et al., 2007; Hamilton, 2001). Some exceptions include the presence of high silicate sands in some areas and less clear partitioning within Princess Charlotte Bay (Hamilton, 2001). The composition of the inner shelf sediments are mostly dominated by fine grain size (<63 µm) (Bannister et al., 2012; Hamilton, 1999). The grain size and mineralogy of the sand fraction (>63 µm) along the 10 m isobath generally shows increasing maturity (i.e., finer and greater quartz contents) when the areas are divided into the influences of major riverine inputs and also where localised complexities (i.e., north-facing embayments and continental islands) are considered (Lambeck & Woolfe, 2000). Tracing of sediments within river flood plumes shows that the <20 µm mineral fraction travels furthest in the GBR lagoon (Bainbridge et al., 2012; 2018; 2021; Bartley et al., 2014) and there is a preferential transport of basaltic soils or expandable clays within the flood plumes (Bainbridge et al., 2016; Douglas et al., 2005; Lewis et al., 2020; Smith et al., 2008).

Most terrestrial organic matter and associated biomarkers discharged to the GBR are confined to the sediments on the inner shelf of the lagoon (e.g., Alongi & McKinnon, 2005; Currie & Johns, 1989; Johns et al., 1994). Very little of the organic matter is exported past the coastal zone except during very large/extreme flood events (Alongi & McKinnon, 2005). It has been calculated that most terrestrial organic matter is quickly degraded by algal and microbial respiration where approximately 1% of combined river and marine organic carbon is preserved within across-shelf sedimentation and around 3% of river and mangrove organic carbon is preserved within a small wind-protected embayment of Hinchinbrook Island (Brunskill et al., 2002). Other calculations support that the vast bulk of benthic carbon delivered to the GBR lagoon (>89%) is mineralised with only 4-8% trapped and buried largely within mangroves and tidal flats (Alongi & McKinnon, 2005). Microbial communities in coastal waters and within unconsolidated sediments have the ability to metabolise nutrients equivalent to the entire dissolved and particulate nutrient load delivered from the land (Alongi & McKinnon 2005). Studies specifically focused on organic carbon and total nitrogen similarly show that 81 to 94% and 74 to 94%, respectively was mineralised following deposition on the seafloor (approximately 50% of the total nitrogen input was subsequently denitrified) while 6-19% of organic carbon and 8-20% of total nitrogen is buried (Alongi et al., 2007). The differences in sedimentation, mineralisation and burial rates are correlated with water depth and to the proximity and discharge of river basins (Alongi et al., 2007). Ullman and Sandstrom (1987) suggested that inner shelf sediments are a source of nitrogen and silica but a sink for phosphorus. The assertion is supported by C:N:P ratios of the sediments which suggest nitrogen is limited due to denitrification while there is preferential retention of phosphorus due to binding with iron and manganese oxyhydroxides (Alongi, 1989).

While the concentration of total phosphorus in the sediments on the seafloor is fairly homogeneously distributed across the GBR shelf, solid phase extraction analysis of the phosphorus in the sediments (i.e., its bioavailability) varies greatly (Monbet et al., 2007). There are two main pools of phosphorus which reside in the sediment including the labile (or easily extractable/bioavailable) organic phosphorus form and the more recalcitrant authigenic form (e.g., apatite minerals, fish debris and phosphorus associated with calcium carbonate). The sediments of the middle and outer shelfs are dominated by the recalcitrant authigenic forms of phosphorus and upwelling on the outer shelf is likely the most important source of bioavailable phosphorus in this area (Monbet et al., 2007). The labile organic phosphorus forms in inner shelf sediments of the GBR lagoon are generally reworked to authigenic phosphorus forms (i.e., remobilisation of labile P in sediment into the water column). Tracing analysis of the terrestrial phosphorus from the inner and middle shelf sections of the GBR lagoon show that it is predominantly sourced to fine-grained basalt soils which are exported >20 km from the coast (McCulloch et al., 2003). The desorption/mineralisation of the labile organic forms of phosphorus occur over longer timeframes (months to years) and are likely driven by sediment anoxia (McCulloch et al., 2003).

Trace metal concentrations within the benthic sediments generally correlate with either the siliciclastic (e.g., aluminium, iron, potassium and silicon) or the carbonate (e.g., strontium, calcium, phosphorus and magnesium) end members and as such display the clear inner-outer shelf partitioning as previously described (e.g., Haynes & Kwan, 2002; Orpin et al., 2004b; Ward et al., 1995). Heavy metals such as copper, zinc, lead, nickel and cadmium have been measured in elevated concentrations (i.e., relative to the offshore bay-fill sediment) in seafloor sediment deposits around shipping ports and commercial harbours (Angel et al., 2010; Brady et al., 1994; Doherty et al., 2000; Esslemont, 2000; Haynes & Loong, 2002; Reichelt & Jones, 1994).

4. Sediment processes

The distinct partitioning/zonation of the inner, middle and outer shelf sediments shown in areas of knowledge 2 and 3 is thought to be primarily controlled by a combination of wind-driven currents and waves associated with the SE trade winds (Orpin & Woolfe, 1999; Woolfe et al., 2000) and from strong (>130 cm s^{-1}) shore-parallel currents that develop during periods of tropical cyclones (Larcombe & Carter, 2004). The shelf bathymetry governs the seafloor sediments that are able to be resuspended from wind-driven waves with ‘frequent resuspension’ occurring at water depths <15 m (maximum resuspension depth ~22 m: Orpin et al., 1999). Indeed, ‘sediment un-mixing’ modelling revealed that the resuspension and redistribution of the poorly sorted bay-fill sediments on the inner shelf during storms/cyclones was able to account for grain size budgets of key coastal (and moderately-well sorted) sedimentary deposits such as beaches, cheniers, mangroves and tidal flats (Orpin & Woolfe, 1999).

Tropical cyclones not only cause the strong shore-parallel currents, but also likely coincide with higher riverine terrigenous sediment loads due to the elevated catchment rainfall as well as remobilisation of middle shelf sediments and subsequent cross-shelf transport to both the inner and outer shelfs (Larcombe & Carter, 2004). Important insights on sediment dynamics (inputs, mobilisation and deposition) during and following the passage of a tropical cyclone were provided from a range of studies that occurred before and after Tropical Cyclone Winifred which crossed the coast near Innisfail in 1986. These studies showed that terrestrial inputs were largely confined to the inner shelf with most plant detritus deposited within 2 km from the river mouth and no further than 15 km offshore (Gagan et al., 1987). While terrestrially-derived hydrocarbons increased in inner shelf sediments following the cyclone, they remained at trace concentrations in middle shelf sediments (Sandstrom, 1988). The cross-shelf sediment composition including grain size, mineralogy, carbonate content and carbon isotope values were similar before and after the cyclone which suggests that storm beds largely formed from resuspension of *in situ* material with the shoreward transport of mud (Gagan et al., 1988). The cyclone caused a large resuspension event across the GBR shelf, although different sedimentary processes were in operation during and following the cyclone. These included the formation of an inner shelf (i.e., <20 m water depth) storm bed formed from terrigenous sediment from river plumes, *in situ* resuspension of inner shelf sediments and resuspension and transport of middle shelf sediments to the inner shelf bed; this middle shelf source was thought to contribute between 10 and 30% to the inner shelf storm bed (Gagan et al., 1990). While there was evidence for the resuspension and transport of sediment from the middle shelf to the inner shelf during Tropical Cyclone Winifred (Gagan et al., 1990), there was evidence for considerable resuspension and offshore movement of terrigenous sediment from Lugger Shoal following Tropical Cyclone Yasi that crossed the coast at Mission Beach in 2011 (Perry et al., 2014).

Following Tropical Cyclone Winifred, it was observed that mud-sized particles at concentrations of 3 to 5 mg L^{-1} throughout the water column were still settling five days after the coastline crossing of the cyclone (Carter et al., 2009). The inner shelf bed of shell lag and/or normally graded bed of terrigenous sand/mud formed largely as a result of wind-wave resuspension and deposition of sediments (Carter et al., 2009) which disturbed the upper ~5 cm of the seafloor (Gagan et al., 1990). In contrast, >6.9 cm of the seafloor was disturbed on the middle shelf (Gagan et al., 1990) as a result of the strong (1.0 to 3.0 m

s^{-1}) shelf-parallel currents produced from the cyclone that produced shelf-longitudinal bedforms including megaripples and ribbons of quartzose and bioclastic sand (Carter et al., 2009). The storm bed on the inner shelf remained well-preserved >1 year after the cyclone, although the storm bed on the middle shelf was strongly bioturbated 3 months following the cyclone and was completely reworked 1 year after the cyclone (Carter et al., 2009; Gagan et al., 1988). A study from Rib Reef also highlighted the dominance of bioturbation on the middle shelf where the top 125 cm of sediment was thoroughly mixed on a sub-centennial scale (Kosnik et al., 2007).

It is recognised that tidal, wind-driven and three-dimensional (3D) currents interplay with the wind-driven sediment resuspension to transport fine sediments predominantly northward; however, cross-shelf tidal currents as well as complex 3D currents created from periods of onshore winds can also move sediment offshore from the inner to middle shelf (Orpin et al., 1999; Wolanski et al., 2008). Wolanski and Spagnol (2000) showed that a nepheloid layer (i.e., sediment-rich bottom water) developed in waters off the coast of Cairns which facilitated movement of sediment across the inner shelf and perhaps reaching the middle shelf (see also Wolanski et al., 2003). Woolfe et al. (2000) showed that bottom return currents driven by wind-waves are capable of transporting sediment offshore but, transport was likely limited to within the inner shelf zone (i.e., within the 20 m isobath).

The findings of modern terrigenous sediment export to the outer shelf discussed in area of knowledge 1 ‘Geological timescale variability’ (e.g., Bostock et al., 2009; Dunbar et al., 2000; Francis et al., 2007) is also supported by the pollen evidence provided by Moss et al. (2005). That study showed that the pollen in the core top of Ocean Drilling Program site 820 was consistent with modern pollen contained within the Barron and Russell Mulgrave River estuaries. Interestingly, the pollen composition in the core tops from Grafton Passage was different, which suggests that while modern pollen is being transported to the outer GBR it is not transported through Grafton Passage as previously thought (Moss et al., 2005).

Large riverine flood plumes can also transit across the shelf and occasionally deliver terrigenous sediments to both the middle and outer shelfs of the GBR (e.g., Devlin et al., 2012; Lewis et al., 2020; Patricio-Valerio et al., 2022). Conversely, studies have shown that riverine terrigenous sediment can be resuspended within the estuary and transported inland due to stronger flood tides (relative to ebb) for the rivers of the GBR catchments that contain large estuaries (i.e., the Fitzroy and Normanby) (e.g., Bryce et al., 1998; Crosswell et al., 2020; Radke et al., 2010).

The sedimentology literature is embedded with the assertions that wind-driven wave resuspension of sediment on the seafloor (i.e., wave induced bed stress) is the dominant driver of turbidity fluctuations in the GBR lagoon, while the influence of flood plumes on turbidity regimes is comparatively a minor and short-term contributor (e.g., Larcombe et al., 1995; Larcombe & Woolfe, 1999b; Macdonald et al., 2013; Orpin et al., 1999; Orpin & Ridd, 2012). Indeed, turbidity logger data (discussed further in area of knowledge 6) from the inner shelf of the GBR lagoon are highly correlated with wind speed and significant wave height, indicating that waves were the key driver of turbidity (e.g., Browne et al., 2013b; Larcombe et al., 1995; Orpin et al., 2004a). This led Larcombe and Woolfe (1999b; see also Orpin & Ridd, 2012) to conclude that there was enough sediment on the seafloor to resuspend (i.e., not sediment limited) and that an increase in sediment supply (i.e., sediment loads) from rivers is unlikely to alter the sedimentation or turbidity regimes at most inshore coral reefs of the GBR. Reefs to the seaward side of the inshore ‘terrigenous sediment wedge’ (termed the ‘feather edge’) were thought to be the reefs potentially susceptible to increased riverine sediment loads as there was less sediment on the seafloor to suspend at such sites (Larcombe & Woolfe, 1999b; Orpin & Ridd, 2012). Much of the turbidity logger data used to derive these assertions were based on relatively short-term records (<1 month) or, alternatively, from relatively drier seasons in terms of river discharge (e.g., Macdonald et al., 2013; Orpin et al., 1999). Renewed investigations using longer-term (>3 years) turbidity time series which coincide with moderate to large discharge seasons show a subtle but clear influence of river discharge on the inshore GBR when the wave height, wave period and tidal range were statistically normalised from the record (Fabricius et al., 2013; Lewis et al., 2020). Subsequent remote sensing data of photic depth variability in the GBR lagoon (discussed further in area of knowledge 7) confirm this river discharge influence across a larger spatial scale that includes the inner and middle shelf (Canto et al., 2021; Fabricius et al., 2014; 2016). It is proposed that newly delivered riverine sediments do not immediately settle and compact on the seafloor but rather form a liquefied veneer that can be more easily resuspended and hence more greatly influence turbidity regimes in the months following large riverine inputs (i.e., years with above average river discharge) (e.g., Bainbridge et al., 2018; Fabricius et al., 2016; Lewis et al., 2014; Margvelashvili et al., 2018).

Nearshore reefs of the GBR lagoon have thrived under relatively high turbidity levels but require low levels of net sediment deposition (e.g., Browne et al., 2012; 2013a; Larcombe & Woolfe, 1999a; Woolfe et al., 1998b). One of the key requirements for coral reefs to initiate is a consolidated and stable substrate that has little net sediment deposition (e.g., Larcombe & Woolfe, 1999a; Woolfe et al., 1998b). Sediment budgets at both regional (e.g., Woolfe et al., 1998b) and reef-specific scales (Browne et al., 2012; 2013a) highlight the limited terrigenous sediment deposition within most sections of the inshore GBR lagoon which host shore-attached and nearshore reefs. For example, over 81% of the sediments delivered to Middle Reef and Paluma Shoals were promptly transported off the main reef structure; the remaining sediment supports relatively high accretion rates (Browne et al., 2013a). On the fringing reef surrounding High Island, a study showed that storms had the ability to resuspend sediment at water depths <5.5 m on the leeward side compared to ~12 m on the windward side of the island (Wolanski et al., 2005). This 'storm resuspension depth' was found to be critical to coral reef development as the substrate below these depths coincided with large sedimentation rates and lacked live coral (Wolanski et al., 2005). A recent study highlights the role of algal turfs on reef sediment budgets where over a 12-day period, the currents flowing over a reef (Orpheus Island) carried a similar amount of sediment to what was stored in the algal turfs (Schlaefer et al., 2022). While coral reefs on the inner shelf of the GBR provide some repository for terrigenous sediments, it has been shown that their seagrass counterparts do not trap considerable amounts of sediment or nutrients with the possible exception of high biomass meadows of *Zostera capricorni* (Mellors et al., 2002).

Sediment processes can also have an influence on nutrient concentrations in the water column. Walker (1981) found that relatively elevated levels of phytoplankton/chlorophyll *a* occurred during periods when secchi disc depth decreased (i.e., times of sediment resuspension) suggesting that either nutrients were released from bottom sediments to fuel algal blooms or that benthic microalgae became suspended into the water column. Indeed, resuspension of sediment during storm/tropical cyclone events can considerably increase the concentration of nitrogen in the water column (e.g., Ullman & Sandstrom, 1987). The interstitial waters of bottom sediments contribute on average 13 and 24% of the nitrogen and phosphorus requirements, respectively of the shelf phytoplankton (Alongi, 1989). A later study on the northern section of the GBR by Lourey et al. (2001) similarly found that that microbial cycling of nutrients contained within seafloor sediments was critical to supply on average 11% and 22% of the nitrogen and phosphorus needs, respectively for phytoplankton production. Interstitial phosphorus, dissolved organic carbon and dissolved organic nitrogen concentrations displayed differences across and along the shelf during the wet season while the other nutrients showed no significant differences in concentration or flux across the sediment-water interface despite the differences in sediment composition (Lourey et al., 2001). The lack of differences in interstitial nutrient concentrations across and along the shelf is thought to be from either longshore sediment transport, rapid processing/uptake of nutrients which mask any temporal trends or, alternatively sediment resuspension/bioturbation (Lourey et al., 2001). Examination of the bioavailable nitrogen concentrations in flood plumes from the Burdekin, Tully and Johnstone Rivers reveal considerable differences in the amount of potential contributions to riverine nitrogen inputs. The flood plumes from the Burdekin River showed relatively high contributions to the bioavailable nitrogen pool contributing between 9% and 30% of the dissolved inorganic nitrogen load through ammonium desorption or mineralisation of particulate nitrogen (bacterial/fungal processing) while there was less bioavailability of the nitrogen in the plumes examined from the Tully and Johnstone Rivers (Garzon-Garcia et al., 2021). This work has also highlighted the rapid desorption (~immediate) and mineralisation (days to weeks) of nitrogen in the GBR lagoon (Garzon-Garcia et al., 2021). This evidence for the rapid processing of particulate nitrogen coupled with evidence described by Alongi and McKinnon (2005) and Alongi et al. (2007) in the 'Sediment composition' section suggests that the residence time for particulate nitrogen may be in the order of days to months rather than years to decades for particulate nutrients as suggested by Brodie et al. (2012b). In contrast, the insights on particulate phosphorus processing by McCulloch et al. (2003: months to years) more closely aligns with the estimates presented in Brodie et al. (2012b).

Estuaries, in particular, are highly productive zones where much of the nutrient cycling occurs through processes such as desorption, mineralisation, denitrification, resuspension and burial. For example, in the Fitzroy estuary the 'zone of maximum resuspension' near the mouth of the river is where considerable sediment volumes are resuspended during flood tides which, in turn, release dissolved nutrients (sourced from terrestrial sediments) into the water column (Radke et al., 2010). The concentrations of carbon and other nutrient (i.e., nitrogen and phosphorus) contents of the seabed sediments were 40 to 65% lower than those of the parent sediments/soils in the catchment which highlights that desorption and/or degradation (i.e., microbial mineralisation) are significant processes that transform nutrients within the estuary (Radke et al., 2010). Most organic matter in the surface sediments of the estuary is refractory, and approximately 30% and 50% of total nitrogen and total phosphorus respectively, is buried in the Fitzroy River estuary (Radke et al., 2010). Similar processes have also been demonstrated for the Normanby estuary where, during the dry season, sediments resuspended during flood tides are carried landwards up the estuary, deposited on floodplains and subjected to the denitrification process (Crosswell et al., 2020). In the wet season, bioavailable nutrients are rapidly transformed/cycled within the estuary due to the resuspension of benthic algae (Crosswell et al., 2020).

5. Flood plume measurements

The changing terrigenous sediment and particulate nutrient composition of riverine flood plume waters have been examined in many studies throughout the estuarine salinity gradient as the freshwaters progressively mix with the saline seawater. The studies show that, once the flood plume waters are exported from the coast and begin mixing with seawater, the concentrations of suspended particulate matter (SPM) and particulate nutrients decline considerably (e.g., Bainbridge et al., 2012; 2021; Devlin & Brodie, 2005; Howley et al., 2018; Livsey et al., 2022). The initial SPM (and associated particulate nutrient) concentrations of freshwater discharge can vary by several orders of magnitude depending on the stage of flow and the river itself. On most accounts, the SPM concentrations generally fall to <10 mg L^{-1} by the 10 PSU zone before more gradually declining over the remainder of the mixing zone (e.g., Bainbridge et al., 2012; 2021; Devlin & Brodie, 2005; Howley et al., 2018). Some exceptions have been reported such as in the Daintree River estuary where SPM concentrations increased within the estuarine zone located upstream from the coast likely due to either channel scour or elevated sediment inputs from land use contributions from the lower catchment area (Davies & Eyre, 2005). However, these instances exclusively occur when the estuarine mixing zone of the river is located upstream from the coast. In any case, the trends in the data show that much of the sediment is deposited in the vicinity of the river mouth, particularly for the rivers with the highest initial SPM concentrations such as the Burdekin and Fitzroy (e.g., Bainbridge et al., 2012; 2021; Devlin & Brodie, 2005). This is in turn, supported by sediment budgets constructed (as previously discussed) for these rivers (e.g., Bostock et al., 2007; Lewis et al., 2014). The rapid settling of suspended sediments exported from the rivers is fostered through various flocculation processes (Bainbridge et al., 2012; 2021; Livsey et al., 2022), although neutrally buoyant (low density) large floc aggregates (>1000 µm in diameter; also known as muddy marine snow) which consist of mineral and organic components can travel large distances (~100 km) within the larger flood plumes (Bainbridge et al., 2012). Analysis of the SPM material shows that the mineral particles are exclusively <20 µm and that the composition of the sediment becomes more organic-rich (with abundant phytoplankton) as the plume transits further out into the GBR lagoon (Bainbridge et al., 2021).

While some of the earlier flood plume monitoring data documented that SPM concentrations were highest within the upper few metres of the water column, subsequent studies have reported considerable variability of SPM concentrations through the water column including higher concentrations at the surface (e.g., Moran et al., 2022); well-mixed SPM throughout the water column (e.g., Bainbridge et al., 2012; Gruber et al., 2020); and concentrated as a nepheloid layer in the lower reaches of the water column (Gruber et al., 2020; Wolanski et al., 2008; Wu et al., 2006) (reviewed in Lewis et al., 2020). The consideration of the dispersal of SPM within flood plumes and in particular, instances where the plumes are well-mixed, have important implications for estimates of the terrigenous export of SPM that may be delivered to the middle and outer shelfs of the GBR (e.g., Lewis et al., 2020). While the exposure of riverine flood plumes is most frequent in the inshore GBR, the plumes occasionally move to the middle and outer GBR, with the frequency depending on the size of the river discharge and corresponding wind conditions as well as the width of the continental shelf (Devlin et al., 2012; Gruber et al., 2020).

6. Turbidity/light logger measurements

Turbidity, water clarity (i.e., secchi disc depth) and light measurements are generally well-correlated with each other and have been used to demonstrate the considerable spatial and temporal variability within the GBR lagoon (e.g., Cooper et al., 2007; 2008; Fabricius et al., 2013; Gruber et al., 2020; Hamilton, 1994; Larcombe et al., 1995; Moran et al., 2022; Schaffelke et al., 2012; Walker, 1981). In particular, turbidity loggers have had a long history of use to illustrate the spatial and temporal variability of suspended sediment concentrations in the inner shelf of the GBR (e.g., Fabricius et al., 2013; Jones et al., 2020; Larcombe et al., 1995, 2001; Lewis et al., 2020; Luter et al., 2021; Macdonald et al., 2013); the key drivers of turbidity (Browne et al., 2013b; Hamilton, 1994; Orpin et al., 2004a: note these have been discussed in the 'Sediment processes' section); various sediment processes and transport mechanisms (e.g., Wolanski & Spagnol, 2000; Wolanski et al., 2003; 2005; 2008: note these have been discussed in the 'Sediment processes' section); and the influence of river discharge on turbidity/light regimes (e.g., Fabricius et al., 2013; Lewis et al., 2020; Schaffelke et al., 2012).

On a spatial scale, the turbidity loggers have shown the presence of distinct water quality gradients that exist across inshore-offshore transects and with increasing distance from river mouths. This includes data from inshore reefs on either side of the inshore terrigenous sediment wedge such as Paluma Shoals (values up to 175 NTU) and Phillips Reef (<15 NTU) (Larcombe et al., 2001) and the distinct gradient that exists in Cleveland Bay (e.g., Jones et al., 2020; Larcombe et al., 1995; Luter et al., 2021). In general, the sites in the sheltered eastern part of Cleveland Bay where much of the terrigenous sediment is deposited (e.g., Orpin et al., 2004b) have the highest turbidity readings (i.e., seagrass meadow site up to ~50 NTU) followed by the nearshore reefs (i.e., Virago Shoal up to ~40 NTU), and an inshore-offshore gradient is apparent for the fringing reefs hosted within the embayments of Magnetic Island (i.e., Picnic Bay ~20 NTU; Geoffrey Bay ~15 NTU; Florence Bay ~ 0 NTU) (Jones et al., 2020; see also Larcombe et al., 1995).

The clear spatial gradients are perhaps best expressed using the statistical summaries of the Marine Monitoring Program (MMP) where almost continuous data (some gaps in data due to instrument fouling/failure) exist for several years (up to 16 years) and cover instances of major resuspension events and major river discharge events. The loggers have been deployed 5 m below the water surface from various sites across four Natural Resource Management (NRM) regions, and data are downloadable via the Australian Institute of Marine Science website (www.aims.gov.au). The data have been published in various journal articles (Fabricius et al., 2013; Schaffelke et al., 2012) and technical reports (e.g., Gruber et al., 2020; Moran et al., 2022). Overall, the statistical summary reveals that the sites nearest to the river mouths and often in the shallowest water depths have the highest turbidity values for the mean, 10th, 50th and 90th percentiles and decline with increasing distance from the major river mouth (Table 8; D90 plot in Figure 5). There is also a gradient in the range between the D10 and D90 values which decrease from inshore to offshore (Table 8). It is difficult to ascertain spatial trends in the turbidity data to compare each NRM region without more detailed statistical analysis, although Figure 5 suggests that the D90 values for the Mackay Whitsunday and Fitzroy regions may be higher relative to distance from river mouth compared to the data from the Wet Tropics and Burdekin regions.

On a temporal scale, the turbidity loggers display the highest concentrations during periods of either elevated river discharge (e.g., Fabricius et al., 2013; Lewis et al., 2020; Schaffelke et al., 2012; Wolanski et al., 2008) or with periods of elevated resuspension driven by wind speed and significant wave height (see 'Sediment processes' section; e.g., Jones et al., 2020; Larcombe et al., 1995; Lewis et al., 2020; Orpin et al., 2004a). Orpin and Ridd (2012) argued that periods of elevated wave-driven resuspension also coincided with the periods of elevated river discharge and, using the time series presented by both Wolanski et al. (2008) and Cooper et al. (2008), suggested that peak turbidity levels measured by the logger often preceded the peak of the adjacent river discharge. Indeed, turbidity values measured by the loggers off the Tully River were higher than those measured in the end of river discharge which suggested that wave-driven resuspension was the dominant process that drove peak turbidity levels (Orpin & Ridd, 2012). Fabricius et al. (2013) has subsequently statistically accounted for wave/tide resuspension and shown that at any given wave height, wave period and tidal range, the turbidity was significantly affected by river flow and rainfall. The analysis showed that across the reefs, turbidity was between 5 and 37% lower in weeks with low rainfall/river discharge, and a distinct dry-wet season trend was also evident in the data (Fabricius et al., 2013). At sites where long-term mean turbidity was >1.1 NTU, turbidity was, on average, 43% lower 250 days into the dry season compared to at the start of the dry season (Fabricius et al., 2013). For sites where long-term turbidity means were <1.1 NTU, the turbidity returned to low levels within weeks following considerable river flows (Fabricius et al., 2013). Similar relationships to those reported by Fabricius et al. (2013) were also found by Lewis et al. (2020) and inter-annual variability in regular monitoring of water clarity parameters such as SPM and secchi disc depth is also evident in the MMP (e.g., Gruber et al., 2020; Moran et al., 2022).

Table 8. Statistical summary of the turbidity logger data produced through the Marine Monitoring Program (e.g., Gruber et al., 2020; Moran et al., 2022). The D10, D50 and D90 represents the 10th percentile (i.e., 10 percent of the data falls below this concentration), 50th percentile (i.e., median value) and 90th percentile (i.e., 90 percent of the data falls below this concentration) values, respectively.

Site/Station	Region	Length of record	Distance from major river of influence (km)	D10 (NTU)	D50 (NTU)	D90 (NTU)	Mean NTU
BUR-13	Burdekin	22/03/2015 to 19/02/2023	7	1.3	5.0	15	7.5
Geoffrey		7/10/2007 to 19/02/2023	110	0.76	1.4	4.5	2.3
Pandora		9/10/2007 to 20/02/2023	170	0.55	0.98	2.3	1.4
Pelorus		9/02/2007 to 20/02/2023	180	0.40	0.66	1.2	0.79
FTZ6	Fitzroy	3/02/2021 to 14/02/2023	8	5.1	15	40	19
Pelican		4/10/2007 to 19/03/2015	29	0.48	1.9	14	5.3
Humpy		3/10/2007 to 10/05/2015; 5/02/2021 to 14/02/2023	34	0.30	0.56	2.2	1.1
Barren		3/10/2007 to 12/05/2015; 2/06/2021 to 13/02/2023	45	0.15	0.27	0.78	0.46
WHI-6	Mackay Whitsunday	7/02/2021 to 16/02/2023	6	2.0	3.5	12	5.5
WHI-7		11/07/2015 to 7/02/2021	20	1.3	3.3	9.6	4.6
Seaforth		6/03/2015 to 16/02/2023	40	0.82	1.4	3.0	1.8
Pine		5/10/2007 to 25/10/2022	50	0.82	2.1	5.7	2.9
Daydream		6/10/2007 to 18/09/2014	65	0.77	1.7	4.5	2.3
Double Cone		6/10/2007 to 17/02/2023	90	0.70	1.2	2.7	1.5
RM10	Wet Tropics	18/02/2015 to 10/12/2022	2	0.91	2.7	9.6	4.2
TUL-10		17/02/2015 to 21/02/2023	2	1.4	3.3	8.7	4.4
Snapper		14/10/2007 to 4/02/2014	4	0.77	1.3	5.3	2.4
High		11/10/2007 to 24/12/2022	8	0.49	0.83	2.0	1.2
Russell		10/10/2007 to 23/02/2023	13	0.37	0.61	1.4	0.87
Dunk		17/10/2007 to 21/02/2023	15	0.77	1.3	7.8	3.0
Fitzroy		12/10/2007 to 28/12/2022	34	0.49	0.79	1.7	1.1

It has been well-recognised that the conversion of turbidity values to suspended sediment concentrations can be complicated and will vary from site to site with scaling factors (i.e., NTU × c = suspended sediment concentration) varying from 1 to 4 (Macdonald et al., 2013; Orpin & Ridd, 2012). It has also been acknowledged that zero point errors in turbidity calibrations can induce uncertainties of up to 2.5 mg L^{-1} on measurements, and hence the instruments have particular difficulty measuring low level suspended sediment fluctuations within the lower turbidity range (Macdonald et al., 2013). This is unfortunate as studies have shown that relatively small changes of SPM concentrations in the water column can greatly impact water clarity (i.e., an increase of 1 mg L^{-1} can reduce secchi disc depth by half) (Lewis et al., 2020). Cooper et al. (2008) also found that 94% extinction of light occurs at values as low as 5 NTU and that prolonged turbidity >3 NTU leads to sublethal stress on corals, while turbidity at >5 NTU corresponds to severe coral stress. A study from Middle Reef showed that the total annual variation in irradiance (light attenuation) at this site is predominantly driven by suspended solids (74-79%), followed by clouds (14-17%) and tides (7-10%) (Anthony et al., 2004). Recent studies have highlighted the importance of the quality of light on photosynthesis efficiency. Indeed, while the quantity of light declines under clouds, the quality of usable light spectra (mainly in the blues) remained unchanged; in contrast both the quantity and quality of usable light decreases when suspended sediments in the water column are elevated (Jones et al., 2020).

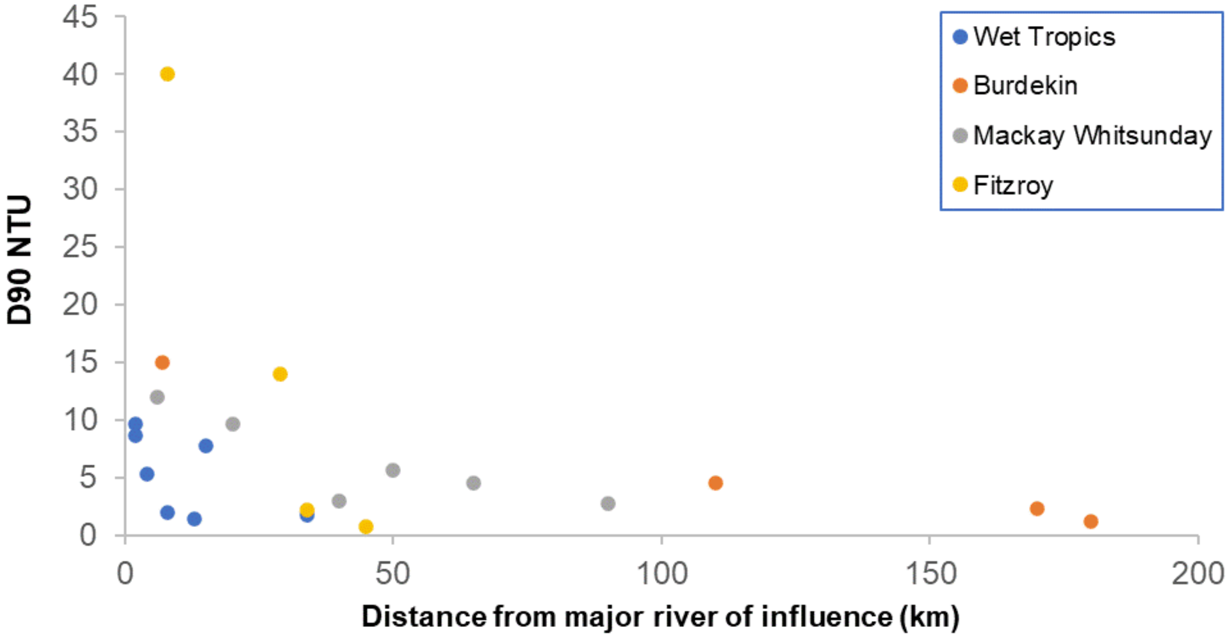


Figure 5. Plot of the Marine Monitoring Program turbidity logger D90 (i.e., 90th percentile) values (NTU) across inshore-offshore riverine gradients of four GBR Natural Resource Management regions (e.g., Gruber et al., 2020; Moran et al., 2022).

7. Remote sensing

Over the past decade, there has been increasing use of satellite remote sensing applications to examine the dispersal and extent of riverine flood plumes in the GBR lagoon (e.g., Ametistova & Jones, 2005; Brodie et al., 2010; Patricio-Valerio et al., 2022); the main drivers of light attenuation in riverine flood plumes (e.g., Petus et al., 2018); and the spatial and temporal variability in photic depth and its causes (Canto et al., 2021; Fabricius et al., 2014; 2016; Weeks et al., 2012). The earlier studies recognised the application of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery to support the field measurements that SPM concentrations in riverine flood plumes decline quickly in the 0 to 10 PSU salinity zone and to highlight that much of the riverine terrigenous sediments are deposited in the vicinity of river mouths (e.g., Ametistova & Jones, 2005; Brodie et al., 2010). Later studies have begun to investigate the next generation of satellites such as Sentinel (e.g., Moran et al., 2022) and Himawari-8 (Patricio-Valerio et al., 2022) which provide improved spatial resolution imagery. For example, Patricio-Valerio et al. (2022) produced a calibrated algorithm to track SPM concentrations using the Himawari-8 satellite to show concentrations >20 mg L^{-1} impinged over the middle and outer shelfs during the 2019 Burdekin flood event.

Satellites have also been used to examine spatial and temporal variability in light attenuation or photic depth and its causes across the GBR lagoon. Petus et al. (2018) used MODIS satellite imagery colour classes calibrated with *in situ* field measurements to show that light attenuation in riverine flood plumes was predominantly caused by SPM and colour dissolved organic matter.

Another important development is the correlation of satellite imagery outputs with secchi disc depth measurements to produce an algorithm to chart the variability of photic depth over large spatial areas and over the period of the MODIS imagery (from 2002) (Weeks et al., 2012). The wave/tide normalised photic depth outputs (i.e., accounting for the wave-tide driven effects of resuspension similar to what was performed in the Fabricius et al. (2013) study on the turbidity logger data) show a significant relationship with river discharge for certain areas of the inner and middle shelfs (Fabricius et al., 2014; 2016). The relationship was much weaker near the chronically turbid coast and for the outer shelf. Importantly, the data show that a significant reduction in photic depth lasting for up to eight months in those inner and middle shelf areas offshore from the Burdekin River occurred for the years that had larger floods over the 2002 to 2012 period (Fabricius et al., 2014). This research was expanded to include the whole GBR lagoon which produced similar findings, although the relationship between the wave/tide normalised photic depth and river discharge was strongest for the inner and middle shelf areas between latitude 14.5 and 19.0° S; here significant reductions in photic depth during the large river discharge years lasted up to six months (Fabricius et al., 2016). Most recently, this approach has been applied using satellite data collected over a 17-year period (2002 to 2019) to develop a benthic PAR index (Canto et al., 2021). This research continues to show the strong spatial and temporal variability across the GBR lagoon and its relationship with river discharge and associated sediment loads (Canto et al., 2021).

8. Modelling

The modelling of sediments in the GBR lagoon extends from studies examining certain sediment processes such as the ability of currents induced by island wake upwelling to resuspend bottom sediments (Blaise et al., 2007; White & Deleersnijder, 2007); models of sediment loading to highlight spatial and temporal variability of sediment exposure/risk from flood plumes (Gruber et al., 2020; Moran et al., 2022; Waterhouse et al., 2017); sediment transport, deposition and budget modelling for certain rivers and embayments (Delandmeter et al., 2015; Lambrechts et al., 2010; Margvelashvili et al., 2006; Wolanski et al., 2021); and eReefs modelling of the influence of river loads on the variability in SPM concentrations, secchi disc depth and benthic PAR for the whole GBR lagoon (Baird et al., 2021). The eReefs modelling also has the capacity to examine broader sediment dynamics such as the transport and fate of different grain size fractions delivered from the rivers (Margvelashvili et al., 2018). The modelling capacity has improved with increasing computer power and increasing availability of field measurement and satellite data that help to refine algorithms that describe sediment processes as well as to validate the confidence of model outputs. Examples include the refining of the algorithm that better accounts for the strong upwelling around island wakes to highlight their ability to resuspend sediment (Blaise et al., 2007; White & Deleersnijder, 2007); a new equation developed within the SLIM model to better describe wave-induced bed liquefaction processes (Lambrechts et al., 2010); and the incorporation of a finer sediment grain size ‘dust’ fraction (i.e., ‘fluff’ particles) within the eReefs model platform to better account for the sediment that is transported longer distances in flood plumes (Margvelashvili et al., 2018). The loading/exposure mapping show that the highest exposure of anthropogenic sediment occurs within the inner GBR shelf area (Figure 6) which supports the findings from the eReefs model (Gruber et al., 2020; Moran et al., 2022; Waterhouse et al., 2017).

The two prominent platforms to model sediment in the GBR lagoon include SLIM (e.g., Delandmeter et al., 2015; Lambrechts et al., 2010; Wolanski et al., 2021) and eReefs (Baird et al., 2021; Margvelashvili et al., 2018). The SLIM platform has been used to calculate more local to regional-scale sediment budgets such as for the Torres Strait (Wolanski et al., 2021), Cleveland Bay (Lambrechts et al., 2010) and the Burdekin region (Delandmeter et al., 2015). Examples of those model outputs largely support the findings from corresponding field sedimentological studies such as that the Fly River supplies limited terrigenous sediment to the Torres Strait (Wolanski et al., 2021) and that most of the sediment load exported from the Burdekin River is deposited and retained in the vicinity of the river mouth, although there is a smaller proportion (~12%) of the load that is transported larger distances offshore (Delandeter et al., 2015). The model of the sediment dynamics within Cleveland Bay suggests that current delivery of terrigenous sediment to the bay (especially during the larger flow events) is more than what is exported from the bay suggesting that the bay is accumulating terrigenous sediment; the exception being during tropical cyclones which allow short periods for net movement of sediment out of the bay (Lambrechts et al., 2010).

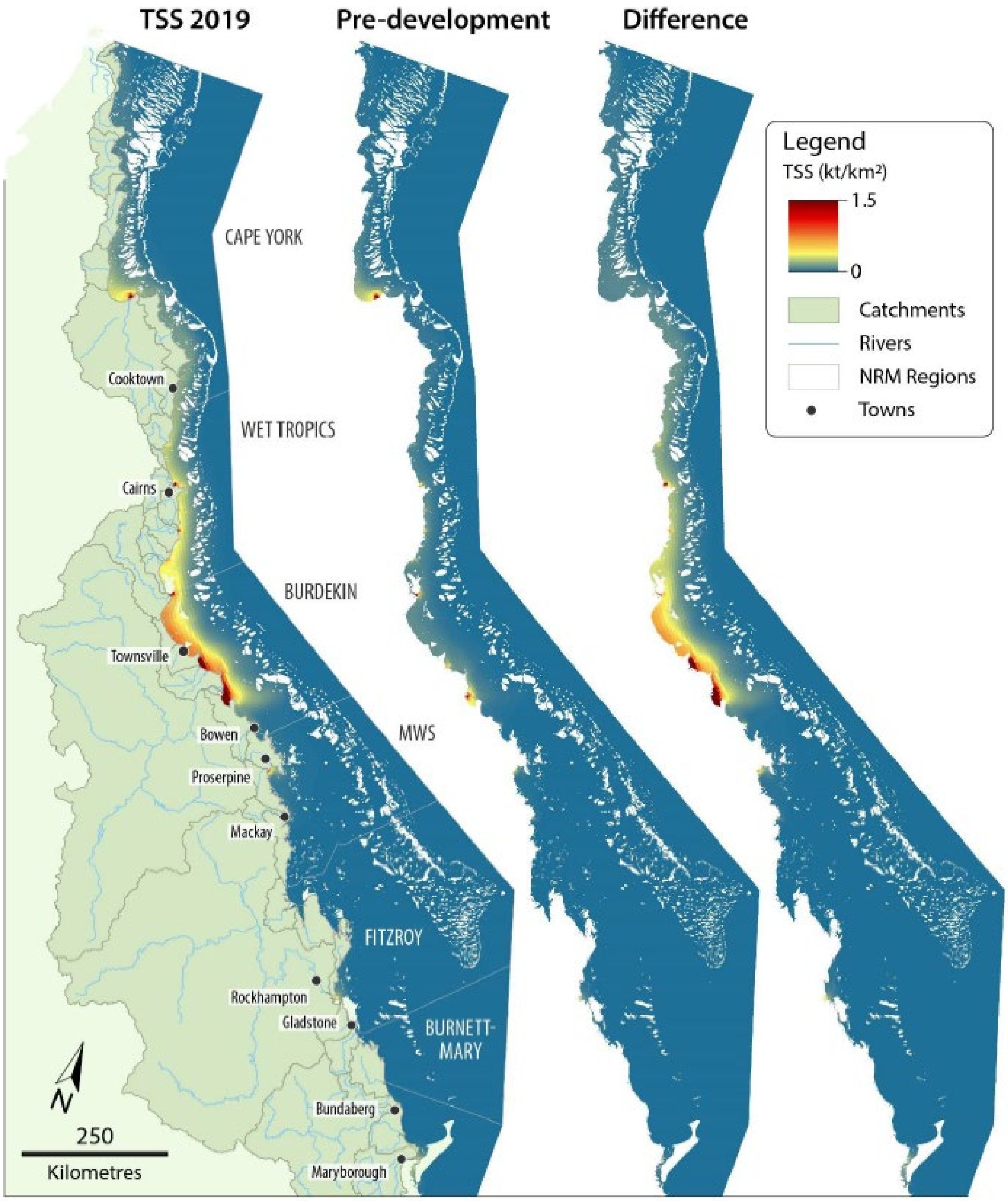


Figure 6. Example of flood plume loading maps for total suspended solids for the 2019 water year and the modelled difference in exposure between current and pre-development arrival loads (from Gruber et al., 2020).

The eReefs sediment model has been developed from the foundations of an early version used to model the sediment dynamics for the Fitzroy River estuary and Keppel Bay (Margvelashvili et al., 2006). The model has been subsequently upscaled to model the whole of the GBR lagoon (Margvelashvili et al., 2018) using additional parameterisation such as the use of benthic sediment distribution maps from Geoscience Australia (Mathews et al., 2007), the incorporation of a finer 'fluff' particle size class

(Margvelashvili et al., 2018) and the inclusion of the latest available sediment loads exported from the catchment (McCloskey et al., 2021). In addition, the model has been calibrated using observational field data including turbidity loggers (Margvelashvili et al., 2018). Overall, the model outputs support the sedimentological field measurements (i.e., area of knowledge 6) and the remote sensing studies on photic depth (i.e., area of knowledge 7) as well as the SLIM model findings. These include that the bulk of catchment sediments are deposited within tens of kilometres of the river mouth, although finer 'fluff' particles can be carried much greater distances and reach the middle and outer shelf regions (Margvelashvili et al., 2018). These finer 'dust/fluff' particles play a critical role in altering optical properties of water masses over the shelf particularly during wetter years (Margvelashvili et al., 2018). The latest eReefs model configuration is able to highlight the spatial areas of the GBR lagoon that are most influenced by anthropogenic sediment loads as well as apply different catchment load reduction scenarios to simulate spatial water quality improvements (Baird et al., 2021).

Variability of turbidity and photic depth in the GBR lagoon (Question 3.1.1)

The literature that addresses this secondary question can essentially be divided into two components: earlier studies that established the foundational knowledge, and the research emerging over the past decade that allowed for the spatial and temporal influence of riverine discharge on turbidity regimes to be examined. The earlier studies used the findings from relatively short-term (generally <1 month duration) turbidity logger data exclusively from the inner shelf of the GBR to highlight the large spatial variability in turbidity in the lagoon as well as to determine the fundamental drivers of turbidity regimes. Importantly, these studies showed that coral reefs of the inner GBR shelf could accrete rapidly under relatively high turbidity fluctuations and were able to endure relatively long periods of reduced light (Anthony et al., 2004; Browne et al., 2013b; Larcombe et al., 1995; 2001; Macdonald et al., 2013). These earlier studies also highlighted that wave-driven resuspension was the dominant control on turbidity regimes on the inner shelf of the GBR (Larcombe et al., 1995; Orpin et al., 1999; 2004a). Based on this finding, as well as data from preliminary flood plume measurements, it was suggested that the contribution of rivers on GBR turbidity regimes was negligible (e.g., Larcombe & Woolfe, 1999b; Orpin & Ridd, 2012).

The emerging research in this field over the past decade has used long-term turbidity logger data (>3 years duration) and applied statistical analysis to account for the effects of wave and tidal resuspension to demonstrate there is a clear impact of newly delivered riverine sediment loads on turbidity regimes in the inner GBR (Fabricius et al., 2013). This research was subsequently extended to satellite photic depth remote sensing analysis to quantify the spatial and temporal variability of river discharge and associated loads on photic depth across the entire GBR lagoon (Canto et al., 2021; Fabricius et al., 2014; 2016). This work shows that photic depth is significantly influenced (i.e., reduced and suppressed photic depth for up to six months) by above average riverine discharge on both sections of the inner and middle shelf of the GBR lagoon compared to years with average or below-average river flows and loads (Canto et al., 2021; Fabricius et al., 2016). Furthermore, this work has been supported by modelling outputs which show the spatial and temporal influence of increased loads on turbidity and light regimes in the GBR lagoon (Baird et al., 2021).

Studies have shown that the quality of the most usable light spectrum is rapidly diminished predominantly by the amount of suspended particulate matter in the water column (Anthony et al., 2004; Bainbridge et al., 2018; Jones et al., 2021; Luter et al., 2021). The finer 'dust/fluff' grain size fractions of the suspended particulate matter can be transported much greater distances in flood plumes, take longer to compact on the seafloor and hence are more easily resuspended and likely play a critical role in altering optical properties of water masses over the shelf particularly during and immediately following wetter years (Bainbridge et al., 2018; Fabricius et al., 2016; Margvelashvili et al., 2018). Hence the available information suggests that there are now multiple lines of evidence (i.e., turbidity loggers, remote sensing and modelling) that increased river discharge and associated loads of sediment and particulate nutrients increase turbidity and lower photic depth for a period of up to 6 months across sections of the inner and middle shelf of the GBR lagoon.

Trends or patterns in outcomes or effects including consistencies or heterogeneity within study findings and reasons why

Overall, there is a high level of consistency in research findings related to spatial and temporal distribution of sediment and particulate nutrients in the GBR, with the possible exceptions on the dominant process that drives the partitioning of the inner, middle and outer shelf and influence of river discharge and loads on turbidity. Indeed, the literature on the geological timescale variability of terrigenous sediment exports have yielded consistent findings (i.e., greater terrigenous sediment inputs to the continental shelf during sea level transgression), including: the clear partitioning of the sediments on the seafloor (and the corresponding physical and chemical composition of sediment) across the inner, middle and outer GBR shelf have been well documented; the rapid processing of particulate nutrients has been found across several studies; the broad sediment processes that shape the inner shelf of the GBR and the main areas of terrigenous sediment deposition have been well and consistently described; evidence for cross-shelf terrigenous sediment transport have been reported, although the key mechanisms require further examination; and the clear inshore-offshore spatial gradients in SPM concentrations in flood plumes and turbidity loggers have also been well replicated.

The dominant mechanisms that shape the partitioning of the inner, middle and outer shelf can vary but are a combination of wind-driven currents and waves associated with the SE trade winds (Orpin & Woolfe, 1999; Woolfe et al., 2000), and from strong (> 130 cm s^{-1}) shore-parallel currents that develop during periods of tropical cyclones (Larcombe & Carter, 2004). While there is wide agreement that wave-driven resuspension is the key driver of turbidity regimes in the inner shelf of the GBR, the 'added contribution' of river discharge and associated loads is still questioned (Larcombe & Ridd, 2018). Earlier studies suggested that riverine inputs and specifically flood plumes have little influence on turbidity regimes based on the comparison of SPM concentrations measured in flood plumes against turbidity logger data from near the seabed (Larcombe et al., 1995; Larcombe & Woolfe, 1999b; Orpin & Ridd, 2012). However, recent evidence from a longer time series of turbidity data from several sites on the GBR inner shelf (Fabricius et al., 2013; Gruber et al., 2020; Lewis et al., 2020; Moran et al., 2022) coupled with additional lines of evidence from remote sensing outputs of the spatial and temporal variability of photic depth (Canto et al., 2021; Fabricius et al., 2014; 2016) and modelling (Baird et al., 2021; Margvelashvili et al., 2018) show that newly delivered sediment into the GBR lagoon during above average flood events cause a significant and prolonged reduction of photic depth for sections of the inner and middle shelf of the GBR lagoon. At this stage there is no literature available that dispute these findings.

4.1.2 Recent findings 2016-2022 (since the 2017 SCS)

While the recent research outputs have made little change to the key conclusions for this question, the new research has strengthened the existing findings and in some cases contributed to form multiple lines of evidence. For example, remote sensing outputs highlight the subtle yet significant contribution of riverine discharge and associated loads on photic depth variability along sections of the inner and middle shelf of the GBR lagoon (Canto et al., 2021; Fabricius et al., 2016). Model outputs with improved parameterisation (i.e., finer sediment grain size) and validation with turbidity loggers provide similar findings (Baird et al., 2021; Margvelashvili et al., 2018). Collectively these new data support an earlier study that applied turbidity logger data to show the influence of river discharge and associated loads on turbidity regimes (Fabricius et al., 2013). Remote sensing of flood plumes show that SPM and coloured dissolved organic matter are the dominant parameters that cause attenuation of light (Petus et al., 2018), while a study using satellite images from the 2019 Burdekin flood plume show that plume waters with SPM concentrations >20 mg L^{-1} reached the middle shelf (Patricio-Valerio et al., 2022). Field measurements of flood plumes continue to show that SPM declines rapidly as the plume waters extend out from the coastline (Bainbridge et al., 2021; Howley et al., 2018). The composition of the sediments become finer in mineral particle size (<20 µm), more organic rich and relatively enriched in expandable clays as the plume moves further offshore (Bainbridge et al., 2016; 2021). A study that compared particle size changes between in situ and laboratory-dispersed (i.e., paired sample treated with calgon and sonication) measurments confirmed that floculation processes are well-advanced for most rivers in this inner estuarine zone (Livsey et al., 2022). Studies of the bioavailable nutrients within flood plumes and river estuaries also continue to highlight the potential for rapid desorption and mineralisation of particulate nutrients in the GBR lagoon (Crosswell et al., 2020; Garzon-Garcia et al., 2021).

New data from turbidity loggers continue to highlight the distinct spatial inshore-offshore turbidity gradient with increasing distance offshore from the river mouth (Gruber et al., 2020; Jones et al., 2021; Lewis et al., 2020; Luter et al., 2021; Moran et al., 2022). The recent focus on the quality of light show that the most 'usable light spectrum' is rapidly diminished under relatively low SPM concentrations and that this particulate matter is the key contributor to this light attentuation (Luter et al., 2021; Jones et al., 2020; 2021).

Modelling of the dispersal of suspended sediments and particulate nutrients through 'plume loading maps' also serve to highlight the extent of exposure within the GBR lagoon and how this likely has changed under increased loads following the arrival of Europeans (Gruber et al., 2020; Moran et al., 2022); importantly these areas of increased exposure broadly match those identified in the remote sensing and modelling outputs. Sediment transport and fate modelling also confirmed the results of previous field studies to show that the Fly River sediment loads have little influence on the islands of the Torres Strait (Wolanski et al., 2021).

Recent studies of inshore fringing coral reefs continue to show the relatively high proportions of terrigenous sediment incorporated within their internal structures and with a clear declining inshore-offshore trend of terrigenous sediment (Ryan et al., 2016a; 2016b; 2016c; 2018). There have also been considerable research outputs on the spatial variability and composition of terrigenous sediment trapped within algal turfs on inshore coral reefs (Gordon et al., 2016; Latrille et al., 2019; Schlaefer et al., 2022; Tebbett et al., 2017; 2018).

4.1.3 Key conclusions

- On geological timescales (i.e., the last 300,000 years covering multiple glacial (ice ages) and inter-glacial periods), the highest terrigenous sediment (i.e., sediment originally eroded from the land) flux to the continental shelf occurred during the periods of sea level transgression (between ~16 and 8 thousand years ago or ka) (i.e., rise from a lowstand when sea levels were at their lowest). Sediment cores reveal that there is modern (defined here as the past 8,000 years when sea level was within 5 m of its present position) terrigenous sediment flux to the continental shelf (up to 13% of the riverine inputs) but the mechanism for such transport is unclear.
- All relevant literature clearly documents three distinct changes in the sediment composition on the seafloor of the GBR lagoon which coincides with water depth and have been classified as the inner, middle and outer shelf zones. This includes the dominance of land-derived 'terrigenous' sediment on the inner shelf (0 to 20 m water depth); mixed carbonate/terrigenous sediment (i.e., combined marine sediment such as shell fragments with land-derived sediment) on the middle shelf (20 to 40 m) which are relict deposits that are continually reworked and; carbonate-dominated (i.e., marine sediment from coral and shells) on the outer-shelf (>40 m) of the GBR lagoon. The physical (colour, grain size) and chemical (organic markers, major and trace element geochemistry and bioavailability of phosphorus) composition of the sediments also follow this clear shelf zonation. The mechanisms that drive this strong zonation are a combination of cyclones that promote strong shore-parallel currents and a product of the dominant southeast trade winds and the water depth limit of wave resuspension (up to 22 m).
- The literature also show that most river-exported terrigenous sediment is deposited within river floodplains, river estuaries, close to river mouths and within the eastern sections of north-facing embayments. In addition, nearshore and inshore fringing coral reefs host considerable amounts of terrigenous sediments within their internal structures and contain decreasing terrigenous to carbonate sediment proportions across inshore-offshore gradients.
- There is strong evidence for cross-shelf movement of terrigenous sediment (i.e., from the inner shelf to the middle and outer shelfs or, conversely, from the middle shelf to the inner shelf) which likely occurs during riverine flood plumes, nepheloid layers (i.e., highly concentrated suspended sediments on or near the seabed that are transported in currents), tidal currents,

cyclones and mushroom jets (i.e., large scale water movements likely triggered by differences in water temperatures coupled with opposing tidal and wind currents), although the dominant transport mechanism is unresolved.

- A wealth of literature exists that considers the dominant influences on turbidity (i.e., water clarity) and photic depth (i.e., the depth in the water column that photosynthetically usable light can reach) in the inner shelf of the GBR lagoon, showing that wave-driven resuspension is the dominant driver, with tidal resuspension acting as a secondary influence. Resuspension of sediments on the inner shelf in conjunction with tidal and wave currents can transport sediments to other sediment respositories such as mangroves, beaches, sheltered embayments.
- Studies on particulate nutrients in flood plumes and river estuaries highlight the potential for rapid transformation of particulate nutrients to bioavailable forms (dissolved nutrient forms that are readily consumed by algae) within coastal areas. Frequent resuspension of sediments within estuaries and the coastal zone helps promote rapid cycling of particulate nutrients which are largely mineralised through microbial communities.
- Several studies show that terrigenous sediments in flood plumes are highest at the river mouths, with a rapid decline in concentrations within the 0 to 10 practical salinity units (PSU; i.e., a unitless scale that measures salinity of the water where 0 PSU = freshwater and ~35 PSU = seawater) salinity zone due to flocculation processes (i.e., when sediment particles stick together as a result of salinity changes or biological production). While most flood plumes are constrained within the inner shelf of the GBR lagoon, appreciable terrigenous sediment loads can be carried to the middle shelf and even the outer shelf during periods of large riverine discharge events (noting the size of the event is difficult to quantify which also relates to the distance to the middle and outer shelf from the river mouth), especially those that coincide with periods of slack winds. Turbidity logger data from the inner shelf of the GBR lagoon show a clear spatial gradient where decreasing turbidity levels are observed with increasing distance from river mouths. This spatial gradient is likely related to the depth of the water column (i.e., ability for wave resuspension) and the availability of sediment on the seafloor to be readily resuspended.
- Statistically accounting for the turbidity generated by wave and tidal resuspension reveals a significant contribution of riverine discharge and associated sediment and particulate nutrient loads on the turbidity regime in sections of the inner and middle shelfs of the GBR. Seasons of above average discharge and loads coincide with increased and prolonged (up to six months) turbidity and corresponding low light in these sections of the GBR compared to below average discharge years.
- The quality of the most usable light spectrum that reaches the seafloor is rapidly diminished predominantly by the amount of suspended particulate matter in the water column. The finer ‘dust/fluff’ grain size fractions of the suspended particulate matter can be transported much greater distances in flood plumes, take longer to compact on the seafloor and hence are more easily resuspended and contribute to longer periods of diminished light. Turbidity as low as <5 nephelometric turbidity units (NTU) can greatly attenuate light reaching the seafloor. Logger readings of turbidity within this lower range have higher uncertainty in terms of the ‘instrument zero point’ (i.e., the variability in background turbidity readings when the instrument is placed in filtered water) as well as for the conversion of turbidity to a concentration of suspended particulate matter.
- Remote sensing and modelling analyses support the findings that river discharge and associated loads significantly influence turbidity and photic depth regimes along areas of the inner and middle shelfs of the GBR lagoon.

4.1.4 Significance of findings for policy, management and practice

Multiple lines of evidence highlight the influence of increased sediment and particulate nutrient loads on increased turbidity regimes and reduced and prolonged photic depth on certain sections of the inner and middle shelf of the GBR lagoon. The evidence has been gleaned from statistical analysis of long-term (>3 years) turbidity logger data, remote sensing analysis of spatial and temporal variability of photic depth and modelling outputs of suspended sediments, secchi disc depth and benthic light. Collectively, the evidence provides a powerful base to demonstrate the need to reduce riverine sediment and particulate nutrient loads in the effort to improve the benthic light conditions in the GBR lagoon.

The latest eReefs modelling can better simulate the riverine sediment inputs as well as its transport and fate in the GBR lagoon and hence the model can be used with improved confidence to develop end-of-basin ecologically-relevant load targets.

While there is still scope for improvement to further develop the knowledge (and quantification) of the complex catchment to reef processes that will further refine the outputs of the eReefs marine model (and as such improved catchment prioritisation), the current level of conceptual and process-based understanding is sufficient to deploy the model for informing catchment-based load targets.

4.1.5 Uncertainties and/or limitations of the evidence

- While terrigenous sediments continue to be delivered from rivers and the resuspension of seafloor sediments on the inner and middle shelfs to outer shelf of the GBR, the dominant mechanism and the specific sediment budget contributed from the inner and middle shelfs to the outer shelf have largely not been quantified.
- The evidence for the spatial and temporal influence of riverine discharge and associated loads on turbidity and photic depth in the GBR lagoon has strenghened over the past decade through a multiple lines of evidence based understanding. We note that there is a wealth of new long-term turbidity logger data from several sites from the inner shelf of the GBR lagoon that could be analysed in a similar way to the data presented by Fabricius et al. (2013). Indeed many are from the same sites analysed in the Fabricius et al. (2013) dataset, although instead of the 3 years of data analysed in that study these sites now have up to 16 years of continuous data. The detailed analysis of these datasets would further strengthen the evidence base.
- There are limited turbidity logger data from the middle shelf of the GBR lagoon. The establishment of continuous turbidity and light logger sites on the middle shelf (informed by remote sensing and modelling outputs) would enhance the understanding of the level of influence of riverine discharge and associated loads in this monitoring-poor area of the GBR lagoon.
- Given the potential uncertainties of the low level turbidity readings, it would be instructive to transition to loggers that measure the light regime (and preferably the quality of light) in the GBR. Despite light being the critical parameter of interest, turbidity has been the traditional unit of measure (almost as a proxy for light) and comparatively light loggers have been used less in the GBR lagoon.
- Basin-specific suspended particulate matter loads that transit past the initial deposition zone including the organic component that forms *in situ* need to be better quantified and linked to areas where prolonged reductions in photic depth in the GBR lagoon have been reported.

4.2 Contextual variables influencing outcomes

The contextual variables for Question 3.1 are summarised in Table 9.

Table 9. Summary of contextual variables for Questions 3.1 and 3.1.1.

Contextual variables	Influence on question outcome or relationships
Climate change (or climate variability)	On geological timescales, the glacial-interglacial cycles have the largest influence on sediment distribution and transport in the GBR. The literature shows that most terrigenous sediment is exported past the continental shelf during periods of sea level lowstands and transgressions (Bostock et al., 2009; Dunbar et al., 2000; Dunbar & Dickens, 2003; Harper et al., 2015; Page et al., 2003; Page & Dickens, 2005). The sediment deposits exposed on the shelf during lower sea levels obviously also become alluvial/co-alluvial deposits.

Contextual variables	Influence on question outcome or relationships
	Since the modern sea level highstand (past ~8 ka), climate influences that induce variability in rainfall (i.e., higher/lower, more intense/less intense, greater inter-annual variability) not only influence river discharge patterns but also the vegetation within the river catchments, which in turn influence the discharge of terrigenous sediment in the GBR. Indeed, larger peak flood events result in a great area of exposure in the GBR lagoon to riverine flood plumes and associated suspended particulate matter. Changes in the wind/storm/cyclone climate also serve to influence sediment resuspension frequencies as well as influence the movement and distribution of sediment across the GBR lagoon. These changes may occur on inter-annual scales, decadal scales or even on centennial–millennial scales.
Land use change	Land use modification of river catchments can alter the amount of sediment exported to – and influence the distribution and exposure in – the GBR lagoon. Dams may trap sediment and reduce sediment loads while land clearing or agriculture may increase sediment exported to the GBR lagoon (Lewis et al., 2021).
River channel avulsion	Changes in the coastal discharge points of rivers alter where the sediment is delivered in the GBR lagoon and hence can change the relative parts that are exposed to sediments (e.g., Lewis et al., 2014).

4.3 Evidence appraisal

Relevance

The relevance of the overall body of evidence used to answer the question was High. The relevance of each individual indicator was Moderate-High for relevance of the study approach and reporting of results to the question, Moderate-High for spatial relevance, and Moderate for temporal relevance. The transport, mobilisation, distribution and fate of terrigenous sediments in the GBR lagoon has been a long-standing topic of research across numerous researchers over the past 50 years. Hence there are several studies that help address the question which fall within the broad areas of knowledge identified in this review. As this question is specific to the GBR, there was little need to consider and draw on data from elsewhere. The spatial and temporal relevance was only assessed based on the evidence provided by the distribution of suspended sediments (or turbidity) and photic depth across the GBR. While the central section of the GBR lagoon has overwhelmingly received the most research attention, the other sections have also been subject to several complementary studies while the photic depth and modelling work cover the entire GBR. This is reflected in a Moderate-High assessment for spatial relevance. Several of the earlier studies which reported turbidity logger data had a relatively low temporal resolution (<1 month) and as such this is reflected by the Moderate assessment for temporal relevance.

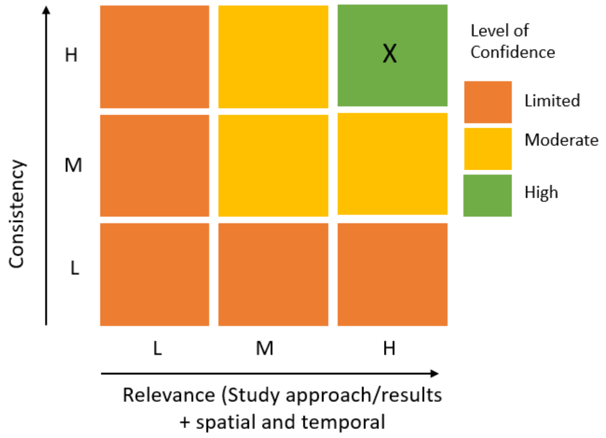
Consistency, Quantity and Diversity

The overall body of evidence showed a High level of consistency in the findings, a High abundance of research outputs (quantity) and a diversity of methods applied to address the question. The synthesis has captured a high sample size of the available peer-reviewed evidence across multiple fields to address this question. The geological-scale processes of terrigenous sediment flux to the continental shelf have been conducted across the northern, central and southern regions and yield consistent results. The distribution of terrigenous sediment and its composition on the seafloor of the GBR lagoon has been extensively mapped while the processes that shape the partitioning of the inner, middle and outer shelf have received wide attention and are generally well understood. Unsurprisingly, there has been a particular focus on terrigenous sediment deposits on the inner shelf of the GBR lagoon where intensive studies have been conducted to examine and map sediment composition, produce local and regional sediment budgets and document key sedimentary processes along the northern, central and southern GBR. As for the spatial and temporal distribution of suspended sediments in the GBR lagoon, there has been a wealth of studies to highlight the inshore-offshore gradients from direct measurements of flood plumes and coastal and inshore waters, turbidity logger deployments, remote sensing and modelling. The data consistently show that the highest concentrations of SPM are closest to river mouths and rapidly decline with increasing distance offshore. The dominant process on sediment resuspension has been well established while the subtle but significant inter-annual influences of riverine discharge and associated loads on turbidity and photic depth in parts of the inner and middle shelf have more recently been documented across a number of different observational, remote sensing and modelling studies.

Confidence

The overall confidence in the body of evidence used to answer both the primary and secondary questions is considered High (Table 10). The cross-shelf distribution, transport processes, deposition, composition, nutrient processing and repositories/budgets of terrigenous sediment have been well described in the literature that spans several decades. Similarly, there is a wealth of information on the drivers and the spatial and temporal trends of terrigenous sediments and particulate nutrients in the water column of the GBR lagoon through observational, remote sensing and modelling efforts.

Table 10. Summary of results for the evidence appraisal of the whole body of evidence in addressing Questions 3.1 and 3.1.1. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	High	
-To the Question	Moderate-High	
-Spatial	Moderate-High	
-Temporal	Moderate	
Consistency	High	
Quantity	High (150 studies)	
Diversity	High (72% observational i.e., monitoring, sediment grabs/cores, 11% combined observational/modelling i.e., remote sensing, turbidity measurements combined with numerical modelling, 7% computational modelling, 7% conceptual understanding, and 3% modelling/experimental studies)	

4.4 Indigenous engagement/participation within the body of evidence

There is no evidence of any Indigenous engagement or participation within the literature used to address this question.

4.5 Knowledge gaps

The knowledge gaps for Question 3.1 are summarised in Table 11.

Table 11. Summary of knowledge gaps for Questions 3.1 and 3.1.1.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
The lack of spatial and temporal light logger data in the GBR lagoon.	To provide a much stronger spatial and temporal observational dataset on light quality and quantity across the GBR lagoon.	A dataset will complement and help validate the findings from remote sensing and modelling. It can also assist in the parameterisation of modelling. Measuring light directly in the GBR lagoon will help overcome the issues related to the uncertainty of the low level turbidity readings.
Additional statistical analysis of existing logger data.	To help confirm the influence of riverine discharge and associated loads on turbidity in the GBR lagoon.	A detailed statistical analysis of the Marine Monitoring Program turbidity logger datasets (and other potential long-term datasets, e.g., Lewis et al., 2020) will potentially provide another valuable line of evidence.
Middle shelf monitoring.	To provide an observational dataset to examine the influence of riverine discharge and associated loads on turbidity in the GBR lagoon.	An observational dataset from targeted locations on the middle shelf will help validate the findings from remote sensing and modelling. It can also assist in the parameterisation of modelling.
The quantification of the sediment loads that travel furthest to the inner and middle shelf sites where photic depth is most affected.	To provide a stronger and more direct link to the prolonged decline in photic depth with 'the more transportable' catchment sediment loads (presently strongest link is with river discharge because the end of river load has been used rather that the load that moves further offshore).	A stronger and direct link between sediment loads and photic depth will allow for more targeted management of sediment erosion in the catchment.

5. Evidence Statement

The synthesis of the evidence for **Question 3.1** was based on 150 studies undertaken in the Great Barrier Reef and published between 1968 and 2022. The synthesis includes a *High* diversity of study types (72% observational i.e., monitoring, sediment grabs/cores, 11% combined observational/modelling i.e., remote sensing, turbidity measurements combined with numerical modelling, 7% computational modelling, 7% conceptual understanding and 3% modelling/experimental studies), and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

There are distinct patterns of sediment composition across the continental shelf of the Great Barrier Reef. The inner shelf (up to 20 metres water depth) is dominated by land-derived 'terrigenous' sediment shifting to predominantly marine sediment derived from corals and shells in the outer shelf (>40 metres depth). These cross-shelf patterns are driven by a combination of the dominant south-east trade winds which typically 'hold' the sediment inshore and drive flood plumes along the coast, the depth limit of wave resuspension which is up to 22 metres, and cyclones that promote strong longshore shelf-parallel currents. While most sediment-laden flood plumes are also constrained within the inner shelf of the Great Barrier Reef, appreciable fine-grained (<20 µm) terrigenous sediment loads can be carried to the middle[10] shelf and even the outer shelf (particularly for the areas northwards of Bowen where the middle and outer shelf zones are closer to the coast) during periods of large riverine discharge that coincide with low wind speeds, although these events occur less frequently. *In-situ* monitoring and remote sensing data show a clear spatial gradient of decreasing turbidity levels with increasing distance from river mouths. This spatial gradient is likely related to the depth of the water column (i.e., ability for wave resuspension) and the availability of sediment on the seafloor to be readily resuspended. Multiple lines of evidence from turbidity loggers, remote sensing and modelling show that elevated and prolonged turbidity levels and corresponding longer periods of diminished useable light in the water column in certain areas of the inner and middle shelfs of the Great Barrier Reef coincide with years of increased river discharge and associated sediment loads. The change in river discharge and increase in sediment loads since the arrival of Europeans greatly influences the area of the inner and middle shelfs affected by the diminished light.

Supporting points

- Several studies show that most river-exported terrigenous sediment is deposited and retained within river floodplains, river estuaries, close to river mouths and within the eastern sections of north-facing embayments. Nearshore and inshore fringing coral reefs also host considerable proportions of terrigenous sediments within their internal structures. Sediment modelling exercises indicate that most of the terrigenous sediment (including both coarse and fine particles) is deposited and retained in close vicinity to river mouths. However, a proportion of the fine terrigenous sediment (<20 µm) load can be carried within flood plumes to the inner and middle shelfs.
- There is abundant literature that show terrigenous sediment concentrations in flood plumes are highest at the river mouths with a rapid decline in concentrations within the 0 to 10 practical salinity units (PSU; i.e., a unitless scale that measures salinity of the water where 0 PSU = freshwater and ~35 PSU = seawater) salinity zone due to flocculation processes which occur when sediment particles stick together as a result of salinity changes or biological production. This 0 to 10 PSU zone typically occurs within 20 km of the river mouth and is dependent on the volume of discharge.
- Studies on particulate nutrients in flood plumes and river estuaries highlight the potential for rapid transformation of particulate nutrients to bioavailable forms (dissolved nutrient forms that

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[10] In terms of bathymetry, which is linked to sediment characteristics, the Great Barrier Reef is defined as inner shelf (up to 20 metres depth), middle shelf (20 to 40 metres depth) and outer shelf (more than 40 metres depth).

are readily consumed by algae) within coastal areas. Frequent resuspension of sediments within estuaries and the coastal zone helps promote rapid cycling of particulate nutrients which are largely mineralised through microbial communities.

- The quality of light for photosynthesis is predominantly influenced by the amount of suspended particulate matter in the water column. Turbidity as low as <5 nephelometric turbidity units (a measure for how cloudy the water is) can greatly attenuate light reaching the seafloor. The quality of light reaching the seafloor is critical to many communities including seagrass meadows and coral reefs.
- The dominant influences on turbidity (i.e., water clarity) and photic depth (i.e., the depth in the water column that photosynthetically usable light can reach) in the inner shelf of the Great Barrier Reef is primarily from wave-driven resuspension with tidal resuspension as a secondary influence. Resuspension of sediments on the inner shelf in conjunction with tidal and wave currents can transport sediments to other sediment repositories such as mangroves, beaches and sheltered embayments.
- Independent remote sensing analysis and modelling outputs support the findings that river discharge and associated loads significantly influence turbidity and photic depth regimes along sections of the inner and middle shelfs of the Great Barrier Reef.
- A proportion of the fine-grained (<20 µm) riverine sediment travels furthest in the Great Barrier Reef, settles as an uncompacted ‘fluffy layer’ on the seafloor and is hence more easily resuspended under less-energetic wave events relative to the existing compacted sediment on the seafloor. This process results in longer periods of diminished light in sections of the inner and middle shelfs in the years of above average discharge and sediment loads.
- Sediment cores taken offshore from the continental shelf (i.e., Queensland Trough) reveal that there is modern (i.e., over the past 8,000 years) terrigenous sediment flux to the continental shelf, accounting for up to 13% of the riverine inputs depending on the location, but the mechanism for such transport is unclear.
- While the recent research outputs (2016-2022 period) have made little change to the key conclusions for this question, the new research has strengthened the existing findings, and in some cases, contributed to form multiple lines of evidence. This includes consistent findings from additional remote sensing and modelling analysis as well as from new monitoring data.

6. References

The ‘Body of Evidence’ reference list contains all the references that met the eligibility criteria and were counted in the total number of evidence items included in the review, although in some cases, not all of them were explicitly cited in the synthesis. In some instances, additional references were included by the authors, either as background or to provide context, and those are included in the ‘Supporting References’ list.

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 3.1

Theme 3: Sediments and particulate nutrients – catchment to reef

Primary Question 3.1 What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef?

Secondary Question 3.1.1 What is the variability of turbidity and photic depth in coastal and marine areas of the Great Barrier Reef?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Stephen Lewis	James Cook University	Sedimentology, sediment distribution, nutrient processing, turbidity measurements	Lead Author	All Sections
2. Zoe Bainbridge	James Cook University	Sedimentology, flood plume water quality	Contributor, consistency checker of data extractions, review and editing	All Sections
3. Scott Smithers	James Cook University	Sedimentology, geomorphology, coral reef records	Contributor, review and editing	All Sections