2022 Scientific Consensus Statement

Question 3.6 What is the effectiveness of gully and streambank restoration works in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?

Question 3.6.1 What is the benefit of vegetation restoration in 1) riparian zones and 2) hillslope and floodplain zones, in reducing sediment and particulate nutrient loss to the Great Barrier Reef?

Andrew Brooks[1], James Daley[1], Tim Pietsch[1]
[1]Coastal and Marine Research Centre, Griffith University

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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 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

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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

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 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

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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.

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

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.

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.

Contents

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Executive Summary

Questions

Primary Question 3.6 What is the effectiveness of gully and streambank restoration works in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?

Secondary Question 3.6.1 What is the benefit of vegetation restoration in 1) riparian zones and 2) hillslope and floodplain zones, in reducing sediment and particulate nutrient loss to the Great Barrier Reef?

Background

Subsurface erosion is the primary source of sediment pollution in the Great Barrier Reef (GBR) lagoon, accounting for up to 80% of sediment export. Sources include gully erosion, scalding, channel erosion (i.e., streambank, from large and small rivers and streams), and potentially unsealed roads (both public and private). Remediation efforts since 2016 have focused on large alluvial gullies and streambank erosion, which are recognised as being dominant sources of sediment and particulate nutrients.

There is strong agreement among scientists about the importance of addressing subsurface erosion to meet GBR water quality targets. Plot-scale trials undertaken in the Normanby catchment prior to 2016 showed total erosion rates could be reduced by up to 80% with appropriate treatment. However, these trials needed to be upscaled to large gully complexes for larger-scale validation.

Policymakers are also interested in the cost-effectiveness of reducing sediment loads by treating major subsurface sources. Remediation strategies have been implemented within gullies and river channels, aiming to reduce sediment exports to the GBR. This Question reviews the evidence in the peer reviewed literature on the effectiveness of these remediation approaches in reducing fine sediment and particulate nutrient erosion in the GBR. The review addresses the evidence for riparian and streambank management (for channel erosion) separately to that of gully erosion. Gully erosion is a process that is primarily confined to the dry tropics, while channel erosion can occur anywhere.

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[5]. 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 Scopus, Web of Science and Google Scholar, supplemented by author databases.
- The main source of evidence was studies derived in the GBR for the gully remediation component of the question (with some international literature reviewed, but not included due to low relevance). For the riparian rehabilitation component of the question literature had to focus on the principles of demonstrated benefits of riparian vegetation to channel stability, due to the limited body of evidence on the topic.

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[5] 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

- A total of 56 items were screened in detail for the gully part of the question, with 33 being eligible for inclusion in the synthesis. For the streambank/channel erosion part of the question a total of 83 items were screened in detail, and 55 were eligible for inclusion in the synthesis.

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 studies published since 1990 were included for the gully review, although some earlier studies were used as supporting information. No constraints were applied to the riparian/channel review.
- The initial searches were framed around studies that had specifically addressed the primary question (i.e., including measured water quality responses of the various remediation/rehabilitation works in terms of fine suspended sediment). However, due to the limited search results, broader searches were performed including studies that covered first principles of the chosen management strategies, particularly in relation to channel erosion.

Note that due to the fundamental differences between gullies and river channels, this synthesis has been structured into two distinct parts which address the evidence for each.

Key Findings

Summary of evidence to 2022

The following conclusions can be drawn from the body of evidence for **gully remediation**:

- There is a low number of studies that assess the water quality outcomes and cost effectiveness of gully restoration in the GBR catchment area. The review highlighted that studies on gully remediation from other parts of the world are of limited value for comparison; as in addition to significant geographic and climatic differences, very few studies measure water quality improvements associated with gully management and typically do not differentiate the fine and coarse sediment fractions. In the GBR, fine sediments (<20 µm) have been identified as being the ecologically significant component of the sediment budget, given that this fraction is dispersed over greater distances and can carry attached nutrients. Furthermore, much of the international literature is based around linear hillslope gullies, which are not the main focus for much of the current remediation effort in the GBR.
- The large-scale remediation of alluvial[6] gullies has been demonstrated to be a highly effective strategy for significantly reducing tens of thousands of tonnes of fine sediment that is being actively delivered to the GBR each year. Gully remediation treatments can include major earth works and reshaping, soil treatment, installation of rock chute structures, earth bunds and water points, fencing and revegetation. A combination of these treatments can achieve over 90% fine sediment reduction within one to two years.
- In contrast, direct hillslope gully treatments appear less effective in reducing fine sediment losses (7 to 17% effectiveness). Destocking catchments may also reduce hillslope gully sediment yields by up to 60% after ~25 years, however there is limited information on the practicality and costs of this approach. Streambank rehabilitation treatments include interventions to increase riparian vegetation, either directly through planting, or indirectly through the removal of disturbance pressures such as grazing to encourage natural colonisation, and in some cases bank reprofiling and stabilisation, which enables subsequent revegetation via planting and/or natural colonisation. The available evidence shows that hillslope gully treatments are less cost-

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[6] There are two major gully types; alluvial (or river associated) and colluvial (or hillslope gullies). This distinction is based on the material the gullies are eroding into: alluvium - sediments deposited overbank from rivers and streams; and colluvium -sediments derived from *in-situ* weathering on slopes and/or downslope processes on hillslopes.

effective when compared with the cost per tonne of fine sediment abated, but also the amount of sediment that can be abated, from large high yielding alluvial gullies. While it may initially seem attractive to save money up front by implementing lower cost and less effective treatments, such an approach carries a greater risk of failure in the future, and potentially higher maintenance costs. At present it is not known whether such a trade-off will be more or less expensive across the design life of the treatment (>30 years).

- In most situations, particulate nutrient reductions typically track the reductions in fine sediment, however this is not the case for dissolved nutrients where organic matter is added to improve soil condition. Organic ameliorants with a high carbon:nitrogen ratio are more likely to ensure that dissolved inorganic nitrogen export is reduced.
- There is limited documented evidence of the production outcomes of gully remediation projects. However, given the relatively small area of high yielding gullies, there is likely to be little private production benefit associated with gully management (i.e., for grazing). Remediation investments funded through the Reef Trust are recommended to be protected through grazing exclusion in the treatment areas (other than rare very short-term dry season maintenance grazing).

The following conclusions can be drawn from the body of evidence for **streambank rehabilitation**:

- There are currently no studies from within the GBR catchment area that demonstrate a relationship between site-scale bank stabilisation, or even reach-scale rehabilitation works, and downstream water quality improvements. The evidence from Australian and international literature is scant and focused on small scale (<150 ha) catchments, with limited applicability to the scale of the GBR river channel network.
- Consistent with previous global reviews of streambank rehabilitation treatments, there is no ability to assess the effectiveness at the catchment scale of individual treatment types, nor derive effectiveness ratios for various treatments. A significant contributing factor to this is the lack of at scale, long-term quantitative monitoring of rehabilitation projects. A key issue is the difficulty to establish an appropriate baseline erosion rate for a channel as, based on current field evidence, it is very difficult to determine whether a riverbank is *eroded* or *eroding*.
- There is no peer reviewed Australian literature on the cost or cost-effectiveness of riparian/channel rehabilitation projects that was relevant to this synthesis. Given the lack of information on baselines, treatment effectiveness and cost data of projects, the cost-effectiveness of streambank rehabilitation could not be evaluated in this review.
- Despite the lack of studies that have focused on measuring the relationship between channel and riparian zone rehabilitation and water quality in the GBR (or anywhere), studies show that bank erosion generally occurs at lower rates on vegetated river reaches than non-vegetated reaches. However, none of these studies demonstrate reductions in bank erosion associated with streambank rehabilitation or revegetation of formerly unvegetated banks. There is also evidence that there is significant hysteresis in channel recovery once river channels have responded geomorphically to vegetation removal. In practice, this may mean that channel changes that took perhaps decades to be fully realised, may take centuries to fully recover. Protection of remaining riparian vegetation is therefore important.
- There is a need to focus efforts at whole-of-system approaches that seek to maximise recovery of riparian vegetation at the reach to subcatchment scale, rather than focus on individual erosion sites.

Recent findings 2016-2022

Gullies

All relevant studies addressing the primary and secondary questions have been undertaken since 2016. At the time the 2017 SCS was published, only two GBR relevant pilot studies had been undertaken, from the same study site at Crocodile Station in the Normanby basin. While these reports were important for setting the direction for future research, and providing the impetus for further investment in scaled-up on-ground gully remediation works, all substantive research that specifically addresses the primary question has been undertaken since 2016.

Streambank

There have been no recent substantive research and development, or rehabilitation monitoring efforts that address the questions regarding the effectiveness of streambank rehabilitation either nationally or in the GBR catchment area. While opportunities exist to provide post-hoc analyses of changes related to streambank rehabilitation in the GBR, no quantitative data have been collected or published to provide effectiveness ratios. One local study demonstrated that condition indices of rehabilitation sites improve with age, based on qualitative on-ground assessments. These data do not relate to erosion indices, including quantitative sediment or nutrient losses, nor provide scope beyond the site scale.

Significance for policy, practice, and research

The evidence from the National Environmental Science Program (NESP Tropical Water Quality Hub (2014 to 2021) research about the effectiveness of **gully remediation** is compelling, however the studies were relatively short term (3-4 years). Establishment of long-term monitoring sites that can track maintenance costs over the long-term and the response of remediated gullies to climate change as well as land management practice change will continue to improve knowledge of the effectiveness of remediation projects. Ideally the sites that have been monitored to date would be the focus of such a long-term program, along with new sites that cover a diversity of gully types, baseline yields and treatments.

Understanding the effectiveness of gully management requires a robust understanding of baseline sediment yields in gullies, based on the latest science. A standardised framework is needed for determining gully baseline sediment yields that reflects the wide diversity of gully evolutionary trajectories found in the landscape.

The long-term performance of gullies that have been remediated to different standards, and the cumulative costs of maintenance is unknown. For example, it is not known if the savings that may be accrued upfront by employing undercapitalised treatments will end up costing more or less over the 25-30 year design life (accounting for higher ongoing maintenance costs) than if the treatment was implemented to the highest standards at the outset. The only way that this question can be addressed is through the implementation of a long-term monitoring program that can track the longitudinal performance of a selection of gullies.

Given the high importance placed on understanding remediation cost-effectiveness, there is a clear need to develop a standardised and peer reviewed accounting framework for measuring gully remediation costs, and cost-effectiveness, using agreed timeframes over which costs are assessed and standardised discount rates. The design life should reflect the timescale over which it is expected the water quality improvements will be maintained, which should be at least up until 2050 (i.e., >25 years). The Reef Credit method is an existing approach that lays out how the baseline assessment and monitoring can be undertaken in a standardised way. This type of analysis should be built into the proposed long-term monitoring outlined above.

Two critical elements emerge from this brief review for **streambank rehabilitation**. The first is the need to adopt system scale, holistic, long-term thinking when considering the structure of any program aimed at reducing catchment sediment exports. This should entail some reconsideration of goal setting and the appropriateness of metrics for judging progress towards identified goals. Policy settings that require precise quantification of 'at site' sediment savings associated with particular interventions can introduce perverse incentives for delivery teams and impede them from finding their place within the recently developed Whole-of-System, Values-Based Framework[7]. The second consideration is to ensure that sediment discharge data are being collected now in such a way that maximises sensitivity to change, minimising the time over which trends can be observed. A monitoring strategy to measure the

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[7] https://wetlandinfo.des.qld.gov.au/wetlands/management/whole-system-values-framework/

cumulative progress towards increased in-channel sediment storage and riparian resilience, needs to take account of the key points outlined above.

Key uncertainties and/or limitations

Some uncertainty exists in the ability to predict the long-term performance of **gullies** in the GBR due to the relatively short-term monitoring undertaken to date (<5 years), and the absence of ongoing maintenance. In particular, the evidence suggests that gullies not treated to the highest standards at the outset, have a higher likelihood of reduced effectiveness, requiring greater maintenance over time. The cumulative costs of maintenance are also a major unknown, which will have implications on whole of life cost-effectiveness assessments.

The absence of long-term catchment sediment export data associated with **streambank** interventions prevents assessment of their effectiveness. Nevertheless, the weight of evidence from across the world strongly supports the continuation of streambank rehabilitation works, particularly those designed to directly or indirectly increase the quantity and quality of riparian vegetation. These interventions can have a number of ecological, social, and geomorphic benefits, including minimising sediment and particulate nutrient export.

The available evidence supports the notion that management efforts should be focused on the small cohort of the highest yielding gullies. Nevertheless, the current evidence base is small, so further monitoring of hillslope gullies could be undertaken to further test the cost-effectiveness of treating small hillslope gullies, ensuring that the logistical costs associated with replicating such treatments across tens of thousands of gullies are also quantified.

There are limited data on the production outcomes of gully and streambank management.

Evidence appraisal

The synthesis of the evidence for Question 3.6 was based on 88 studies (33 gully remediation and 55 streambank remediation), undertaken in the GBR catchment area and other national and international locations, published between 1990 and 2022 with some earlier streambank studies. This synthesis includes a Moderate diversity of study types: 58% observational, 19% reviews, 16% experimental and 7% modelling.

The overall confidence for the gully studies was rated as Moderate, based on Moderate relevance and Moderate consistency. Despite the low number of studies reviewed overall, the evidence as to the effectiveness of treatments addressing large alluvial gully remediation is strong.

The confidence with which the body of evidence for the effectiveness of streambank intervention was Moderate, based on a Moderate overall relevance (but Low relevance to the question) and Moderate to High consistency. No research was directly relevant to the situation in the GBR catchments, though several articles from other regions, and considerations from first principles, support the general contention that remediation, particularly that based on extensive revegetation, will result in a lowering of catchment sediment and nutrient export.

1. Background

It is now well understood that subsurface erosion is the primary source of anthropogenic sediment pollution to the Great Barrier Reef (GBR) lagoon (Furuichi et al., 2016; Olley et al., 2013). Subsurface sources are typically considered to be represented by gully erosion, scalding (or shallow gullying) and channel erosion. It should also be highlighted that there are other possible sources of 'subsurface' erosion, such as erosion from roads, particularly unsealed roads, which to date, have not been included in GBR sediment budget models. The best estimate from empirical data is that around 80% of the sediment budget to the GBR is derived from these subsurface sources– varying considerably in the relative dominance of different processes from the wet and dry tropics, and varying as a function of land use intensity in different parts of the landscape (Brooks et al., 2013; Hughes et al., 2009, Olley et al., 2013; Tims et al., 2010; Wilkinson et al., 2015b).

In the Bowen catchment, which is estimated to contribute around 30% of the fine sediment load to the entire GBR (Bainbridge et al., 2014), subsurface sources are estimated to contribute up to 96% of the fine sediment load delivered to the GBR lagoon (Hancock et al., 2014). To date, only one study in the Herbert catchment (Bartley et al., 2004) departs substantially from those estimates, as they found subsurface sources were only around 50% of the measured load. The study by Tims et al. (2010) from the same catchment several years later found that 80% of the sediment load had a subsurface origin. The divergence between these studies has subsequently been explained as being a result of the sampling for the two studies occurring before and after Cyclone Larry (Olley et al., 2013).

Modelled data have subsequently been used to estimate the relative contributions of gully and channel erosion to the overall subsurface contribution of fine sediment to the GBR. The best estimates from this work suggest that, on average, around 53% of the fine sediment load delivered to the GBR is sourced from gully erosion (McCloskey et al., 2016), although this proportion is only loosely constrained, and varies considerably between catchments. In some catchments (e.g., the Bowen) it is around 60%, and others substantially less. It should be highlighted, however, that gullies have a very broad definition within the model, and are assumed to include many small ephemeral channels as well as "real" gullies. Subsequent field studies (e.g., Thwaites et al., 2022) do not support this definition, and hence it is possible that the net contribution of sediment from gullies is in fact an overestimate, and conversely the contribution from channel erosion, if small ephemeral channels were added, is an underestimate. It should also be noted that many small streams are currently characterised as gullies in the Paddock to Reef (P2R) Source Catchments model, which is a source of internal error within the model, given that different approaches are required to manage erosion from small streams compared to gullies.

Of the subsurface gully sources, large alluvial[8] gullies are the most connected sources of fine sediment, delivering sediment in many cases directly into the mainstream channels of the largest rivers draining to the GBR. Hence, a major focus for remediation efforts since 2016 has been on these large alluvial gullies. A recent study has also demonstrated that alluvial gullies are major sources of particulate nutrients to the GBR (Garzon-Garcia et al., 2016). Hence, significantly reducing the loads derived from these alluvial gullies is critical if the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) water quality targets are to be met (Australian and Queensland Governments, 2018).

Despite some uncertainty over the relative contributions from different subsurface erosion processes, there was a strong consensus about the dominance of these subsurface erosion sources in the 2017 Scientific Consensus Statement (SCS) (Bartley et al., 2017). This is primarily a result of the accumulated evidence from sediment tracing studies (Hancock et al., 2014; Olley et al., 2013; Wilkinson et al., 2013) and empirical sediment budget studies using direct measurements of erosion from repeat lidar (e.g., Brooks et al., 2013). Consequently, there was a major pivot around 2016 towards investing in the rehabilitation of these subsurface sources as a means of reducing sediment inputs to the GBR, and

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[8] There are two major gully types; alluvial (or river associated) and colluvial (or hillslope gullies). This distinction is based on the material the gullies are eroding into: alluvium - sediments deposited overbank from rivers and streams; and colluvium -sediments derived from *in situ* weathering on slopes and/or downslope processes on hillslopes.

meeting the Reef 2050 WQIP water quality targets (refer also to Question 7.1, Coggan et al., this SCS, regarding water quality investment programs).

Prior to this, a series of plot-scale (~7 x 20 m) trials were undertaken in the Normanby catchment between 2011 and 2013 with extremely promising results, indicating that total erosion rates could be reduced by as much as 80% over a few years with the appropriate treatment of the dispersive alluvial soils (see Brooks et al., 2016; Shellberg & Brooks, 2013). However, these plot scale trials needed to be upscaled to complete alluvial gully complexes and different treatments tested at the whole of gully scale, with more rigorous monitoring of water quality and topographic change to ensure that the sort of results achieved at the plot scale can be replicated at the gully complex scale.

Given this recent history and the focus in recent years through programs like the Australian Government's Reef Trust Phase IV program which included major investment in remediation and rehabilitation of gullies and stream channels, there is now considerable interest among policy makers to understand the relative cost-effectiveness of reducing sediment loads through the treatment of these major subsurface sources of sediment and particulate nutrients. Consequently, the focus of this Question is on the evidence that can identify where resources should be expended to achieve the greatest lasting reductions in fine sediment in the shortest time per dollar of investment.

A broad range of remediation strategies have been implemented in recent years, both within gullies, but increasingly within river channels. In some cases, this may be at a site scale where a single eroding bank has rehabilitation works undertaken in an effort to reduce the erosion from the site to the whole river. Increasingly, however, works are being undertaken revegetating extended river reaches relying more on the "ecosystem engineering" role played by riparian vegetation to modify the amount of channel erosion that occurs as a function of the imposed cumulative stream power within the reach. Strategies such as this, while not necessarily stopping erosion, modify the rates of erosion, and importantly, deposition, back towards rates that more closely resemble the "natural rates of variability" that might have existed prior to European colonisation.

This synthesis of evidence reviews the literature to understand the extent to which the remediation approaches used for addressing both gully and stream channel erosion have reduced fine sediment and associated particulate nutrient export to the GBR. Since the 2017 SCS, a number of full-scale gully remediation treatment experiments have been implemented in the GBR, and they, along with other Australian and any relevant studies from other parts of the world are the focus for this review.

1.1 Question

Primary question	**Q3.6 a)** What is the effectiveness of gully and streambank restoration works in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? **Q3.6 b)** What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? **Q3.6 c)** What are the production outcomes of these practices?
Secondary question	**Q3.6.1** What is the benefit of vegetation restoration in 1) riparian zones and 2) hillslope and floodplain zones, in reducing sediment and particulate nutrient loss to the Great Barrier Reef?

The primary question, as framed, cannot be answered because it is asking whether the change associated with site-scale works can be detected at a catchment scale (i.e., sediment and particulate export from the GBR catchments). There are no datasets currently available that would enable this question to be answered. Hence, the question was reframed by focusing on the site or river reach scale. This review focused on evidence of the effectiveness of rehabilitation/remediation/restoration works at either the end of gully or within a defined river reach, or subcatchment, but not to the end of system. Definitions for each of the terms used in the search can be found in Table 2.

The term **restoration** is defined in the literature with a specific meaning, and is generally considered to be the return of a system to a prior state. In the context of this Question, the term has been interpreted as a management intervention. This could be covered by the terms system rehabilitation, remediation, restoration or repair. For the purposes of this review, the term "remediation" has been adopted for gullies, and "rehabilitation" for streambanks/riparian zones. The former typically involves more intensive earth works and soil amelioration than those required for streambanks.

Production outcomes are here defined as a private benefit flowing from the management intervention to a landholder's farming business.

Spatial variability refers here to the variation between different regions (e.g., Far North Queensland, to Central Queensland).

Climatic variability refers both to inter-annual variability in climatic conditions and differences in climatic zones between regions.

To define **costs**, the costs associated with a management intervention need to be attributed to a specific area, for which there is also treatment effectiveness data (i.e., measurements of sediment and particulate nutrient loads before and after the treatment). To be relevant to the GBR, costs need to be either in $AUD (i.e., Australian studies) or currencies associated with similar developed economies where it could be expected that they could be readily converted to $AUD. Consequently, this generally rules out examples from developing economies that include cheaper labour costs.

Cost-effectiveness is the dollar value of abatement for a unit mass of sediment and/or particulate nutrient per year.

1.2 Conceptual diagram

The conceptual model demonstrates the factors required to change the two dominant components of the GBR sediment budget (streambank – or channel erosion; and gully erosion) to a new state in which the supply from these sediment and particulate nutrient sources are significantly reduced as a result of management measures. The key considerations for determining whether restoration or rehabilitation works are effective at the site scale include the methods or treatments used, the sediment fraction characteristics, how long the treatment has been in place and the magnitude of events (e.g., storms, floods) the works have experienced, and the risk of failure under these events. This is determined through ongoing monitoring. In order to assess cost-effectiveness, it is critical to know the initial costs and follow-up maintenance costs, as well as the baseline against which management effectiveness is being measured.

Gullies and streambanks are inherently different landscapes and have unique contextual considerations and variables for assessing effectiveness. The type of river or gully must also be considered to determine the effectiveness or success of works in reducing sediment or particulate nutrient export. Spatial considerations are important in terms of the geoclimatic region of studies, measures of monitoring improvements or sediment reductions and whether studies have directly assessed a rehabilitation project or comparing different sites (e.g., different land cover). For streambank rehabilitation, the context of the project within the broader catchment is important, including whether catchment-scale reductions can be assessed from the rehabilitation works. Likewise, global reviews of gully erosion provide important examples of treatments undertaken within other regions, however, the extent to which they are relevant to the GBR is a significant issue.

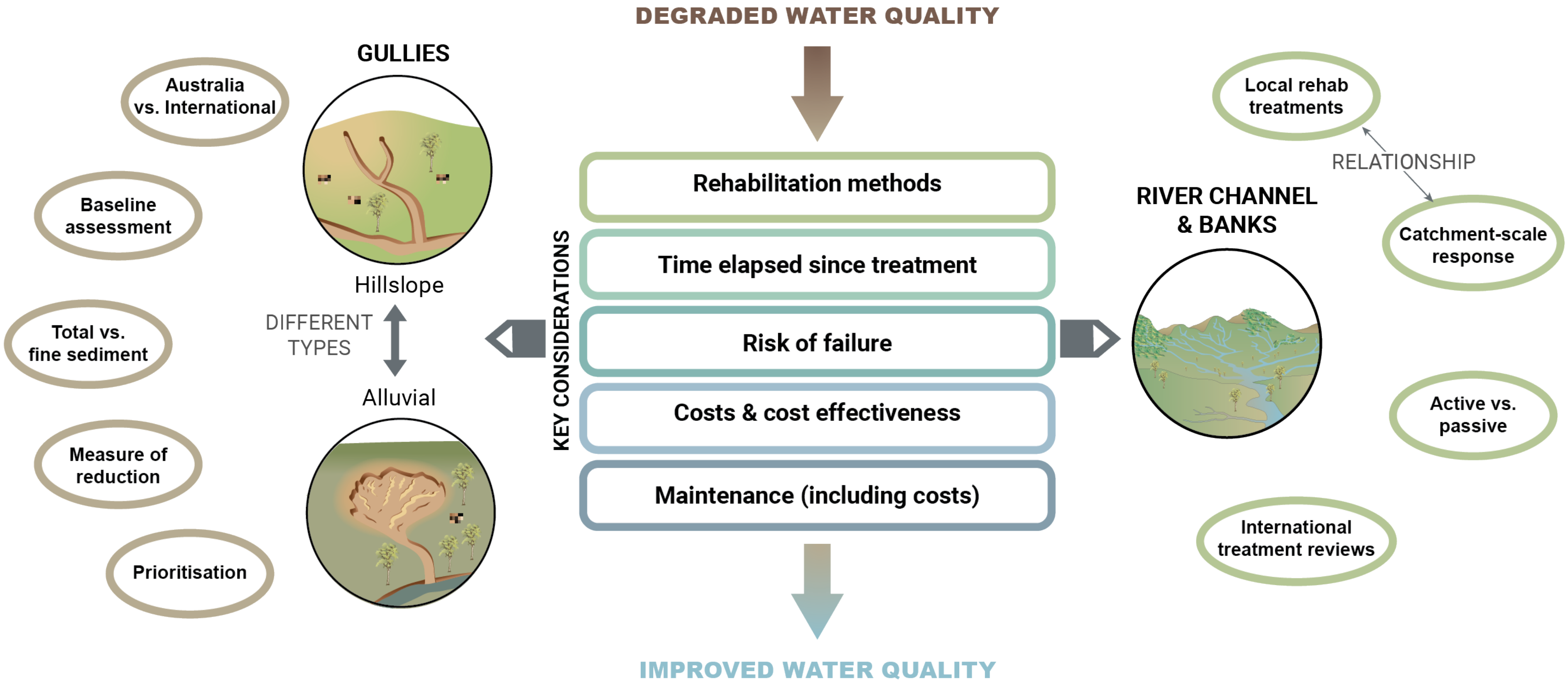

Figure 1. Conceptual model of the logic underpinning the review into the gully remediation and river channel/streambank erosion rehabilitation.

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 question linkages for this question are listed below.

Links to other related questions	**Q3.4** What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient loss to the Great Barrier Reef and how have these drivers changed over time? **Q3.5** What are the most effective management practices (all land uses) for reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, do these vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? (Effective management practices for reducing export to the Great Barrier Reef, cost-effectiveness, spatial variations, production outcomes; practices can act on the catchment processes and biophysical drivers.) **Q7.1** What is the mix of programs and instruments (collectively and individually) used in the Great Barrier Reef catchments to drive improved land management actions for Great Barrier Reef water quality benefits and how effective are they?

2. Method

A formal Rapid Review approach was used for the 2022 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[9]. 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 is the effectiveness of gully and streambank restoration works in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?***

The secondary question is: ***3.6.1 What is the benefit of vegetation restoration in 1) riparian zones and 2) hillslope and floodplain zones, in reducing sediment and particulate nutrient loss to the Great Barrier Reef?***

In addressing the questions, the authors also considered:

- What is the relevance to the GBR catchments of riparian restoration works outside of the GBR (Queensland, non GBR; Australia non GBR; international)?
- Is there an agreed method for determining the baseline against which to measure the effectiveness of streambank/river reach management effectiveness?
- For the secondary question – it was determined that the role of vegetation restoration on hillslopes and floodplains was being addressed by other questions (Question 3.5, Bartley & Murray, this SCS). As such this secondary question was not directly addressed in this question. The role of riparian vegetation ended up being a key focus of the whole assessment for the channel erosion component.

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[10] 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?

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[9] 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

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

Table 1. Description of question elements for Question 3.6.

Question S/PICO elements	Question term	Description
A) Gully		
Subject/Population	Fine sediment, particulate nutrients	Gully Sediment yield (or the mass of sediment delivered from a gully).
Intervention, exposure & qualifiers	Rehabilitated, restored, remediated or repaired gully	Gully management may cover one or more of several types of intervention (Grenfell et al., 2007; Lima et al., 2016): (i) restoration is the full reversion to pre-gully land use, which is uncommon for permanent gullies, (ii) remediation is the active intervention towards a new state, (iii) rehabilitation involves controlling the factors causing erosion and assisting recovery towards pre-gully condition. Repair is a colloquial term that is also used in some circumstances.
Comparator	Geographic location, gully type, soil type, treatment type	Geographic location: 1) GBR catchments; 2) rest of Queensland; 3) rest of Australia. Gully type: alluvial or hillslope gully, permanent and ephemeral gullies, badass, ravines, etc. (see Thwaites et al., 2022). Soil type; sodic versus no sodic soils; black soils, chromosols, goldfields soils, vertosols, vertisols, sodosols.
Outcome & outcome qualifiers	Efficacy in improving water quality in the GBR	Sediment or particulate nutrient (PN) abatement; sediment load, sediment concentration, sediment load reduction; baseline sediment load; historical sediment load – conceptually applies to gullies and stream/river channels in the same way – although there are very different methods required for determining efficacy in each.
B) Streambank		
Subject/Population	Fine sediment, particulate nutrients	Stream channel sediment yield, sediment loads.
Intervention, exposure & qualifiers	Rehabilitated, restored, remediated or repaired streambank, riparian zone	Streambank or riparian management may cover one or more of several types of intervention (Fryirs & Brierley, 2012): (i) restoration is the full reversion of a stream to its pre-disturbance state (highly unlikely), (ii) remediation is the active intervention towards a new state, (iii) rehabilitation involves controlling the factors causing erosion and assisting recovery towards pre-disturbance condition. Repair is a colloquial term that is also used in some circumstances.
Comparator	Geographic location, gully type, soil type, treatment type	Geographic location: 1) GBR catchments; 2) rest of Queensland; 3) rest of Australia. Alluvial sites/reaches only.
Outcome & outcome qualifiers	Efficacy in improving water quality in the GBR	Sediment or PN abatement; reduction in sediment load, sediment concentration, sediment load reduction; reduced bank retreat rate; baseline sediment load; historical sediment load.

Table 2. Definitions for terms used in Question 3.6.

Definitions	
Effectiveness	The ratio of the baseline sediment and/or particulate nutrient (SPN) yield minus the post "intervention" SPN yield all over the baseline yield. This can be expressed as a ratio (e.g., 0.9 - which would mean that the post remediation yield is 90% less than the pre-treatment yield) or as a percentage. A full explanation of this definition can be found in Brooks et al. (2021). This then requires a definition of how baseline SPN yield is calculated and the spatial scale at which the baseline is measured. Many studies refer to % reduction – however for consistency, we refer throughout the document to effectiveness ratios (between 0 and 1.0). In one case a ratio of >1.0 is reported).
Gully	The Paddock to Reef model defines **gullies** according to the definition in the "Yellow Book" (Australian Soil and Land survey field Handbook, 3rd Edition), however as outlined in Thwaites et al. (2022), this definition is very broad, and includes all "actual gullies" as well as all small ephemeral streams. Hence for the purposes of this review, the narrower more technical definition of gullies was considered, as outlined in Brooks et al. (2020a) and Thwaites et al. (2022), as these are the most common features for active gully management efforts nowadays. The authors are not aware of any examples of small ephemeral stream active management (as a gully). **Gully Definition–** the defining characteristics of a gully (from Brooks et al., 2019; 2020a; Thwaites et al., 2022) are: a) A persistent erosional landscape feature > 0.5 m deep (from the surrounding residual land surface) that has multiple modes of expansion, but typically including headward retreat into an otherwise undissected (since land use intensification) landscape. b) An active headscarp at the upslope limit, and sometimes the lateral margins of the gully. In some cases, there may be a series of headscarps representing multiple incisional phases. A scalded area (i.e., an area stripped of its topsoil with degraded vegetative cover) may often fringe the upslope area of the headscarp. c) The land upslope of, or beyond, the gully may be a swamp or drainage depression in keeping with the incisional caveats above. d) Gullies are typically driven by ephemeral flows (i.e., associated with direct rainfall on the gully and in the gully catchment), although there are some alluvial gullies that can experience overbank flooding or backwatering from river channels to which they are connected (sensu Brooks et al., 2009; Shellberg et al., 2013). e) Sediment transported from a gully is primarily sourced from within the erosion feature itself (i.e., it is dominated by an "autochthonous" source). f) While gullies can have temporary depositional units within the gully floor, comprising materials predominantly eroded from within the feature, these units are not as spatially organised as the depositional features within a stream channel bed, which will include materials that can be identified as deriving from outside the feature location (i.e., "allochthonous" sources). g) There is a wide diversity of gullies, differentiated into two fundamental types: Alluvial and Hillslope (i.e., in residual soil or colluvium) gullies (as well as their possible intergrade/ combination type). They are also found in a wide variety of soils, soil materials, and sediment types. The diversity of gullies is described in Brooks et al. (2019) and Thwaites et al. (2022).
Sediment	Mineral **sediment** particles sourced from gully or stream channel erosion and transported through the channel network to the GBR lagoon. The review is primarily concerned with the fine suspended sediment fraction, which is defined as the fraction that is less than 20 µm.
Particulate nutrients	**Particulate nutrients** are assumed here to refer to the particulate nitrogen (PN) pools. Garzon-Garcia et al. (2016) and (2022), found that there is a good correlation between sediment yields and particulate nutrient yields, hence it is reasonable to assume that strategies that reduce sediment loads, will also reduce particulate nutrient yields by a

Definitions	
	similar proportion. Particulate nutrients are defined by Garzon-Garcia et al. (2019) as being composed of the following: 1. Solubilised dissolved inorganic nitrogen (DIN) - fast occurring process at source in which the DIN (all the nitrate (NO_3-), nitrogen (N) and the N fraction of the ammonium (NH4+-N) not adsorbed onto sediment) in the eroded soil pore water and leached from the soil and litter enters the aquatic environment via runoff. This fraction is transported to the stream system irrespective of the bulk soil being delivered. 2. Mineralisable particulate organic nitrogen (PON) and dissolved organic nitrogen (DON) (Potential mineralisable nitrogen). This is a slow occurring process with a timeframe of days to weeks (depending on the length of time sediment is in suspension and or water travel time) in which the organic fraction of particulate N associated with the eroded sediment and the organic fraction of dissolved N that has been mobilised from eroded soil, vegetation litter or microbial processes are mineralised to DIN during stream transport by the action of micro-organisms (bacteria and fungi). A fraction of the DON may be directly bioavailable to phytoplankton without the need to be mineralised. 3. Desorbed ammonium-N - This is a physico-chemical process in which the ammonium ion (NH4+) adsorbed to negatively charged silt and clay particles in eroded sediment is desorbed (becomes soluble) through exchange processes with other ions in water. This process is particularly likely to occur when terrestrial sediment enters saline water containing high concentration sodium and magnesium in the estuaries.
Streambank	The term "**streambank**" is defined in a broader sense to include the whole channel and riparian zone, rather than a specific bank. This is based on the authors' experience in which projects are increasingly focusing on the revegetation/treatment of whole stream reaches as a management intervention. Hence just focusing on a streambank is too narrow a focus for the review. Furthermore, many channels have a complex cross section with more than one bank face – so it is not helpful to just use the term "streambank" as this would require identifying which bank, on which part of the channel cross section is being treated. This does not preclude from the review sites that may have just treated a single bank, providing they meet the other criteria for inclusion.
Baseline yields	**Baseline yields** can be readily determined for gullies, and there are agreed methods in the National Environmental Science Program (NESP) Tropical Water Quality Hub Project 3.1.7 (Brooks et al., 2021) as well as the Reef Credit gully methods (Brooks et al., 2020) and the gully toolbox (Wilkinson et al., 2022). The same cannot be said for the calculation of baseline sediment yields for streams. Effectiveness of a management intervention within streams needs to be considered in a fundamentally different way to the way the term is used in gullies. Stream channels by definition are dynamic complex systems, in which there is erosion and deposition, and in which retention of sediment and particulate nutrients is spatially and temporally variable. So, it is really only possible to determine general trajectories of change and whether the trend is in a positive or negative direction. *For the purposes of this review, to determine the effectiveness of a riparian/streambank project, there would need to be some quantitative measure of the sediment and particulate nutrient loads prior to the intervention and some measure of the post-rehabilitation water quality that can be tied directly to the effect of the intervention.*
Riparian	A consistent definition of what constitutes the "**riparian zone**" has yet to be derived for Queensland rivers. For the purposes of this review, the riparian zone is defined as the land encompassing the river or stream channel and its immediate surrounds (includes the in-channel zone above the low flow channel). It also includes an indeterminate amount of land on the bank top, extending away from the channel. Quantifying the extent of land that should be considered to be "riparian" is a major research need in its

Definitions	
	own right, and will need to be flexible enough to vary as a function of river type, scale and flow regime. The relative benefit of riparian versus floodplain versus hillslope revegetation is very complex and is deemed to be beyond the scope of this review. Hillslope processes are being dealt with in Question 3.5 (Bartley & Murray, this SCS) and Question 4.6 (Thorburn et al., this SCS), and to date no one in the GBR is undertaking, or proposing to undertake, whole of floodplain revegetation (i.e., from a situation where it is currently cleared). As such, it is regarded that assessing the relative importance (for water quality) of revegetating riparian zones versus floodplains (which some considered to be riparian anyway) is unfeasible at this point in time.
Erosion	The removal of sediment particles by the action of water, including overland flow, stream flow and raindrop impact.
Restoration, rehabilitation, remediation or repair	For the purposes of this review, the term **gully restoration** has been taken to be interchangeable with the terms gully remediation, rehabilitation, reclamation and repair. For rivers and streams, the term **streambank rehabilitation** is considered to include any works undertaken within a stream channel, channel banks or adjacent riparian area with the intent of improving ecosystem outcomes. Although the terms *restoration, rehabilitation* and *remediation* are considered within academic literature to be different and have different meanings (Rutherfurd et al., 2000), for the purposes of this review, the term "remediation" has been adopted for gullies, and "rehabilitation" for streambanks/riparian zones.
Abatement	Avoided future erosion.
TSS	Total suspended solids.
SSC	Suspended sediment concentration.

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 in:

- 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 Question 3.6.

Question element	Search terms
Subject/Population	Suspended sediment, particulate nutrient, fine sediment, TSS, SSC
Exposure or Intervention	Channel, gully, restoration, rehabilitation, remediation, streambank, riparian
Comparator	GBR, Great Barrier Reef, Queensland, Australia
Outcome	Sediment load reduction, water quality improvement, particulate nutrient load reduction, deposition rate

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.

Search strings
Gully restoration search:
(gully AND “sediment reduction”) AND (Australia)
(gully AND “nutrient reduction”) AND (Australia)
gully AND (rehabilitation OR restoration OR remediation) AND (Australia)
TITLE-ABS KEY ((gully AND (rehabilitation OR restoration OR remediation) AND (australia)) AND NOT (min**))
Streambank/channel rehabilitation search:
(streambank OR channel OR riparian) AND (rehabilitation OR restoration OR remediation) AND (Australia)
(streambank OR channel) AND (stabilisation) AND (Australia)

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 Question 3.6 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Sediment, TSS, SSC, particulate nutrients	Coarse sediments; No assessment factor of streambank/channel management; no quantitative data; no focus on water quality; gullies – geographical context too different to GBR.
Exposure or Intervention	Channel, gully, restoration, rehabilitation, remediation, streambank, riparian	
Outcome	Reduction, effectiveness, abatement, improvement, change	No direct or inferred sediment or particulate nutrient load data, or in some way quantify the treatment effectiveness (e.g., through lidar terrain analysis) associated with the treatment; poor study design; no contribution to primary question.
Language	English	Non-English publications
Study type	Primary studies: Observational, experimental Secondary studies: Reviews, synthesis; Conceptual or modelling approaches for background relevance	Modelled data Studies published before 1990 for gullies, but no time constraint for riparian/streambank.

3. Search Results

A total of 114 studies (43 gully studies and 71 streambank studies) were identified through online searches for peer reviewed and published literature. Additionally, 24 studies were identified manually through expert contact and personal collections, which represented 17% of the total evidence. Three additional studies were added during the review process. Overall, 88 studies (33 gully studies and 55 streambank studies) were eligible for inclusion in the synthesis of evidence (Table 6) (Figure 2). Three identified studies were unobtainable.

Table 6. Search results table, separated by A) Academic databases, B) Search engines and C) Manual searches. The search results for A and B are provided in the format X (Z) of Y, where: X (number of relevant evidence items retained); Y (total number of search returns or hits); and Z (number of relevant returns that had already been found in previous searches).

Date	Search strings	Sources	
Gully			
A) Academic databases		Scopus	Web of Science
February 2023	(gully AND (rehabilitation OR restoration OR remediation) AND (australia)) AND (effectiveness)	38 of 754	0 of 13
February 2023	(gully AND (rehabilitation OR restoration OR remediation) AND (australia)) AND (effectiveness) AND NOT (min**) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "EART"))	0 of 133	20 (20) of 1328
B) Search engines (Google Scholar)			
February 2023	(gully AND (rehabilitation OR restoration OR remediation) AND (australia)) AND (effectiveness)	5 additional items of 18,100 (only first 200 checked)	
	Total items online searches	**43 (78%)**	
C) Manual search			
Date	Source	Number of items added	
February 2023	-Author personal collection (gully) -Studies cited in the Gully and Streambank Toolbox v3	4 reports 8 articles	
	Total items manual searches	12 (22%)	
Streambank			
A) Academic databases		Scopus	Web of Science
February 2023	{riparian} OR {channel?} OR {streambank} AND {rehabilitation} OR {restoration} AND {Australia} AND {effectiveness}	3 of 16	3 of 38
February 2023	{riparian} OR {channel?} OR {streambank} AND {rehabilitation} OR {restoration} AND {effectiveness} AND {sediment} OR {nutrient?}	4 (3) of 51	7 of 126
February 2023	{riparian} OR {channel?} OR {streambank} AND {rehabilitation} OR {restoration} AND {effectiveness}	16 of 249	9 of 256

Date	Search strings	Sources
B) Search engines (Google Scholar)		
February 2023	*{riparian} OR {channel} OR {streambank} AND {rehabilitation} OR {restoration} AND {Australia} AND {effectiveness}*	*32 items of 4,340 (only first 200 checked)*
	Total items online searches	*71* **(86%)**
C) Manual search		
Date	Source	Number of items added
February 2023	*-Author personal collection* *-Citations from Paul et al. (2018)*	*6 papers, 2 reports* *4 papers*
	Total items manual searches	*12* **(14%)**

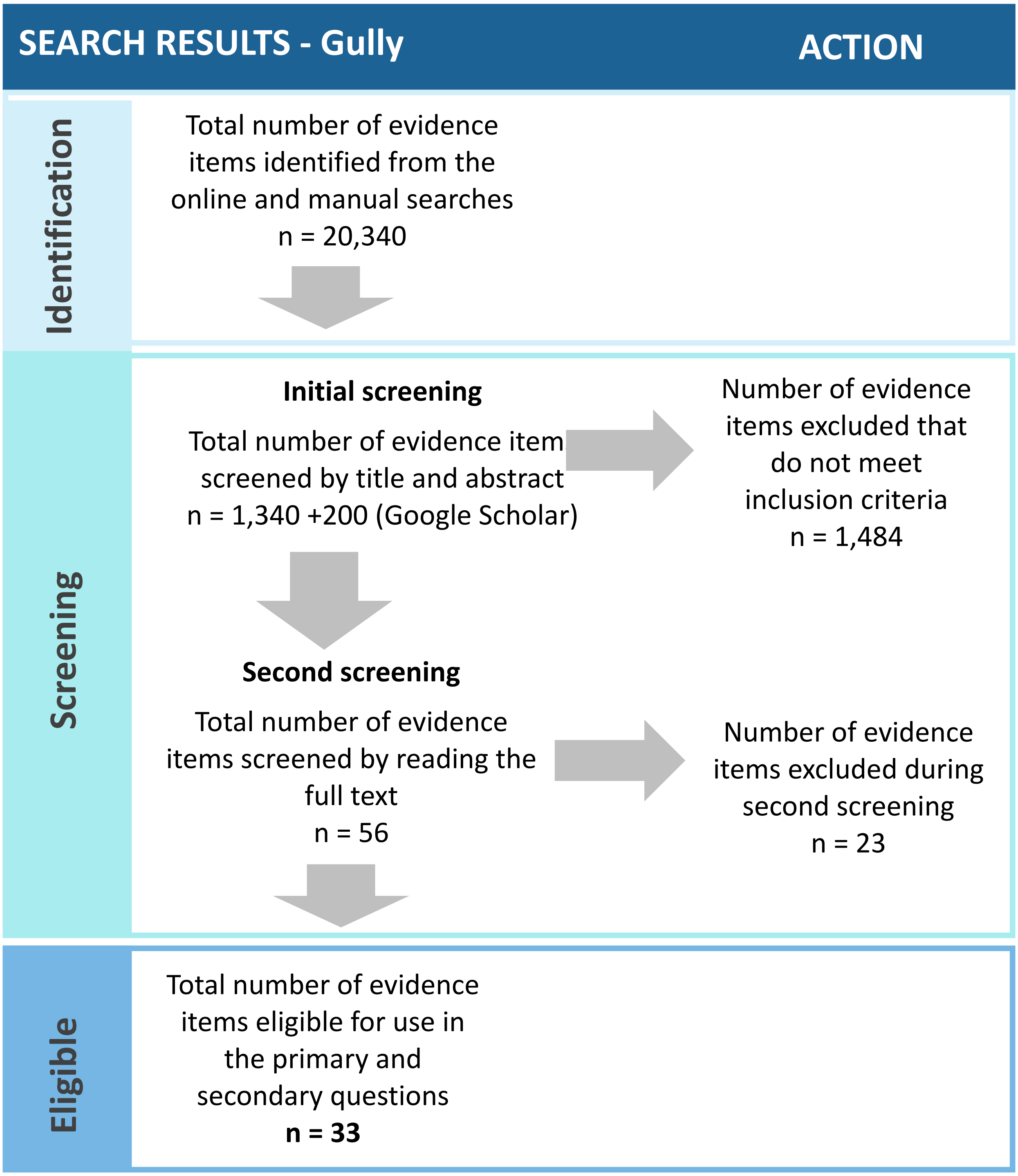

Figure 2a. Flow chart of results of screening and assessing all search results for Gully Remediation.

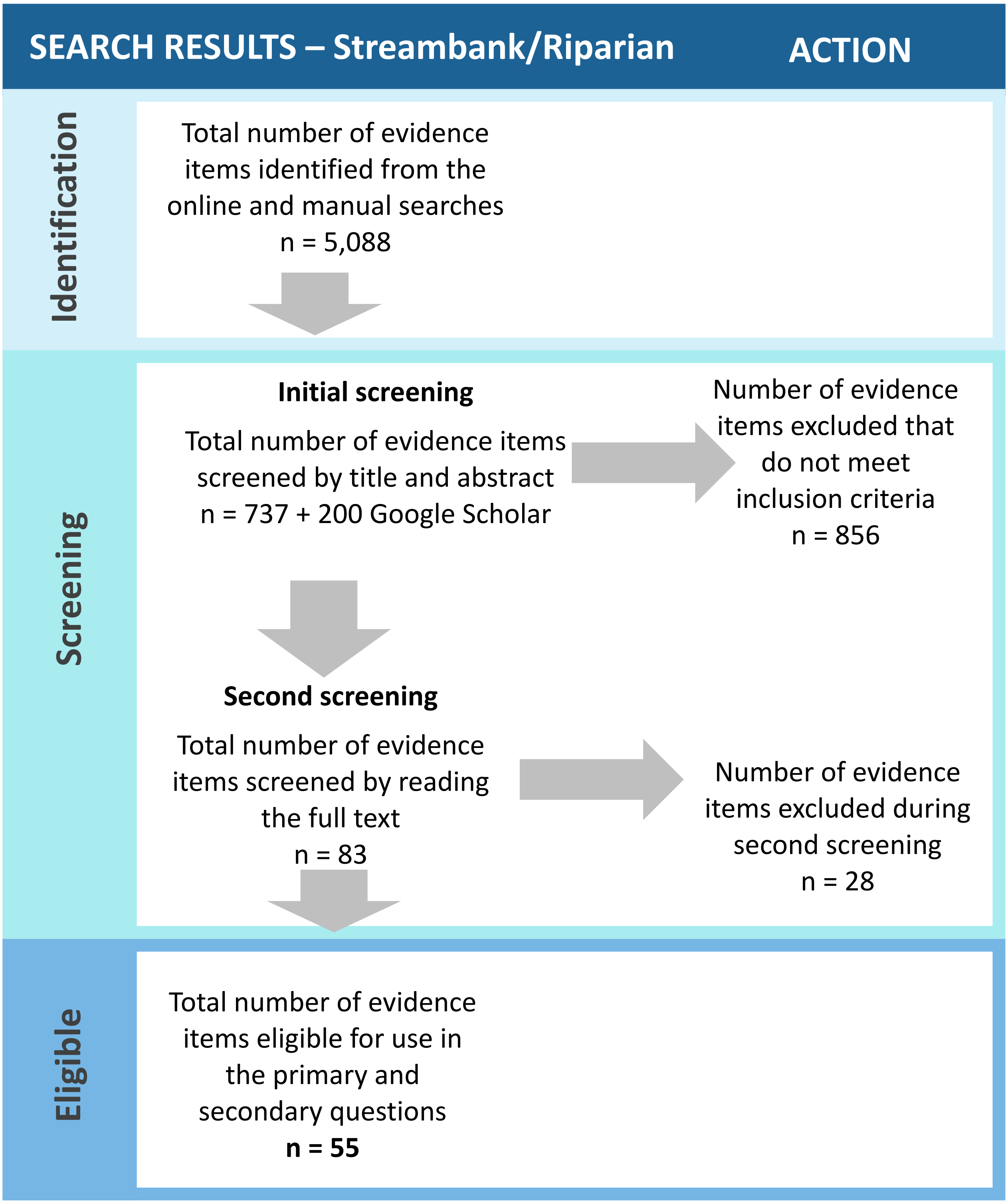

Figure 2b. Flow chart of results of screening and assessing all search results for streambank/riparian rehabilitation.

4. Key Findings

4.1 Narrative synthesis

4.1.1 Gully

Q3.6i Primary question:

- What is the effectiveness of **gully** restoration works in reducing sediment and particulate nutrient loss from Great Barrier Reef catchments, does this vary spatially or in different climatic conditions?
- What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions?
- What are the production outcomes of these practices?

Note on Definitions

For the purposes of this review, the term *gully restoration* has been taken to be interchangeable with the terms gully remediation, rehabilitation, reclamation and repair. This is despite the fact that entire papers have been written about the differences between such terms, particularly in the context of mine site remediation (e.g., Lima et al., 2016) and river rehabilitation (Fryirs & Brierley, 2012; Rutherfurd et al., 2000). The objective was to determine where there was *any* evidence that treatments *of any kind* have had a measurable impact on water quality emanating from gullied lands. Hence which term is applied to the treatment is largely irrelevant for the purposes of this literature review. It also became readily apparent in undertaking the review that there is no consistency among researchers in the usage of these various terms in the context of gully management, and hence by preferencing one term over the other meant that we risked missing evidence from the literature. As a personal preference, from hereon in, the term remediation is used, as it is in common usage for the sorts of gully treatments this review is interested in.

Summary of study characteristics

Following a wide search of the international scientific literature, encompassing > 1,000 potentially relevant studies, including peer reviewed reports (primarily from the NESP Tropical Water Quality Hub) focused on GBR catchment management, a subset of 56 studies were reviewed in detail. Of these, a short list of 33 studies were considered to have some specific relevance to the primary question. However, it must be said that the number of studies globally that have quantified the effectiveness of gully remediation at improving water quality is extremely limited, particularly in terms of the fine-grained suspended sediment fraction and/or particulate nutrients. In this regard, the work undertaken within the GBR catchments stands out as far as the quality of the science and, unsurprisingly, the specific relevance of the data and analysis to the questions being addressed in this review.

Of the shortlisted studies, four were global reviews about gully erosion, all of which touched on aspects of gully remediation. On the whole, these reviews provided little useful insight to help answer the primary question. Indeed, the global literature reviews primarily served the purpose of highlighting how few studies there are that have quantified the water quality benefits of gully remediation programs (Bartley et al., 2020a; Castillo & Gomez, 2016; Frankl et al., 2021; Vanmaercke et al., 2021). Most of the international (non-Australian) studies that looked at gully remediation were more focused on documenting the reduction in the progress of gully headscarp migration and the associated loss of productive land (e.g., Addisie et al., 2018; Ayele et al., 2018) and/or the trapping of coarse sediment in gully floors or in ephemeral channel beds (Alfonso-Torreño et al., 2022; Wei et al., 2018). It could be inferred that gully headscarp migration rates have a bearing on sediment yields, but this review only considers studies that either directly measured the impact of treatments on water quality, and/or where a method was presented to translate the headscarp retreat rate into an annual sediment load (Koci et al., 2021, for example).

Of the shortlisted studies, 62% were Australian, and of these 78% were from within the GBR catchments (Figure 3a). Any understanding of gully remediation in the GBR needs to distinguish whether they are dealing with alluvial or hillslope gullies (sensu Brooks et al., 2009). Of the studies that focused specifically on alluvial gully erosion, all were from Australia, and all but one, were from the GBR catchments (Figure 3b). In part this reflects the fact that the science that has identified fundamental differences between alluvial (gullies within alluvium) and hillslope gullies (gullies within colluvium), has been undertaken in Australia (Brooks et al., 2009; Shellberg & Brooks, 2013; Shellberg et al., 2013; 2016; Thwaites et al., 2022), and the greatest investments in gully remediation have been made within the GBR catchments.

Most of the international studies that focus on gully remediation are typically concerned with linear hillslope gully erosion measures, which overwhelmingly consists of the installation of check dams spaced along the length of the gully. Most of the studies that have quantified the effectiveness of check dams are, however, focused on total sediment load (i.e., bedload and suspended load), and as such are of limited relevance to the GBR, given the primary focus in the GBR is on the reduction of fine suspended sediment loads. Only one study by Koci et al. (2021), evaluated the effectiveness of check dams as a management strategy in the GBR, and they found that this strategy was largely ineffective at reducing suspended sediment loads, with silt and clay yields only being reduced by between 7-19% after 8 years, and these were in gullies with relatively low specific total sediment yields of 0.4-3 t/ha/year to start with, and much lower fine sediment yields. A limitation of the Koci et al. (2021) study, was, however, that fine sediment reduction was not directly measured. Rather than being derived from the particle size of sediments in water samples, it was inferred from the particle size of the material trapped behind the check dams, and the potential yield was inferred from the particle size data from soil samples within the materials into which the gullies were eroding. Such an approach is not regarded as being "best - practice" for determining fine sediment loads, hence it is likely that these data would have a higher uncertainty than for some of the other effectiveness data discussed below.

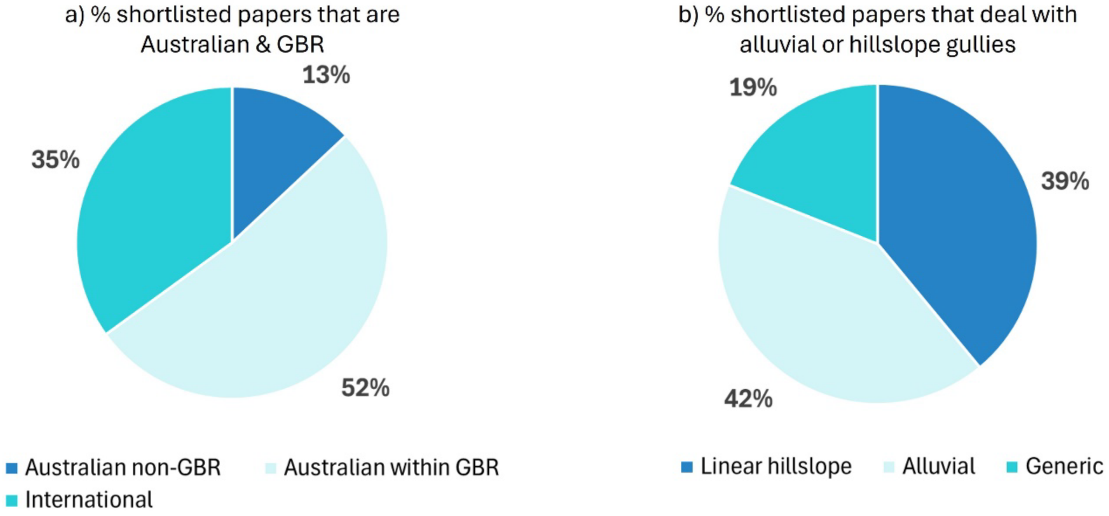

Figure 3. a) percentage of shortlisted studies that are specifically Australian and GBR focused; b) percentage of studies that focus on either alluvial gullies or hillslope gullies.

Summary of evidence to 2022

The importance of different gully types for understanding effectiveness

Since the 2017 SCS (Bartley et al., 2017), several studies have highlighted that some large gullies, which are predominantly the alluvial type, are disproportionately contributing fine sediment to the GBR from a small number of sites (Brooks et al., 2020b; Daley et al., 2021). With the availability of high-resolution mapping, as outlined in Daley et al. (2021), it has become increasingly apparent that major inroads into water quality targets can be made by treating this small number of high yielding sites. As a result of these insights, in the period since 2017 a substantial proportion of investment into gully remediation in the GBR has been focused on alluvial gullies. Hence it is clear that any assessment of the effectiveness of gully remediation treatments, must differentiate between the type of gully being treated and whether it is wholescale reshaping treatment of high yielding gullies, or treatments of low lower yielding linear gullies. Findings from studies focused on check dams in gullies can only be applied to similar applications in the GBR, and conversely findings from alluvial gully studies can only be applied to treatments of alluvial gullies. The review found no studies outside of Australia that have treated alluvial gullies and/or Badlands (see Brooks et al., 2009; Thwaites et al., 2022) using approaches that in any way resemble those being applied in most gully remediation projects now being undertaken within the GBR catchments. Hence the synthesis that follows focuses on the findings that are specifically relevant to either alluvial or hillslope gully treatments within the GBR.

Table 7. Summary of the shortlisted literature by study type.

Type of Study	Comments	Authors
International literature reviews which include some reference to gully remediation.	Despite the broad sweep of the reviews, these reviews highlight the fact that there are very few studies that have measured water quality (particularly suspended sediment) as a primary response to gully remediation.	Bartley et al., 2020b; Castillo & Gomez, 2016; Frankl et al., 2021; Vanmaercke et al., 2021
Gully process studies that shed light on establishing baseline sediment yields.	Studies that highlight rigorous methods for establishing baseline sediment yields for gullies, or components thereof, including the important role that direct rainfall plays as a driver of erosion in some gullies.	Anderson et al., 2021; Bartley et al., 2007; Brooks et al., 2020b; Daley et al., 2021; 2023; Doriean et al., 2020; Shellberg et al., 2013; 2016; Wilkinson et al., 2018
Studies focused on understanding different types of gullies.	Studies that highlight fundamental differences between key gully types - particularly as a basis for understanding remediation requirements and baseline yields.	Brooks et al., 2009; Thwaites et al., 2022
Studies focused on the role of check dams in linear gullies.	Wide array of studies - primarily focused on the role that check dams have on reducing total sediment yield.	Addisie et al., 2018; Alfonso-Torreño et al., 2022 ; Ayele et al., 2018; Koci et al., 2021; Wei et al., 2018; Yitbarek et al., 2012
Studies that have assessed the economics of gully remediation.	Very small number of studies that have attempted to determine the cost-effectiveness of gully remediation.	Bartley et al., 2020b; Brooks et al., 2021; Rust & Star, 2018; Star et al., 2021; Yitbarek et al., 2012
Studies that have measured fine sediment reduction associated with gully remediation.	These studies are all from within the GBR.	Bartley et al., 2020a; 2020b; Bartley & Brooks, 2021; Brooks et al., 2016; 2021; Doriean et al., 2021; Shellberg & Brooks, 2013
Studies that have quantified nutrient yields and/or reductions from gullies in association with gully remediation.	With the exception of the Saxton et al. paper, each of these studies are from GBR catchments.	Bartley et al., 2020b; Brooks et al., 2016; 2021; Doriean et al., 2021; Saxton et al., 2012

Prioritising and targeting gully erosion management

The evidence that highlighted the significance of alluvial gullies was considered before reviewing the evidence of treatment effectiveness from studies within the GBR. While there are likely hundreds of thousands of gullies across the entire GBR catchment area, it is now clear that the population is highly skewed, with a small proportion of the gullies contributing a substantial proportion of the erosion and therefore sediment runoff to the GBR (Daley et al., 2021). High resolution gully mapping and characterisation using a combination of lidar data, satellite imagery and field survey shows that there are distinct differences between alluvial and colluvial (or hillslope gullies) in terms of their sediment yield and morphological characteristics. The following section summarises the findings from Daley et al. (2021) who outlined the mapping process and the results from this survey regarding the distribution of gullies in selected areas of key GBR catchments, and their relative sediment yields.

Key findings from high resolution gully mapping

Gully mapping and sediment yield analysis across 5,300 km^2 of the Bowen-Broken-Bogie (BBB), Normanby and Fitzroy catchments show that gullies comprise between 0.26% and 1.32% of the landscape (Table 8) (Daley et al., 2021). These areas were selected for mapping and analysis on the basis that they had an above average density of gullies per unit land area than the rest of the catchments, so in that sense they were biased samples. The majority of the GBR catchments will have a lower average density and specific sediment yield associated with gully erosion than these studies report. However, there is no reason to believe that the general trends that emerge from these data are unrepresentative of the GBR-wide gully population. In each catchment, the gully lifetime sediment yield is highly skewed, with a small number of gullies contributing a substantial proportion of the net gully lifetime sediment yield. In the Bowen, Broken Bogie (BBB), 2% of gullies contribute 30% of the total sediment yield; whereas 6% contribute 50%. In the Fitzroy, 1.5% of gullies produce 30% of the sediment yield whereas 4% of the gullies produce 50% of the yield, while in the Laura catchment (tributary of the Normanby), 3.5% of gullies produce 30% of the sediment yield and 10% of the gullies produce 50% of the yield (Daley et al., 2021). These data highlight the need for targeting the high yielding gullies as a means of efficiently and cost effectively achieving catchment water quality targets. Table 8 shows the relative breakdown between alluvial and colluvial gullies in the three catchments. Interestingly, while the highest yielding gullies in all catchments are alluvial gullies, there are a greater number of colluvial gullies in the BBB than alluvial gullies – some of which are large and high yielding. Hence there is a need to remediate a proportion of these larger high yielding gullies in this catchment, as well as the alluvial gullies.

Table 8. Breakdown of gully area and type in the three catchments sampled using high resolution mapping (Daley et al., 2021).

	BBB	Fitzroy	Normanby	Total
Area of analysis (km^2)	3,507	1,210	571	**5,288**
No. gullies	22,311	1,785	1,820	**25,916**
Gully area (ha)	4,621	312	563	**5,496**
Proportion of land gullied (%)	1.32	0.26	0.99	**1.04**
Proportion alluvial:hillslope (%)	43	60	91	**49**

Sediment reduction treatment effectiveness in GBR gullies

To date, there are only two major studies in GBR catchments, both NESP studies, that have quantified the effectiveness of gully treatments on improving water quality (Table 9). Both studies use best-practice Before After Control Impact (BACI) study designs which incorporate multiple lines of evidence to measure reductions in both sediment and nutrient loads. The study by Brooks et al. (2021) focused on five separate alluvial gullies on the Laura River in Cape York, and ten gullies at Strathalbyn Station in the lower Burdekin. Bartley et al. (2020b) analysed a selection of paired hillslope gullies (control and treatment) at five sites throughout the Burdekin catchment, and alluvial gullies at two sites in the Bowen subcatchment.

At the completion of the NESP Tropical Water Quality Hub Program, results from the alluvial gullies reported in Bartley et al. (2020b) showed a fine sediment Remediation Effectiveness Ratio (RER) of 0.85 (at End of Gully) in sediment yield at the Mount Wickham site, based on three years of post-treatment monitoring data (Table 9). The data from the Glen Bowen study was inconclusive at that point, given that it had only been monitored for one year, albeit showing extremely encouraging results based on the initial TSS concentration data. Both these sites involved the complete reshaping of alluvial gullies, with soil amelioration and the application of organic mulch on the surface, coupled with revegetation using exotic grasses. The treatment also included strategic placement of contour banks and rock chutes at active gully heads and as bed-control structures within the gully floor.

Alluvial gully remediation effectiveness reported in Brooks et al. (2021) and Doriean et al. (2021) from the Crocodile site on the Laura River, demonstrated that an effectiveness of 0.795 was achieved for the < 20 µm sediment fraction based on the water quality monitoring data, for the fully reformed gully and its catchment. The terrestrial lidar change detection demonstrated that the treated part of the gully (i.e., excluding the catchment) achieved an RER of 1.02 within three years of remediation (Table 9). Combining the two different lines of evidence demonstrates that all the sediment being delivered to the gully outlet after the treatment, was sourced from the catchment above the gully, some of which was trapped within the treated gully, giving rise to the situation where the treatment effectiveness was marginally greater than 1.0. The three other gullies that were also monitored as part of this experiment, only had partial treatments using rock chutes at the gully heads (i.e., gully sidewalls were not treated). Insufficient water quality monitoring data was collected over the first two years post-treatment from these sites to fully quantify effectiveness, particularly in year two, however it was clear that in the first year post-treatment sediment yields had increased above the baseline and control. This was a function of a major rain event that occurred during the remediation construction period when earth works were underway. The fact that monitoring was underway during construction and captured this event was unusual and is unlikely to be replicated in any of the other studies. A single sample from each of the sites in the second year post-treatment showed that the fine sediment RER was between 0.08 and 0.51. However, given these results are based on a single sample from each gully, they should be viewed with some caution. Lidar change detection from the same sites, reveals a different story, with effectiveness ratios of 0.75 - 0.95 based on Control/Impact data, or 0.62 – 0.77 based on before/after data, apparent after two years. The lidar data, however, does not account for the sediment delivered during construction, given that it is based on the post-treatment surface condition compared with subsequent post-wet season topographic surveys.

A more comprehensive dataset is available for the Strathalbyn site based on both before/after and Control/Impact monitoring across ten discrete gullies over four years, in which there was a phased implementation of the remediation strategy (Brooks et al., 2021). The results of the remediation at these gullies are summarised in Table 10, and show that the mean RER across all sites, one to three years after treatment is 0.98 (Table 9). Treatments 1 – 8 all involved complete gully reshaping, soil amelioration and surface capping of the reformed surface with either rock and organic mulch or imported soil and mulch. All treatments that used reshaping, amelioration and capping with rock and mulch demonstrated considerable consistency in their effectiveness ratios, regardless of which method is used to quantify effectiveness. Two of the treatments (2 and 6) were established to test the effectiveness of cheaper surface capping materials (T2 – locally sourced topsoil and jute matting + revegetation; and at T6 mulch and bunding bunds on the slope contours – coupled with revegetation). The results in Table 10 show that these treatments were not as effective as the treatments incorporating rock surface capping.

Sites Reef Trust (RT) 4 I, RT4 II and RT4 III (Table 10) were a separate experiment that involved some reshaping of the active areas of the gully heads and sidewalls, but were primarily set up to assess the potential for the use of short-term intensive cattle grazing as a remediation method on gully floors (so called “cattle stomping”). While the results in Table 10 suggest these treatments were quite effective (0.64 – 0.98), it should also be pointed out that subsequent spatial stratification of the analysis at the RTI & II sites (Daley, 2022), demonstrated that most of the response at these sites (i.e., the bulk of the sediment reduction) could be attributed to the reshaped and capped sections of the treatments (RER 0.999) and these were the highest yielding parts of the gullies. The changes in areas subject to the intensive grazing had RERs between 0.47 – 0.87 across three years, with a significant area below the limit of detection of the high resolution lidar.

Table 9. Synthesis of the treatment history and monitoring results for all sites within NESP Tropical Water Quality (TWQ) Hub Projects 2.1.4, 5.9 and 3.1.7, and includes sites funded by the Landholders Driving Change Program in the Bowen Broken Bogie catchments in the Burdekin region.

	NESP TWQ Hub Projects 2.1.4 and 5.9 (Bartley et al., 2020b)							**NESP TWQ Hub Project 3.1.7 (Brooks et al., 2021)**	
	Virginia Park	**Meadowvale**	**Strathbogie**	**Minnievale**	**Mt Wickham**	**Glen Bowen**	**Mt Pleasant**	**Crocodile Station**	**Strathalbyn Station**
Basin	Upper Burdekin	Upper Burdekin	Bogie (Burdekin)	Don (Burdekin)	Bowen (Burdekin)	Bowen (Burdekin)	Bogie (Burdekin)	Normanby	Burdekin
Gully type	Linear hillslope gullies	Linear hillslope gullies	Linear hillslope gullies	Linear hillslope gullies	Major alluvial gullies	Major alluvial gullies	Linear hillslope gullies	Large alluvial gully system	Large alluvial gully system
Catchment area[a]	1.3 ha	5.0 ha	41 ha	25 ha	14 ha	2.7 ha	259 ha	37.4 ha	122 ha
Treatment area-active/passive[b]	0.13 ha / 1.17 ha	NA / 3 ha	~1 ha /40 ha (proposed)	3 ha / 23 ha	~8 ha / 9 ha (proposed)	~2.4 ha / 0.3 ha	0.5 ha / 258 ha	0.9 ha / 36.5 ha	19.8 ha /102 ha
Treatment	- Disc plough above gully - Fencing - Porous check dams in gully	- Fencing - 30% gully catchment has cattle exclusion	- Hillslope flow diversion banks with drains - Fencing - Small rock revetment neat headcut	- Hillslope ripped and seeded - Fencing - Porous check dams	- Major earth works, soil treatment, rock chute structures - Fencing - Revegetation	- Major earth works, soil treatment, rock chute structures, earth bund, water points - Fencing (pending) - Revegetation	-Landscape rehydration -V-notch log rock sill structures and earth bank to divert flows -Fencing (pending)	- Gullies 2.234: Fully reshaping, soil treatment, rock capping, rock check dams - Gullies 0.1, 0.2 and 1.1: rock chutes, reshaping, soil treat.	10 gully treatments including: - Catchment treatments (e.g., fencing, diversion and rock chutes to control flows) - Gully Scarp treatments (e.g., earthworks to reshape gully, soil treatment, rock capping) - Gully bed and other soil enhancement treatments
Total cost ($AUD)	$3,500	$3,800	$44,000	$27,000	$595,000	$840,000	$95,000	$182,000	$2,510,000

	NESP TWQ Hub Projects 2.1.4 and 5.9 (Bartley et al., 2020b)							**NESP TWQ Hub Project 3.1.7 (Brooks et al., 2021)**	
	Virginia Park	**Meadowvale**	**Strathbogie**	**Minnievale**	**Mt Wickham**	**Glen Bowen**	**Mt Pleasant**	**Crocodile Station**	**Strathalbyn Station**
Monitoring	3-4 yrs	3-4 yrs	4 yrs	4 yrs	3 yrs	1 yr	1 yr	4 yrs	4 yrs
Land condition	Improved	Improved	Declined	Improved	Improved	Not significant	Not significant	Improved	Improved
Vegetation	Improved	Improved	Not significant	Improved	Improved	NA	NA	Improved	Improved
Erosion rate	Improved	Improved	Improved	Improved	NA	NA	NA	Improved	Improved
Sediment concentrations	Improved	Not significant	Improved	Improved	Improved	Improved	Not significant	Improved (overall)	Improved (overall)
Sediment load reductions	Not significant	Not significant	Improved	Not significant	Improved	NA	Not significant	Improved	Improved
Treatment effectiveness	NA	NA	0.952[c]	NA	0.85[b]	NA	NA	0.62-1.002	0.51-1.00 (average 0.98)
Sediment delivery Ratio for EOS[e] calcs	0.5	0.5	0.85	0.96	0.87	0.87	0.85	0.45	0.96
Cost-effectiveness at EOS[f]	Estimated >$1,500/t	Estimated >$1,500/t	~$70/t[d]	Estimated >$1,500/t	$300-$600/t	Insufficient data	Insufficient data	$58-$128/t or $673 - $1,490/t/yr[g]	$43-$85/t or $282 - $680/t/yr[g]
Comment	Low baseline erosion rates and fine sediment trapping efficiency <20%	Baseline erosion rates relatively low, but good improvement in cover and biomass	Only has 1 year of post-treatment data, so this is a preliminary estimate	Low baseline erosion rates	Cost-effectiveness varies with the baseline erosion rates applied	Baseline erosion rates very high, further data pending.	Baseline erosion rates relatively low, so cost-effectiveness for erosion likely to be poor	Based on cost-effectiveness method 3 yrs post treatment data	1 – 3 yrs post treatment data

NA = new site with insufficient data [a]Catchment area above monitoring station at treatment site; [b]Treatment area: active (e.g., earth works, porous check dams), passive (e.g., fencing, grazing management); [c] Estimated as a change in measured (flow derived) sediment loads between a control and treatment gully, both before and after rehabilitation; This figure has been significantly revised since this report was published – the following year showed that effectiveness declined to 0% [d] Additional data needed in subsequent wet seasons to improve certainty on this result – see comment in Text from Bartley ; [e]End of System (EOS). [f]Calculated using Gully Toolbox method / equivalent; [g]Calculated over 25-year period with a discount rate of 7% per annum, the figures expressed in $/t/yr are based on the full treatment cost at the time of implementation for the mean annual baseline erosion rate.

Table 10. Summary statistics showing the Lidar DEM of Difference (DoD) erosion data for the various treatments from Sept 2019 to May 2020. Mean bulk density for conversion of volume to mass was 1.67. Note these are total erosion figures. Erosion rates for each treatment gully are shown in terms of total annual load (t), specific yield (t/ha), and specific yield per mm of incident rainfall recorded on site. Also shown are the Remediation Effective Ratios (RERs) both as a comparison between the control based on the adjusted rainfall normalised load (t/ha/mm) and the 'before' baseline data for the same site. Last row = water quality monitoring data. At the time when these data were captured Treatment 1 had been in place for three wet season, sites 2,3,4,7 & 8 RT4I & II for two wet seasons, and site 6 for one wet season. (from Brooks et al., 2021). Note all effectiveness values have been referred to as ratios not percentages throughout this report for consistency.

May 2020 – Sept 2019	**Annual RF (mm) = 514**								
Treatment	Area (ha)	t	t/ha	t/ha/mm	Adjusted load of baseline (t/ha/mm)	RER$_{CI}$ (lidar)	RER$_{BA}$ (lidar)	Diff. (cntrl vs Bf)	Effectiveness ratio SSY/m^3
Control	2.77	815.64	294.84	0.57	0.57				
RT 4 I	0.54	3.33	6.17	0.01		94%	97%	2%	
RT 4 II	0.48	0.80	1.67	0.00		98%	64%	35%	
RT 4III (control)	0.25	26.49	104.41	0.20		Cntrl			
Site A1	1.08	34.88	32.29	0.06	0.95	-65%	10%	75%	
Treatment 1	0.73	0.00	0.00	0.00	0.00	100%	100%	0%	99%
Treatment 2	1.12	17.79	15.87	0.03	0.21	63%	80%	17%	
Treatment 3	1.45	2.40	1.65	0.00	0.00	99%	100%	0%	98%
Treatment 3-4 Ext	1.08	5.40	5.01	0.01	0.02	96%	98%	2%	
Treatment 4	1.93	0.00	0.00	0.00	0.00	100%	100%	0%	99%
Treatment 6	2.58	93.00	36.08	0.07	0.28	51%	74%	22%	84%
Treatment 7	1.51	0.87	0.58	0.00	0.00	99%	100%	0%	
Treatment 8a	2.41	12.89	5.35	0.01	0.03	95%	97%	2%	
Treatment 8b	0.54	11.30	21.09	0.04	0.21	63%	80%	17%	
Totals	**18.46**	**1,024.79**							
		All treatment average	**7.0**	**0.014**		**98%**			
		All control average	**278.8**	**0.542**					

Hillslope gully monitoring - from Bartley et al. (2020b)

Quantitative data on the effectiveness of treatments applied to hillslope gullies were also presented in Bartley et al. (2020b), with some updated figures presented in Bartley and Brooks (2021). Of the five sites monitored, effectiveness values were only able to be derived at one site, despite 3 – 4 years of monitoring at all sites. This one site (at Strathbogie Station), which was treated by diverting flow from its large (40 ha) catchment with a diversion bank, produced an effectiveness ratio of 0.95 derived from on Before/After and Control/Impact loads estimates. However, more recent unpublished data (Bartley pers. comm) has seen this effectiveness ratio significantly reduced to 0.5 as the high value from the first year was largely a function of below average rainfall. The following year effectiveness reduced to zero (i.e., back to baseline), hence it is questionable as to whether it is appropriate to consider an average effectiveness ratio of 0.5 at this site. Longer term monitoring would be required to determine whether a statistically significant trend emerges. As is the case with most of the international literature on linear gullies that have employed porous check dams as the primary remediation strategy, the anecdotal evidence is that they have primarily trapped coarse bedload sediments, with a very low fine sediment fraction (see Koci et al., 2021).

Hillslope gully yields associated with grazing exclusion (Wilkinson et al., 2018)

Some evidence also exists that long term (>20 year) grazing exclusion can lead to a reduction in sediment yield from small linear hillslope gullies. Wilkinson et al. (2018) compared untreated gullies at Virginia Park with gullies from the Townsville military training area that was a grazing property purchased in 1989, and from which cattle have been largely excluded ever since (apart from some drought grazing around 2000). The study began monitoring gullies in 2013 which by that stage had cattle excluded for 24 years. Monitoring data collected over the following four years were compared with grazed sites at two other properties with similar soils and terrain. The study showed that the gully catchment area specific fine sediment yield (in this case defined as <63µm) were around 60% lower than the grazed catchments. While this study suggests there is a positive water quality benefit from long-term grazing exclusion, unfortunately these data cannot form the basis for comparison with short-term monitoring data, and hence as a basis for comparing the cost-effectiveness of contemporary treatments, because the trajectory of the change over the missing 24 years is unknown. Furthermore, it is unlikely that broadscale grazing exclusion will be regarded as a viable management strategy for most graziers. This is regardless of whether it occurs as whole of property exclusion or as a result of the individual fencing of all gullies.

Nutrient treatment effectiveness

Changes to nutrient concentrations and loads associated with gully remediation have been quantified at a subset of the gullies reported in both Brooks et al. (2021) and Bartley et al. (2020b). At the time of publication, the data on nutrient responses from the sites reported in Bartley et al. (2020b) were inconclusive, although only total nitrogen (TN) was being monitored. As outlined below, changes in TN can be misleading, depending on the response with the different forms of the nutrients. Trends in post-treatment particulate nitrogen (PN) and particulate phosphorus (PP) nutrient response were shown to essentially track the sediment reductions at both the Crocodile Station and Strathalbyn Station sites (Brooks et al., 2021). Responses in dissolved N and P fractions, were more complex, varying with the nature of the surface treatment. The response at Crocodile Station, which used rock capping without the addition of organic matter, showed a similar proportional reduction in dissolved loads as the particulate loads, albeit with greater variability between events. However, at Strathalbyn, the dissolved loads increased to levels above the baseline (pre-treatment) loads. These findings highlighted that monitoring TN alone, does not explain the net impact on bioavailability of nutrients associated with gully remediation. The complexity of the treatment response associated with different nutrient species was further explored by Garzon-Garcia et al. (2022) who continued to monitor the Strathalbyn site for a further two years, undertaking detailed analyses of the mechanisms driving the reductions in PN and increases in dissolved inorganic nitrogen (DIN).

Garzon-Garcia et al. (2022) found that gully remediation using organic amendments reduces the export of TSS and particulate nutrients, but at some sites increases the concentration of soluble organic nutrients and DIN. After remediation, the majority of exported carbon, N, and P is in the form of the dissolved fractions. Most dissolved N is shown to be in the form of DON before remediation and DIN becomes dominant afterward. Although TN discharge decreases after remediation, the bioavailable nitrogen load can increase due to an increase in the concentration of DIN. Investigating further, Garzon-Garcia et al. (2022), found that soil amendments were the main cause of the increase in soluble organic nutrients and DIN. They found that the decomposition of organic amendments (soil and hay) can either consume DIN (where the material has a high C:N ratio) or produce DIN (where the organic material has low C:N ratio). The imported soil amendment, along with one Rhodes grass treatment (*Chloris gayana*) which had been sourced from an area irrigated with abattoir effluent, increased DIN production, whereas another Rhodes grass mulch sourced from a different area, as well as sorghum (*Sorghum bicolour*) and bagasse (sugarcane pulp), consumed DIN, thereby resulting in a net DIN reduction. Hence, the type and source of soil amendment is critical for achieving the desired outcome from gully remediation. The balance between DIN producers and consumers in the soil and surface amendments determines whether there is a net production or consumption of DIN from the amendments. Hence, the authors recommend that amendments for gully remediation should have a high C:N ratio so that DIN production is delayed until vegetation is established in the gully, which can act as a sink for DIN produced. Field-based monitoring and empirical modelling suggest that the sites with low C:N ratio amendments will continue to deliver dissolved nutrients at levels above baseline for up to 10 years or more. The use of rock surface capping without organic amendments in gully remediation, as was the case at Crocodile Station in the Normanby catchment, has been shown to produce a net reduction in total, particulate, and dissolved forms of N and P, as well as sediment (Doriean et al., 2021).

Evidence for a robust understanding of the baseline conditions against which effectiveness could be tested

An important aspect of determining the effectiveness of gully remediation treatments, particularly in situations where long-term baseline monitoring prior to treatment is not possible, is the development of methods for establishing the baseline sediment and nutrient yields using methods not dependent on water quality monitoring. To date, only one peer reviewed method for deriving baseline sediment yields has been developed which can be applied to hillslope or alluvial gullies (see Brooks et al., 2020a). The method was developed as the basis for the Reef Credits methodology (see https://eco-markets.org.au/reef-credits/), and requires the development of a multi-decadal analysis from historical air photos to determine a trajectory of areal change through time. The area change is then transformed to a volumetric change through the application of an area:volume relationship. Ergodic reasoning (or space for time substitution) has been widely used in the geomorphic literature as a basis for reconstructing past landscapes (Brosens et al., 2022; Frankl et al., 2013a; 2013b; Fryirs et al., 2012; van der Sluijs et al., 2023). The approach is based on the empirical relationship between area and volume for similar features in the landscape that are on different stages of their evolutionary pathway at a fixed point in time. A key feature of the gully evolutionary method outlined in Brooks et al. (2020a) is that it does not assume that all gullies evolve in a linear trajectory, nor are all gullies on a declining evolutionary trajectory over management timescales, as Wilkinson et al. (2015a) have proposed as the default for most gullies in the GBR. The method acknowledges that all gullies are on a unique evolutionary trajectory, which needs to be empirically derived. The approach also acknowledges the role that direct rain-splash erosion plays in driving gully evolution, particularly in highly erodible deep alluvial soils (Daley et al., 2023). According to data presented in Daley et al. (2023) as much as 80% of the total sediment yield in alluvial gullies can be driven by rain-splash erosion on bare subsoil surfaces within a gully, a process that is below the level of detection of current best-practice lidar based topographic methods for determining short term (<decade) erosion rates. This process can be measured through the use of erosion pins (Bartley et al., 2007; Daley et al., 2023). This process is also responsible for non-linear growth rates, and if not accounted for can lead to gross underestimates of contemporary sediment yields in alluvial gullies. Understanding rain-splash driven erosion and accommodating its influence in gully evolution, is critical for accurate determination of effectiveness and for deriving appropriate remediation strategies. However, this process will only dominate in certain gully types, and as such applying the appropriate evolutionary model to the right gully types (sensu Thwaites et al., 2022) is an important aspect of determining remediation effectiveness.

Data on cost-effectiveness of water quality improvement through gully remediation

This review includes seven studies that address some aspect of the costs associated with gully remediation. Of these studies, one was an example from Ethiopia (Yitbarek et al., 2012), which due to the fundamentally different economic situation, along with the treatment types, was deemed to have little relevance to the GBR. Two of the studies (Brooks et al., 2016; Shellberg & Brooks, 2013) were from initial experimental trials of alluvial gully remediation in the GBR, but due to scale issues were not considered to be relevant in the scaled-up approaches currently being undertaken throughout the GBR. Apart from being important steps on the journey to fully scaled up gully remediation on an industrial scale, these small plot scale studies provide little useful cost-effectiveness data that is relevant to the situation at the time of writing.

A study by Rust and Star (2018), provides the first example of a study that applies an appropriate economic model to understanding gully remediation cost-effectiveness in terms that enable comparison with other investments using standard economic metrics. The cost-effectiveness is calculated across a 10-year period, with a discount rate of 7%, producing relative costs in terms of dollars per tonne of sediment abated. The study reported that the median cost-effectiveness of building specific structures to remediate erosion from gullies in the Fitzroy region was \$163.11 per annual m^3 of sediment (\$108.74 per annual tonne), with individual figures ranging from \$100.40 to \$774.35 per annual m^3 of sediment (\$66.93–\$516.23 per annual tonne). The shortcoming of this study was that the sediment reductions were all modelled reductions based on the assumed effectiveness of particular treatments. Consequently, the cost-effectiveness estimates from this study should be treated with some caution.

Two further studies (Bartley et al., 2020b; Brooks et al., 2021) were able to derive cost-effectiveness estimates at end of gully, based on measured sediment reduction rates along with capital works costs provided to the respective projects by the project managers who oversaw the remediation works (Table 9). As outlined above in the discussion of the sediment reduction effectiveness data, only one of the sites presented in Bartley et al. (2020b) provide a reliable effectiveness ratio, from which a cost-effectiveness figure could be derived. Updated results presented in Bartley and Brooks (2021) suggest that the cost-effectiveness values for three of the sites (using non-standard economic metrics which only account for upfront capital costs and a single years’ worth of sediment abatement) was >\$1,500/t, based on modelled estimates of effectiveness. One site initially indicated that it was reducing sediment at around \$70/t, but the effectiveness figure was later significantly adjusted, so should be regarded as being unreliable. One further site was estimated to have generated reductions at the rate of \$300-\$600/t. Cost-effectiveness values for the gullies at Crocodile and Strathalbyn Stations, respectively, were \$58-\$128/t and \$43-\$85/t (Table 9), calculated across 25 years and using a 7% annual discount rate (Brooks et al., 2021). It should be noted, that in assessing the cost-effectiveness data, the unit cost per tonne of sediment is not the only metric that should be considered. Given the amount of sediment abatement required to achieve the Reef 2050 targets is >800,000 t/yr of fine sediment reduction by 2025, it is also important to consider the net amount of sediment abatement that can be practically achieved through the implementation of each strategy.

From the perspective of determining the relative cost-effectiveness of treating hillslope or alluvial gullies in the GBR, it is interesting to compare the measured fine sediment reductions from the hillslope gullies reported in Koci et al. (2021) and the alluvial gully treatment at Strathalbyn Station, reported by Brooks et al. (2021). Koci et al. (2021) showed that the remediation of two hillslope gullies at Virginia Park Station in the Burdekin reduced the fine sediment load by a total of 0.264 t yr^{-1}; whereas the alluvial gully remediation at Strathalbyn (Brooks et al., 2021) reduced the fine sediment load by around 5,000 t yr^{-1} (~5,500 since the control gully was treated). While there were much higher costs at the Strathalbyn site (~\$2.5M - on-ground costs only), it would require the remediation of ~38,000 (or 42,000 including the control) hillslope gullies similar to those at Virginia Park to achieve an equivalent outcome at end of gully. Taking into account the differential sediment delivery ratio (SDR) of the two sites (0.41 cf 0.94) it would require the remediation of ~92,000 (or 102,000 including the control) similar hillslope gullies, assuming they were in the Upper Burdekin. This number would be lower downstream of Burdekin Falls dam, but still in the tens of thousands of gullies (assuming they are comparable to the Virginia Park gullies).

Reported costs (Table 9) indicate the hillslope gully treatments cost $1,750 for each gully (not adjusted for inflation), while the ~17 ha of alluvial gully treatment at Strathalbyn cost ~$2.5M (2020 figures). Fine sediment reduction at Virginia Park cost $13,260 t yr^{-1}, compared with ~$500 t yr^{-1} at Strathalbyn. This means that, at the end-of gully, the Strathalbyn gullies were 26.5 times more cost effective than the hillslope gully treatments at Virginia Park. If the difference in sediment delivery is taken into account, the Strathalbyn gullies are 60.8 times more cost effective than the Virginia Park hillslope gullies. To achieve a similar amount of sediment reduction as at Strathalbyn via the treatment of > 90,000 hilllslope gullies, the logistical costs of accessing this many gullies would need to be added, likely pushing the differential to more than two orders of magnitude (100-fold differential).

Spatial and climatic variability

Large scale gully erosion is a process predominantly specific to the dry tropics GBR catchments; so, in this sense, there is a clear spatial and regional climatic pattern in the distribution of the process. Within the Dry Tropics catchments there is also huge spatial variability in gully distribution, particularly in terms of the different types of gullies, driven by land type, landscape context and soil type. The basis for understanding the spatial variability in the distribution of different gully types is outlined in Daley et al. (2021) and Thwaites et al. (2022).

A key question that is often posed is how well gully remediation sites will hold up as the climate continues to warm and rainfall and floods becomes more intense. Fortunately, some very intense storms have been experienced at the sites monitored in the Normanby and Burdekin catchments. For example, one of the sites at Crocodile Station documented in Brooks et al. (2021) experienced a major river backwater event, which inundated the remediated gully to a depth of ~3.5 m, without any impact on the integrity of the works. Similarly, the sites at Strathalbyn Station experienced one of the wettest years on record in 2018/19, and again, this had little impact on the sites that were constructed to a high standard (Brooks et al., 2021). The sites that were constructed to a lower standard experienced some damage, but even these faired remarkably well. Hence, based on the experience to date, and providing the remediation works are constructed to a high standard, and do not rely entirely on vegetative treatments, remediated gullies should withstand the climate extremes (i.e., both drought and flood) that are projected over the next 25 years, provided timely maintenance works are carried. Maintenance works required at the Strathalbyn sites in the first three years amounted to around 1.4% of the capital works costs (Brooks et al., 2021).

Production outcomes

Considering that the gully erosion that could incur some sort of remediation in order to meet the Reef 2050 WQIP water quality targets represents a very small proportion of the landscape (likely <0.1% of the landscape), there is likely to be little private production benefit associated with their management (i.e., for grazing). A key consideration here is that the land currently subject to gully erosion often has at best a zero productive output, and it could be argued that this land has a negative impact on land value. Current requirements are for the remediation investments on this very small fraction of the landscape should be protected through grazing exclusion (other than rare very short-term dry season maintenance grazing) (Wilkinson et al., 2022). Hence, the worst-case scenario is that there is a net zero grazing production benefit, with a likely net positive land value benefit due to the removal of highly visual erosion scars which can negatively affect property value. There could be some productivity benefits associated with the local economic activity associated with the remediation industry. There is also a potential benefit to landholders and Traditional Owners associated with Reef Credits, if this market-based approach to gully remediation gains acceptance (see https://eco-markets.org.au/reef-credits/).

Recent findings 2016-2022 (since the 2017 SCS)

The highly relevant studies that have addressed the primary and secondary questions have all been undertaken since 2016. When the 2017 SCS was published there were only two GBR relevant studies that had been undertaken, and these were the plot scale trials documented in Shellberg and Brooks (2013) and Brooks et al. (2016). Both reports were from the same study site at Crocodile Station in the Normanby catchment, with the latter including additional monitoring. While these reports were important for setting the direction for future research, and providing the impetus for further investment in scaled-up on-ground gully remediation works, all substantive research that specifically addresses the primary question has been undertaken since 2016.

4.1.2 Streambank

Q3.6ii Primary question:

- What is the effectiveness of **streambank** restoration works in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions?
- What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions?
- What are the production outcomes of these practices?

Notes on definitions

For the purposes of this review, the term *streambank restoration* is considered to include any works undertaken within a stream channel, channel banks or adjacent riparian area with the intent of improving ecosystem outcomes. Although the terms *restoration, rehabilitation* and *remediation* are considered within academic literature to be different and have different meanings (Rutherfurd et al., 2000), within this review the terms are considered synonymous and interchangeable, meaning any action taken to improve the functional biophysical condition of a channel site from a degraded state. For the purposes of this review, the term *streambank rehabilitation* was adopted to describe these actions, as *restoration* typically refers to the return of an ecosystem to a previous condition. In most cases, restoration is neither the objective nor the outcome of works. In practice, streambank rehabilitation works are comprised of interventions undertaken to increase riparian vegetation, either directly, through planting, or indirectly through bank reprofiling and stabilisation, which enables subsequent revegetation, via planting or natural colonisation.

Effectiveness is taken as the ratio of fine sediment and/or particulate nutrient loads measured at or near the river mouth, or at a defined point within a subcatchment (such as a gauging station), before and after intervention(s).

Summary of study characteristics

Following a wide search of the international scientific literature, encompassing >1,000 potentially relevant studies, including peer reviewed reports focused on GBR catchment management (primarily from the NESP TWQ Hub Program), a subset of 83 studies were reviewed in detail. The number of studies globally that have quantified sediment or nutrient reductions associated with streambank rehabilitation is extremely limited. Of the reviewed studies, a shortlist of 55 studies were considered to have some relevance to the primary question (Figure 4), albeit only 11 studies provided direct evidence relevant to the primary question, with limited evidence from Australia and the GBR (Figure 4). There are no studies within GBR catchments that directly address the primary question and only two studies within Australia, of which one is based in a headwater catchment directly adjacent to one of the GBR catchments (Mary River). Only one study was able to provide insight into the cost of streambank rehabilitation in Australia. There are likely various Queensland-based reports and management guidelines outside of the scientific literature that could inform the primary question, however these reports do not meet the inclusion criteria of this review (i.e., peer reviewed and publicly available). The majority of streambank rehabilitation projects are undertaken by environmental consultants and/or community-based groups, often with short-term project timeframes that lack ongoing quantitative monitoring and evaluation of success, particularly from a water quality perspective.

Given the dearth of scientific literature directly addressing the primary question, the search was expanded to consider publications that provided either: a) proxy evidence for sediment reductions, such as geomorphic impacts; or b) evaluations of riparian conditions, for example different land cover types in riparian zones. Of the shortlisted studies, 67% are Australian, and of these 31% are from within the GBR catchments. While 22% provide direct evidence to answer the primary question, 41% provide indirect or inferred evidence and another 37% relevant contextual information. Notably, 81% of these studies occurred prior to the 2017 SCS, and hence do not constitute a new body of evidence that could alter the conclusions previously drawn.

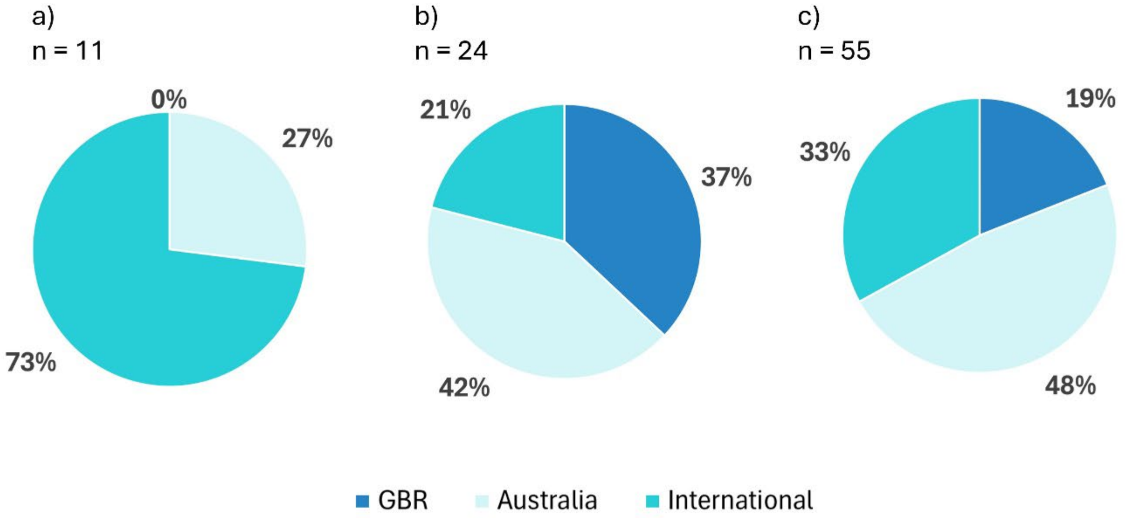

Figure 4. Proportion of scientific studies in Australia that provide: a) direct evidence; b) inferred evidence; and c) relevant evidence or contextual information for addressing the primary question.

Observational studies from other Australian regions (n = 2) and internationally (n = 9) investigating the effectiveness of streambank rehabilitation on sediment and nutrient loads have been limited to mostly small (<150 ha) catchments. None of the studies investigate the efficacy of large-scale streambank rehabilitation sites that are the dominant focus for current GBR rehabilitation works, for example large bank failures in high order channels. The dominant methods evaluated include riparian revegetation and stock exclusion through fencing, although rehabilitation works are often undertaken in concert. Assessed practices are generic agricultural best management practices and typically involve the selection and planting of endemic species in a fairly narrow buffer or corridor along a waterway. Spatial, climatic and ecological factors are highly variable, and impact degradation processes and vegetation establishment rates. The studies have been conducted in New Zealand and the contiguous United States, in very different geoclimatic and social settings to the GBR environments and thus results are not directly translatable to GBR catchments. Only one observational study undertaken in a headwater catchment in the subtropical Maroochy River (Marsh et al., 2004; 2005) is geographically relatable to GBR catchments. Related research has been undertaken on the practice of establishing buffer strips alongside creek lines adjacent to agricultural areas. The practice is similar to riparian rehabilitation in that vegetation, typically either perennial grasses or woody vegetation, is planted in a narrow strip along low order drainage lines and waterways to improve farm runoff by trapping sediment and nutrients. To some extent, this type of study overlaps with Question 3.5 (Bartley & Murray, this SCS) in terms of agricultural land management practices and hillslope erosion. Consequently, the review of this literature is out of the scope in this question. Most studies report on observations made within 3-7 years following rehabilitation.

Summary of evidence to 2022

What is the effectiveness of streambank rehabilitation in reducing sediment and particulate nutrient loss?

This review of the literature has found no examples of studies examining the effectiveness of streambank rehabilitation activities in GBR catchments to reduce sediment and particulate nutrient losses. This is consistent with similar reviews undertaken previously (e.g., Bartley et al., 2016; 2017; Wilkinson et al., 2022). The purpose of this review is not to evaluate the efficacy of different streambank rehabilitation techniques in achieving at-site reductions, as there is an uncertain relationship between at-site reductions and end-of-catchment reductions; it aims to determine whether meaningful reductions in sediment and particulate nutrient losses have been measured at the catchment, subcatchment or reach scale following streambank rehabilitation in the GBR catchments.

The absence of evidence for streambank rehabilitation effectiveness should not be mistaken for evidence of absence. There is an extensive body of evidence on the role of vegetation in modifying river channel behaviour, which includes the role of wood in rivers, some of which can be directly related to sediment dynamics, erosion and storage (Bendix & Stella, 2013; Corenblit et al., 2007; González et al., 2015; Gurnell & Bertoldi, 2022; Merritt, 2022). Much of this literature also highlights the importance of vegetation in other values of river systems including terrestrial and aquatic biodiversity, carbon and nutrient cycling, other water quality parameters, geomorphic functioning, and habitat complexity. Reviewing that body of literature is beyond the scope of the present task. Nevertheless, there are numerous studies that demonstrate local scale geomorphic effectiveness of streambank rehabilitation and revegetation in reducing erosion (González et al., 2015; Prosser et al., 2000) and at the reach scale even reversing net erosional areas to depositional (Brooks et al. 2004; 2006; Hughes, 2014). Such studies provide valuable inference into the efficacy of streambank rehabilitation.

Local scale interventions can produce substantive improvements in streambank condition, but catchment scale drivers and impacts must first be addressed if meaningful results are to be achieved (Sims & Rutherfurd, 2021). The scientific evidence to attribute effectiveness ratios to treatment types is scant, particularly given the important contextual variations between different geoclimatic regions and hydromorphic aspects of river systems. This is compounded by the general lack of appropriate post-construction monitoring data for streambank projects throughout the world. A review of 576 streambank rehabilitation projects in southwest USA, found few conclusions could be drawn on the effectiveness and efficacy given the dearth of information on the implementation, maintenance and monitoring of project sites (Follstad Shah et al., 2007). Similar conclusions were drawn on a global review of 345 globally published evaluations of stream rehabilitation techniques (Roni et al., 2008). Even within a single catchment, understanding the differences in effectiveness of treatment types can be challenging (Sims & Rutherfurd, 2021). While many treatments have demonstrated promise in restoring streambank ecosystems, particularly revegetation and stock exclusion, long-term monitoring studies remain wanting. This is also the case within the GBR catchment.

Observational studies undertaken in other global settings (n = 11) have demonstrated that statistically significant downstream reductions in suspended sediments and turbidity can be achieved through streambank rehabilitation practices (Collins et al., 2013; Richardson et al., 2011; Wilcock et al., 2013). Up to 81-85% reductions in suspended sediments were reported following streambank rehabilitation (Carline & Walsh, 2007; Line et al., 2000; Williamson et al., 1996). Another study reported up to an order of magnitude reduction in suspended sediments in Albany, WA (McKergow et al., 2003). Consistent downward trends in sediment loss rates are reported across studies, with generally improved water clarity. It is worth noting that most of these observational studies do not measure bank erosion rates but focus on changes in water quality, the inference being that improved water quality are the result of increased channel stability and lower rates of erosion. Nutrient loads, including total and particulate nutrients, were far more variable, with some studies reporting no changes, some observed mixed results between nutrient types while others demonstrated reduced loads. This highlights the complex nature of sediment and nutrient coupling and other complex contextual factors in fluvial environments. Drainage buffers resulted in reductions of >80% of bed and 65% of TSS recorded in wet tropical catchments (McKergow et al., 2004). Similar rates have been reported internationally where buffers have used agriculturally productive woody crops (Fortier et al., 2015; Rosa et al., 2017). Drainage buffers are not streambank rehabilitation per se, but are designed to intercept sediment and nutrient runoff. Thus, their applicability is limited in this discussion but still of some practical relevance in the transfer of principles in reducing sediment loads. Studies show that bank erosion generally occurs at lower rates on vegetated river reaches than non-vegetated reaches (Beeson & Doyle, 1995; Micheli et al., 2004; Stott, 1997). However, none of these studies demonstrate reductions in bank erosion associated with streambank rehabilitation or revegetation of formerly unvegetated banks. There is, however, clear evidence that grasses reduce erosion and sediment loads compared to unvegetated banks in small streams (Prosser et al., 2000). However, in small headwater catchments, changes from grass to woody vegetation can initially increase sediment (and associated nutrient) loads related to rehabilitation-associated disturbances, such as vehicle access, cut-and-fill or bank reshaping and exotic vegetation clearing (Marsh et al., 2004), or changes related to environmental succession as riparian forests mature (Davies-

Colley, 1997; McBride et al., 2010; Trimble, 1997). The interim time between woody vegetation shading out ground cover and establishing a stable riparian corridor can increase sediment loss associated with channel widening. But global examples demonstrate this impact typically stabilises over short to moderate timescales as geomorphic complexity increases (Davies-Colley, 1997; McBride et al., 2010; Parkyn et al., 2005; Trimble, 1997). It is important to note that this is an issue of scale mostly related to the dynamics of small headwater streams that are the focus of these cited studies (Davies-Colley, 1997; Zimmerman et al., 1967), while higher order streams are likely to experience a very different dynamic related to riparian vegetation and flow dynamics. It is uncertain how translatable these circumstances are to Australian environments, such as ephemeral streams in open woodland.

While this evidence is limited and complicated, observations from small catchments (<150 ha) provides useful demonstration of the conceptual framework underpinning sediment and nutrient export reductions and generally supports first principles of streambank rehabilitation. But those observations cannot be readily scaled up and transferred to larger systems and catchments. In large part this is due to the changing dominance of process zones in fluvial systems. In low order channels, such as those studied above, fluvial scour dominates erosion processes and sediment is derived from localised sources (Abernethy & Rutherfurd, 2000; 2001). As channel size and catchment area increase downstream, there is a transition to a dominance of mass failure and much greater interaction with allochthonous sources of sediment and material. The scale of treatment likewise changes, with different treatment types and methods employed. The dynamics of riparian vegetation likewise changes, with grasses having a much greater impact than woody vegetation on sediment storage in small catchments in some ecosystems (Davies-Colley, 1997; Trimble, 1997). But as catchment area increases, the role of woody vegetation is greatly increased, with a significant role in root reinforcement and bank stability from mass failure processes (Simon & Collison, 2002; Pollen, 2007).

Furthermore, in large catchments, the variability in discharge and sediment concentration over multiple orders of magnitude propagates to a yet larger range in sediment discharge (e.g., Figure 5). Thus, the ability to attribute the effectiveness of a local scale streambank rehabilitation treatment at reducing catchment-scale sediment or particulate nutrient losses is indeterminate. In almost all circumstances, the reductions achieved by any single treatment activity is entirely dwarfed by the magnitude of variability. Determining effectiveness, in relation to the scope of the primary question, may only effectively be achieved through long-term monitoring programs, conducted at a catchment scale. Darnell et al. (2012) estimates that a monitoring period of over 50 years would be required to detect a 20% change in end-of-catchment load in the GBR catchments. This is one of the reasons provided by Bartley et al. (2017) to justify the use of catchment modelling as the primary tool used to estimate end-of-catchment loads to the GBR. However, reanalysing the same Burdekin data used by Darnell et al. (2012), Wang et al. (2015) argue that the time horizon for trend detection can be considerably shortened to perhaps as low as 10 years through the inclusion of high-resolution continuous turbidity data. This finding gives (new) impetus to the monitoring effort.

The absence of effectiveness evidence for treatments is further explained by the following:

1. Site scale assessments of intervention effectiveness are complicated as rivers behave non-linearly, typically not responding to drivers as they have in the past (at an exact site) nor necessarily coevally with a comparative site. While erosion may have occurred at a particular site, that does not suggest erosion will continue at the same rate, or even at all. At the reach scale, the past is but a guide, and may not provide a realistic basis to predict future conditions (Brierley & Fryirs, 2016). Erod*ing* sites/reaches cannot necessarily be distinguished from erod*ed* sites/reaches, hence estimates of site scale effectiveness will always be accompanied by a large uncertainty due to the need for extrapolation.
2. Site scale assessments of intervention effectiveness do not consider the off-site impact of stabilisation of a given reach or bend. A stream adjusts in concert its width, depth, slope, suspended sediment discharge and flow resistance in response to imposed discharge/stream energy (Leopold & Maddock, 1953). Removing one or more of these degrees of freedom could result in unanticipated adjustments downstream. For example, a stream prevented by bank hardening from increasing its length could instead accommodate the attendant increase in

velocity through increasing its depth. While site scale assessments may indicate effectiveness, that success may be offset by erosion and energy expenditure initiated elsewhere. Intervention may simply serve to delay the river as a whole reaching its maximal stability (Kondolf, 2011).

3. The scale of intervention required at any site is dependent on conditions upstream, complicating estimates of effectiveness and cost-effectiveness. Streambank rehabilitation treatments will be impacted by conditions upstream of the reach and materials transported into the treatment site, which can have impacts on site scale measurements of effectiveness (Collins et al., 2013). Alternatively, and more importantly, expensive interventions downstream may be obviated by relatively cheap interventions upstream – for example, efforts to fortify the seed source and moderate motive hydraulics in upper reaches may make light-touch assisted natural regeneration possible downstream (Fryirs & Brierley, 2021).

While the role that any individual isolated bank erosion treatment has in reducing catchment sediment and particulate nutrient loss is likely indeterminate, catchment scale revegetation of the riparian zone has profound effects on channel and sediment dynamics, and, where appropriately scaled, increases the interception of hillslope derived sediments (e.g., McKergow et al., 2004; Rosa et al., 2017). Extensive revegetation, facilitated in the main by assisted natural regeneration, combined with the establishment of an ‘Espace de Liberté’ (Kondolf, 2012), within which the river can adjust as it self-manages excess stream energy, provides the most tractable means of minimising catchment sediment and nutrient export. Mabbott and Fryirs (2022), for example, show a doubling of channel roughness (and hence a halving of stream power) in response to ~50 years of passive revegetation of the Allyn River in the Hunter Catchment in New South Wales. Channel roughness is a critical element influencing sediment transport (Hession & Curran, 2013). A longitudinal study of New South Wales’ coastal streams has demonstrated increased passive revegetation and rehabilitation in all catchments over the last 30 years, with associated changes in streamflow trends and flood travel times, related to shifts in socioeconomic values and river management (Cohen et al., 2022).

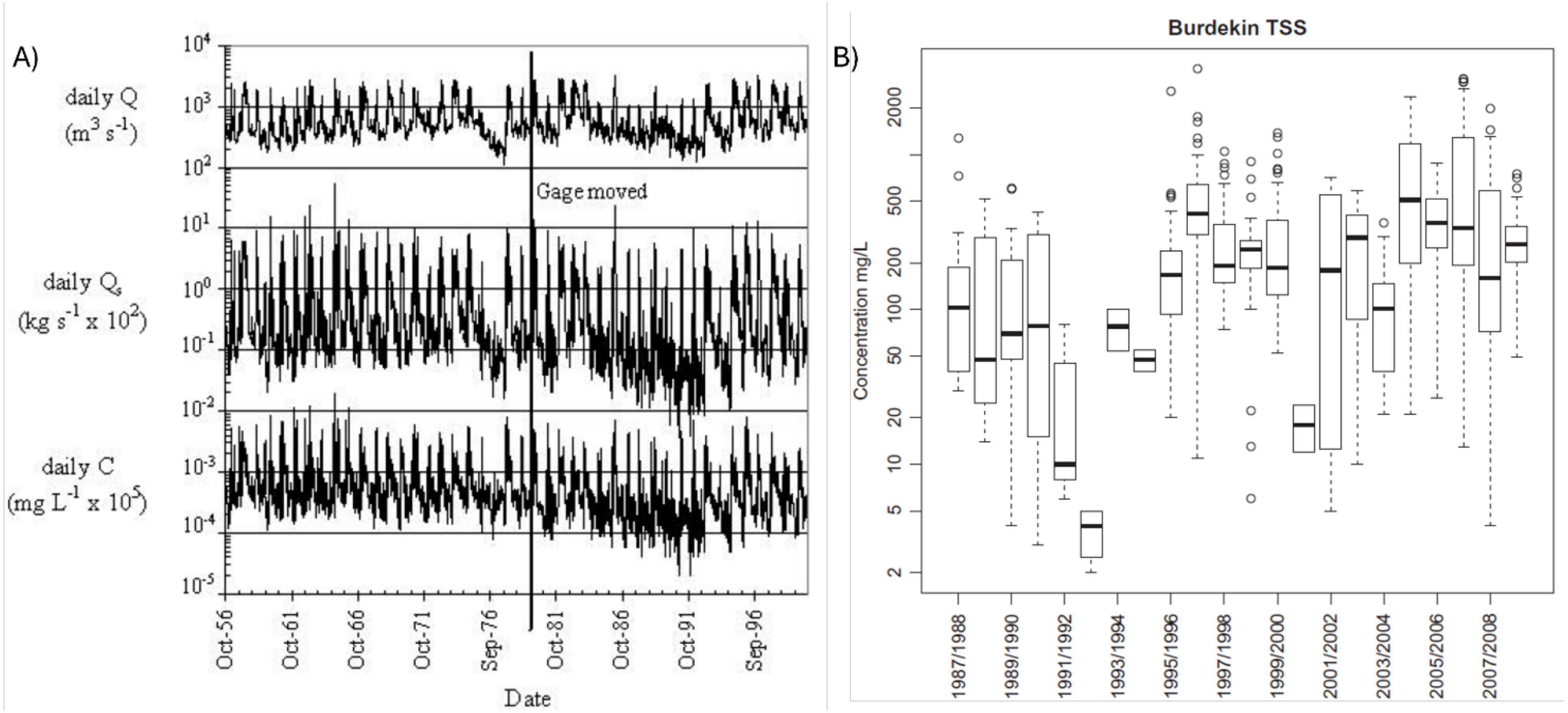

Figure 5. Examples of sediment discharge variability. Note logarithmic scale of y axes. A) Long term records for daily water (Q) and sediment (Qs) discharge and concentration (C) for the Sacramento River at Sacramento (from Wright & Schoellhamer, 2004); B) Distribution of measured TSS values for the Burdekin River at Inkerman Bridge (from Darnell et al., 2012).

In the Hunter River, several studies have documented changes in catchment condition that allow some conclusions to be drawn regarding the impact to catchment sediment losses in the GBR. Given the high hydrological variability across the catchment (Rustomji et al., 2009), it provides a useful comparative catchment to many GBR streams. Following catastrophic flooding in the 1950s that destabilised much of the main river channels, extensive rehabilitation projects have been undertaken across the following decades (Spink et al., 2009). More recently, passive recovery of riparian vegetation has resulted in a 19% net increase in the quantity of vegetation in river corridors across the catchment and a 26% increase in trunk stream since 1987 (Cohen et al., 2022). This has been associated with significantly slowed flood travel times. Moreover, geomorphic stabilisation of many river reaches has occurred with the development of in-channel benches and islands associated with increased sediment retention (Fryirs et al., 2018; Mabbott & Fryirs, 2022). Catchment erosion and subsequent sedimentation in the estuarine zone of the Hunter River has been a long-term management issue, requiring constant dredging of the harbour. However, to date, there has not been any research to quantify the changes to catchment sediment supply and the dredge maintenance program in Newcastle Harbour.

There have been similar shifts and social drivers across Australia, though, with some important regional differences. In the Mossman River catchment, while an overall increase in riparian forest was achieved between 1944 to 2000, there was a significant shift in the spatial distribution of vegetation with approximately similar amounts lost as was gained (Lawson et al., 2007). Changes in riparian woody vegetation extent in GBR catchments could be quantified, but as yet there are no longitudinal studies that have analysed the water quality response to collective streambank rehabilitation, via passive or active treatments, across the GBR catchments. There are no studies that have analysed recent rehabilitation in large catchments against the catchment-scale sediment and nutrient losses.

What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions?

Given the lack of evidence for streambank rehabilitation effectiveness, a secondary assessment of cost-effectiveness is not possible. Moreover, as most streambank rehabilitation works are undertaken within a competitive framework in the private sector, there is little to no data publicly available on the costs and cost-effectiveness of rehabilitation works. Project costs are often commercial-in confidence and may vary considerably dependent on contextual variables such as location, site access, material costs, mobilisation costs, environmental conditions, delivery timelines and program frameworks (e.g., hierarchy of consultation). As such, documentation and scientific analysis of the economic costs and benefits surrounding streambank rehabilitation is insufficient to enable any rigorous evaluation (Dobes et al., 2013). While analyses of program costs have been undertaken in other regions (Follstad Shah et al., 2007), these are unlikely to provide much insight into the cost of streambank rehabilitation in Australia due to highly regionalised program objectives, histories and economies. Analysis could potentially be undertaken using data for current Reef Trust, Great Barrier Reef Foundation or other Australian government agency programs, but to-date this has not been performed, and such studies would be complicated by the aforementioned uncertain relationship between at-site effectiveness and impact at the catchment scale. Undertaking such analyses using unpublished data was beyond the scope of this review.

Further, the lack of systematic monitoring across most projects and programs has critically hindered public evaluations of the cost-effectiveness of rehabilitation, particularly across long-term timescales. As such, in addition to cost information being required, effective long-term monitoring of project success and sediment/nutrient reductions is also required. This is further complicated by the fact that no objective method currently exists to determine the longer baseline for a site, other than the site by happenstance coinciding with a long-term gauging station. Post-hoc analyses could provide a starting point if data were made available for both project cost and outcome components. Paul et al. (2018) provide an initial approach to post-hoc evaluation of 41 existing streambank rehabilitation sites in GBR catchments. The study demonstrates improvements in overall site condition, based on qualitative riparian ecosystem metrics, and water quality improvements could be inferred from these results. However, the approach does not provide quantitative data on sediment/nutrient export reductions and qualitative erosion condition scores were not related to age.

What are the production outcomes of these practices?

The production outcomes of streambank rehabilitation depend on the particular practice. Intensive re-engineering of rivers (e.g., protecting the bank with rock) designed primarily to stabilise the present location of the bank have, by design, minimal impact on production. These practices are usually enlisted where a landholder is undertaking cropping right to the edge of the river bank. In these instances, it is the prevention of the loss of cropping land that provides the impetus to undertake the work, rather than a desire to reduce catchment sediment export. These types of intensive interventions, though an obvious economic benefit to the landholder (assuming they are being paid for by someone else) are increasingly difficult to justify from a dollars per tonne of sediment saved perspective. The Gully and Streambank Toolbox (Wilkinson et al., 2022) for example, asserts that the most cost-effective means of reducing sediment derived from erosion of the channel margin is to ensure the largest reach possible is returned to a fully vegetated state. Intensive bank hardening exercises divert funds from this aim and may not add materially to altering the trajectory away from wholesale channel expansion towards channel contraction.

Recent findings 2016-2022 (since the 2017 SCS)

There have been no recent substantive developments to address the questions regarding streambank rehabilitation effectiveness. Within the catchments of the GBR, research and development, and rehabilitation monitoring, have not been set up or established to address these questions. While opportunities exist to provide post-hoc analyses of changes related to streambank rehabilitation, no quantitative data have been collected or published to provide effectiveness ratios. Paul et al. (2018) demonstrate that condition indices of rehabilitation sites improve with age, based on qualitative on-ground assessments. But these data do not relate to erosion indices, including quantitative sediment or nutrient losses, nor provide scope beyond the site scale.

The reanalysis of Burdekin sediment load data by Wang et al. (2015), though published just prior to the window of interest, has not, to the best of our knowledge, been considered in previous reviews, nor has the advice to include continuous turbidity monitoring been implemented as a core element of the GBR Catchment Loads Monitoring Program. This study reanalysed the same Burdekin data used by Darnell et al. (2012), who claimed it would take 50 years of monitoring to detect a 20% change in the sediment delivery at the end of system. Wang et al. (2015) argue that the time horizon for trend detection can be considerably shortened, to perhaps as low as 10 years, through the inclusion of high-resolution continuous turbidity data. This finding gives (new) impetus to the monitoring effort.

4.1.3 Key conclusions

Gully

The following conclusions can be drawn from the body of evidence that passed the criteria for inclusion in this review:

- There is a low number of studies that assess the water quality outcomes and cost effectiveness of gully restoration in the GBR catchment area. The review highlighted that studies on gully remediation from other parts of the world are of limited value for comparison; as in addition to significant geographic and climatic differences, very few studies measure water quality improvements associated with gully management and typically do not differentiate the fine and coarse sediment fractions. In the GBR, fine sediments (<20 µm) have been identified as being the ecologically significant component of the sediment budget, given that this fraction is dispersed over greater distances and can carry attached nutrients. Furthermore, much of the international literature is based around linear hillslope gullies, which are not the main focus for much of the current remediation effort in the GBR.

- The large-scale remediation of alluvial[11] gullies has been demonstrated to be a highly effective strategy for significantly reducing tens of thousands of tonnes of fine sediment that is being actively delivered to the GBR each year. Gully remediation treatments can include major earth works and reshaping, soil treatment, installation of rock chute structures, earth bunds and water points, fencing and revegetation. A combination of these treatments can achieve over 90% fine sediment reduction within one to two years.
- In contrast, direct hillslope gully treatments appear less effective in reducing fine sediment losses (7 to 17% effectiveness). Destocking catchments may also reduce hillslope gully sediment yields by up to 60% after ~25 years, however there is limited information on the practicality and costs of this approach. Streambank rehabilitation treatments include interventions to increase riparian vegetation, either directly through planting, or indirectly through the removal of disturbance pressures such as grazing to encourage natural colonisation, and in some cases bank reprofiling and stabilisation, which enables subsequent revegetation via planting and/or natural colonisation. The available evidence shows that hillslope gully treatments are less cost-effective when compared with the cost per tonne of fine sediment abated, but also the amount of sediment that can be abated, from large high yielding alluvial gullies. While it may initially seem attractive to save money up front by implementing lower cost and less effective treatments, such an approach carries a greater risk of failure in the future, and potentially higher maintenance costs. At present it is not known whether such a trade-off will be more or less expensive across the design life of the treatment (>30 years).
- In most situations, particulate nutrient reductions typically track the reductions in fine sediment, however this is not the case for dissolved nutrients where organic matter is added to improve soil condition. Organic ameliorants with a high carbon:nitrogen ratio are more likely to ensure that dissolved inorganic nitrogen export is reduced.
- There is limited documented evidence of the production outcomes of gully remediation projects. However, given the relatively small area of high yielding gullies, there is likely to be little private production benefit associated with gully management (i.e., for grazing). Remediation investments funded through the Reef Trust are recommended to be protected through grazing exclusion in the treatment areas (other than rare very short-term dry season maintenance grazing).

Streambank

The following conclusions can be drawn from the body of evidence for **streambank rehabilitation**:

- There are currently no studies from within the GBR catchment area that demonstrate a relationship between site-scale bank stabilisation, or even reach-scale rehabilitation works, and downstream water quality improvements. The evidence from Australian and international literature is scant and focused on small scale (<150 ha) catchments, with limited applicability to the scale of the GBR river channel network.
- Consistent with previous global reviews of streambank rehabilitation treatments, there is no ability to assess the effectiveness at the catchment scale of individual treatment types, nor derive effectiveness ratios for various treatments. A significant contributing factor to this is the lack of at scale, long-term quantitative monitoring of rehabilitation projects. A key issue is the difficulty to establish an appropriate baseline erosion rate for a channel as, based on current field evidence, it is very difficult to determine whether a riverbank is *eroded* or *eroding*.
- There is no peer reviewed Australian literature on the cost or cost-effectiveness of riparian/channel rehabilitation projects that was relevant to this synthesis. Given the lack of information on baselines, treatment effectiveness and cost data of projects, the cost-effectiveness of streambank rehabilitation could not be evaluated in this review.

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[11] There are two major gully types; alluvial (or river associated) and colluvial (or hillslope gullies). This distinction is based on the material the gullies are eroding into: alluvium - sediments deposited overbank from rivers and streams; and colluvium -sediments derived from *in-situ* weathering on slopes and/or downslope processes on hillslopes.

- Despite the lack of studies that have focused on measuring the relationship between channel and riparian zone rehabilitation and water quality in the GBR (or anywhere), studies show that bank erosion generally occurs at lower rates on vegetated river reaches than non-vegetated reaches. However, none of these studies demonstrate reductions in bank erosion associated with streambank rehabilitation or revegetation of formerly unvegetated banks. There is also evidence that there is significant hysteresis in channel recovery once river channels have responded geomorphically to vegetation removal. In practice, this may mean that channel changes that took perhaps decades to be fully realised, may take centuries to fully recover. Protection of remaining riparian vegetation is therefore important.
- There is a need to focus efforts at whole-of-system approaches that seek to maximise recovery of riparian vegetation at the reach to subcatchment scale, rather than focus on individual erosion sites.

4.1.4 Significance of findings for policy, management and practice

Gully

The evidence from the NESP TWQ Hub research about the effectiveness of gully remediation is compelling, however the studies are relatively short term (3-4 years). Establishment of long-term monitoring sites that can track maintenance costs over the long-term and the response of remediated gullies to climate change as well as land management practice change will continue to improve knowledge of the effectiveness of remediation projects. Ideally, the sites that have been monitored to date would be the focus of such a long-term program, along with new sites brought on-line that cover a diversity of gully types, baseline yields and treatments. Understanding the effectiveness of gully management requires a robust understanding of baseline sediment yields in gullies, based on the latest science (e.g., Daley et al., 2023). A standardised framework is needed for determining gully baseline sediment yields that reflects the wide diversity of gully evolutionary trajectories found in the landscape.

The long-term performance of gullies that have been remediated to different standards, and the cumulative costs of maintenance is unknown. For example, it is not known if the savings that may be accrued upfront by employing undercapitalised treatments will end up costing more or less over the 25-30 year design life (accounting for higher ongoing maintenance costs) than if the treatment was implemented to the highest standards at the outset. The only way that this question can be addressed is through the implementation of a long-term monitoring program that can track the longitudinal performance of a selection of gullies.

Given the high importance placed on understanding remediation cost-effectiveness, there is a clear need to develop a standardised and peer reviewed accounting framework for measuring gully remediation costs, and cost-effectiveness, using agreed timeframes over which costs are assessed and standardised discount rates. The design life should reflect the timescale over which it is expected the water quality improvements will be maintained, which should be last up until 2050 (i.e., >25 years). The Reef Credit methodology (Brooks et al., 2020), is an existing approach that lays out how the baseline assessment and monitoring can be undertaken in a standardised way.

Streambank

Two critical elements emerge from this brief review. The first is the need to adopt system scale, holistic, long-term thinking when considering the structure of any program aimed at reducing catchment sediment export. This will necessarily entail some reconsideration of goal setting and the appropriateness of metrics for judging progress towards identified goals. Policy settings that require precise quantification of ‘at site’ sediment savings associated with particular interventions will likely introduce perverse incentives for delivery teams and impede them from finding their place within the recently developed Whole-of-System, Values-Based Framework[12]. Goal setting which attempts to disentangle components of the system and treat them in isolation to meet inappropriate metrics risks creating phantom results. This problem is recognised within the Gully and Streambank Toolbox, where

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[12] https://wetlandinfo.des.qld.gov.au/wetlands/management/whole-system-values-framework/

activities such as fencing and revegetation in reaches that are not eroding are assigned an 'effectiveness value' in order to make them an attractive option to delivery partners. Without this, delivery partners would be incentivised to overlook work which is important at the systems scale but hard to justify at the local scale. In this approach the 'effectiveness value' becomes (merely) a settable lever, whereby delivery partner behaviour can be fine-tuned by adjusting the relative rewards for undertaking different types of work at a larger spatial scale.

The problem here is not the vision of the river as a connected system, nor the response of delivery partners to signalling from the developers of the Toolbox, but rather the way this is implemented. The real metric here should be something like 'progress towards reinstating the greatest possible extent of riparian vegetation throughout the whole river', which justifiably also represents the state where sediment and nutrient export are minimised, particularly if targeted to river type. Note that in some rare instances this progress might take the form of bank stabilisation works, undertaken to facilitate revegetation, but for the most part it will be fencing combined with active and passive revegetation that will do the heavy lifting of erosion control. The use of, or more precisely the description of, the metric as tonnes saved per year, invites the incorrect assumption that summing the stated 'savings' from all the individual interventions will enable one to arrive at the total catchment savings. Total catchment savings are a function of changes in:

1) The overall rate of change in volume of the void occupied by the river channel(s).
2) The rate of overall change in the volume of long-term sediment stores (e.g., floodplains).
3) The rate of overall change in the composition of the channel margin (where one is primarily interested in only part of the sediment flux i.e., the fine fraction),
4) The overall rate of change in the 'transmissivity' of the channel network to sediment supplied from the catchment, through, for example, the formation of in-channel benches (e.g., Pietsch et al., 2015). Changes in flood celerity (flood wave travel time – sensu Cohen et al. (2022)) mediated in the main by increases in riparian vegetation will influence in-channel bench formation.

In consideration of these, some interventions will work in concert, hence there will be synergistic savings additional to the summed at-site savings, while other interventions will work in opposition to the catchment trend. This uncertainty as to the combined impact of multiple interventions means that care should be taken in prioritising those interventions. Efforts to ensure ample seed cascade from upstream combined with the setting aside of potential colonisation areas downstream, within a management context that can tolerate channel dynamism, are likely to yield greater sediment savings over the medium term than a system driven by site-by-site measurement of erosion.

The second more prosaic consideration is to ensure that sediment discharge data are being collected now in such a way that maximises sensitivity to change, minimising the time over which trends can be observed, with the approach of Wang et al. (2015) providing a possible example.

A monitoring strategy to measure the cumulative progress towards increased in-channel sediment storage (sensu Pietsch et al., 2015) and riparian resilience, needs to take account of the four key points outlined above.

4.1.5 Uncertainties and/or limitations of the evidence

Gully

Some uncertainty exists in the ability to predict the long-term performance of gullies due to the short periods of time that they have been monitored to date. All of the GBR-based monitoring studies have been relatively short term (<5 years), so there is some uncertainty about the long-term performance of these treatments, particularly in the absence of ongoing maintenance. In particular, the evidence suggests that gullies not treated to the highest standards at the outset, have a higher likelihood of reduced effectiveness (Brooks et al., 2021), requiring greater maintenance over time. The cumulative cost of maintenance through time is also a major unknown, which will have some bearing on whole of life cost-effectiveness assessments. It is unclear whether smaller up-front investments, with lower treatment effectiveness, will have a higher or lower lifetime cost-effectiveness. This is particularly the case given the higher costs associated with future maintenance, due to both inflation and equipment mobilisation costs.

Streambank

As discussed above, the absence of long-term measurements of catchment sediment export, along with the inherent uncertain relationship between any particular intervention and its expression within the sediment discharge record at the catchment base prevents any assessment of effectiveness of riparian interventions. Nevertheless, the weight of evidence from across the world strongly supports the continuation of a program of streambank restoration works, particular those designed to directly or indirectly increase the quantity and quality of riparian vegetation. The totality of interventions work in concert to yield a number of ecological, social, and geomorphic benefits, including minimising sediment and particulate nutrient export. For this work to proceed however, decision makers will need to contend with unavoidable and inherent uncertainty, devising systems to support individual activities which in themselves have no certain outcome.

As with gullies, there is considerable uncertainty about the ongoing requirements for maintenance, to ensure the continuation of riparian rehabilitation effectiveness for many decades. This is particularly the case in situations reliant on native vegetation (i.e., most cases). Weed invasion has the capacity to kill and replace native vegetation and so ongoing weed maintenance will be required, potentially at considerable cost. Furthermore, the maintenance of riparian fencing is a major cost. If fencing is not maintained, and stock are allowed to access the riparian zones, the effectiveness of rehabilitation efforts can be significantly reduced, or negated altogether. Systematic research is required to quantify the whole of life costs of riparian rehabilitation that fully accounts for the ongoing costs of maintenance. There is a considerable body of data continued within the grey literature on maintenance costs, which could be drawn upon, but which was not eligible to be used in this review.

4.2 Contextual variables influencing outcomes

A summary of the contextual variables influencing the relationships in Question 3.6 is presented in Table 11.

Table 11. Summary of contextual variables for Question 3.6.

Contextual variables	Influence on question outcome or relationships
Climatic zones	Landscape processes occurring in different climatic zones (e.g., Wet Tropics versus Dry Tropics) mean that effectiveness results from one treatment type in one zone cannot be readily transferred to effectiveness in other zones without consideration of climatic context.
Land use pressures	Both historical and ongoing land use pressures will impact on the success and effectiveness of rehabilitation works at both a local and catchment scale. For example, if cattle continue to access a site post-rehabilitation, they will impact the success of the site by potentially causing further damage (Shellberg et al., 2016; Shellberg, 2020).
Gully specific variables	
Gully type	There are a wide range of fundamentally different gully types, and this needs to be taken into account when designing and monitoring gullies (Thwaites et al., 2022).
Soil materials	There are a wide range of soil types, and these need to be taken into account when designing and monitoring gullies (Thwaites et al., 2022).
Streambank specific variables	
Hydrological variability	Hydrological variability relates to the frequency and magnitude of flow events, particularly the magnitude of difference between high and low flows. There are large gradients of hydrological variability in the GBR catchments (Rustomji et al., 2009) and this has particular relevance to fluvial processes, drivers of degradation and natural

Contextual variables	Influence on question outcome or relationships
	recovery timelines. Consideration of this factor is important in assessing and evaluating streambank rehabilitation works.
River types – biophysical characteristics	There is considerable variability in the behaviour of rivers, based on a broad range of hydromorphological characteristics. These characteristics are largely based on climatic and geological/geographical variables but determine the nature by which rivers can respond to drivers and pressures. Understanding the type of river provides capacity to interpret the needs and challenges for rehabilitation (Brierley & Fryirs, 2022). The results from one river type are not directly transferrable to others.
Alluvial sediment characteristics	The sediments comprising the bed, banks and depositional units of a river are critical to the nature of streambank erosion (Klavon et al., 2017), rehabilitation and success. For example, processes and treatments within a sand-bed dominated system will be different to a gravel-bed system or those with very fine bank materials. Further, this has important consequences for the quantity of fine-sediment available for downstream transport or end-of-system loads.
Riparian vegetation communities	The vegetation communities that inhabit streambanks throughout the GBR, and across the world, are highly variable (Accad et al., 2023). This will impact the density of vegetation, capacity of different species to retain / trap sediments, density and depth of root growth to reinforce the banks of the stream. This is particularly relevant for revegetation projects in terms of the community that is created.
Geological & social historical contingencies	The history of a river channel captures the sum of different drivers, pressures and processes experienced by the river over both geological and management timescales. Different rivers will be in different stages and have experienced very different processes and this will impact on their capacity for further adjustment in response to remediation (McMahon et al., 2020). As such, effectiveness of treatment in one river cannot be simply translated to another.
Fire and flood regimes	The term fire and flood 'regime' refers to the frequency, magnitude, duration and seasonality of fire and flood events. Over the breadth of the GBR, the regimes experienced in different river systems is dramatically different and will impact on streambank rehabilitation treatments, giving different consideration to treatment options but also these differences will impact the success or effectiveness of different treatment sites. These regimes are important to consider in climate change scenarios.
Non-linearity in fluvial processes	Rivers exhibit complex, chaotic behaviours and patterns in both spatial and temporal domains, rarely behaving in a predictable and expected way (Phillips, 2003). As such, the effectiveness of any specific streambank treatment cannot be determined, as future behaviour (e.g., erosion rate) cannot be predicted.
Concert of treatment types	The effectiveness of an individual streambank treatment is further complicated by approaches that often integrate multiple treatment methods into a design; for example, including fencing, revegetation, bank reprofiling rock revetment. Success may be linked to the concert of these different treatments (Wilkinson et al., 2022) and the effectiveness of one treatment option on its own cannot be adequately separated.
Timing of treatments	In both a seasonal and inter-annual domain, the timing of treatment works can be critical to their success. This is particularly the case with revegetation works, where the success of the revegetation depends on having appropriate flow conditions for the recruitment and stabilisation of the vegetation. Young vegetation may be particularly prone to major weather events including floods or drought.

4.3 Evidence appraisal

Relevance

The relevance of the overall body of evidence was Moderate for both the gully remediation and streambank rehabilitation effectiveness aspects of the question. The relevance of each individual indicator was Low - Moderate for relevance of the study approach and reporting of results to the question for the streambank and gully components, respectively, and Low-Moderate for spatial and temporal relevance, overall. Of the 33 articles included in the review of the gully aspect of Question 3.6, most were given a Low- Moderate score for overall relevance to the question, with the exception of 6 studies from within the GBR (20%) which had a High overall relevance score. Of the 55 items reviewed for the streambank component of the question, individual scores for overall relevance were Low-Moderate.

Consistency, Quantity and Diversity

Gullies

The quantity of evidence upon which the gully review is based is Low-Moderate with 33 studies in total of which 18 studies were from the GBR (including 4 separate studies involving rigorous monitoring, 2 from the Laura/Normanby catchment in Cape York, and 2 from the Burdekin/Bowen catchments) – with an additional study based on modelled data in the Fitzroy. Collectively, however, this body of evidence is based on data from ~30 separate gullies. The quality of the data from the GBR sites stands out when compared with international literature as being of a uniquely high standard. Most of the international gully remediation literature does not directly monitor the water quality outcomes, instead studies typically only monitor the total sediment load reductions through the use of treatments such as check dams. Furthermore, most of the international literature addresses linear hillslope gullies. Such studies highlight the fact that check dams in linear gullies are not a particularly effective treatment, and in particular are not effective at reducing fine suspended sediment.

Streambanks

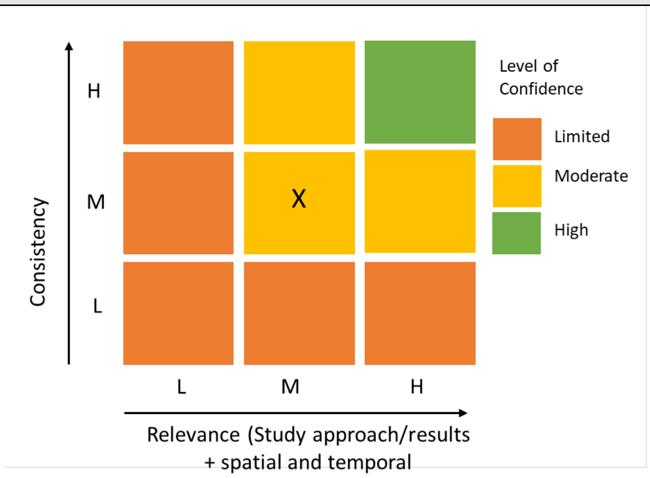
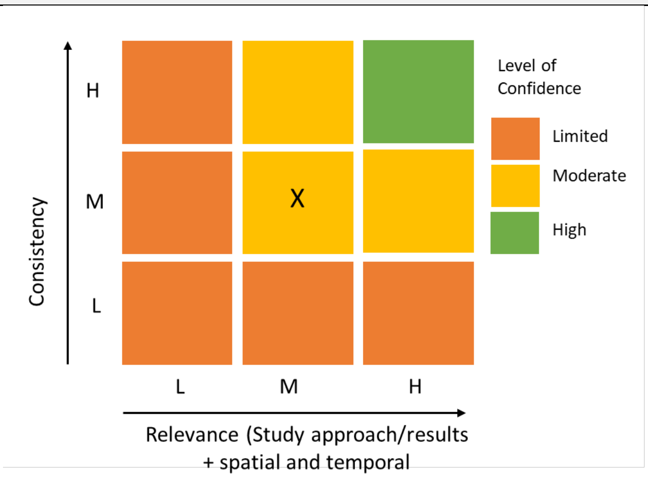
The quantity of evidence items relevant to the question of catchment scale effectiveness of streambank interventions is Low-Moderate, with 55 studies overall, but zero in relation to the GBR. No published research is available which shows the effectiveness of individual streambank treatments, or combinations of treatments, in affecting the sediment or nutrient discharge from GBR catchments. However, there was a Moderate-High degree of consistency in the theoretical contextual information about the role of riparian vegetation and associated woody debris as a primary factor controlling channel erosion, maximising in-channel deposition and limiting sediment throughput from the whole channel network.

Confidence

The confidence in the body of evidence for the effectiveness of streambank interventions was Moderate. No research was directly relevant to the situation in the GBR catchment region, though several papers from other regions, and considerations from first principles, support the general contention that remediation, particularly that based on extensive revegetation, can result in a lowering of catchment sediment and nutrient export.

As far as gullies are concerned, despite the low number of studies reviewed overall, the evidence as to the effectiveness of treatments addressing large alluvial gully remediation is strong and confidence was rated as Moderate.

Table 12. Summary of results for the evidence appraisal of the whole body of evidence in addressing the question for (a) gullies and (b) streambanks. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

<table>
<tr><td colspan="3">a) Gullies</td></tr>
<tr><td>Indicator</td><td>Rating</td><td>Overall measure of Confidence</td></tr>
<tr><td>Relevance (overall)</td><td>Moderate</td><td rowspan="7"> </td></tr>
<tr><td>-To the Question</td><td>Moderate</td></tr>
<tr><td>-Spatial</td><td>Low-Moderate</td></tr>
<tr><td>-Temporal</td><td>Low-Moderate</td></tr>
<tr><td>Consistency</td><td>Moderate</td></tr>
<tr><td>Quantity</td><td>Low-Moderate
<i>33 total (18 GBR)</i></td></tr>
<tr><td>Diversity</td><td>Moderate
<i>22 Australian; 18 GBR; 10 international</i></td></tr>
<tr><td colspan="3">b) Streambanks</td></tr>
<tr><td>Indicator</td><td>Rating</td><td>Overall measure of Confidence</td></tr>
<tr><td>Relevance (overall)</td><td>Moderate</td><td rowspan="7"> </td></tr>
<tr><td>-To the Question</td><td>Low</td></tr>
<tr><td>-Spatial</td><td>Low-Moderate</td></tr>
<tr><td>-Temporal</td><td>Low-Moderate</td></tr>
<tr><td>Consistency</td><td>Moderate-High</td></tr>
<tr><td>Quantity</td><td>Low-Moderate
<i>55 studies total (0 GBR).</i></td></tr>
<tr><td>Diversity</td><td>Moderate
<i>11 direct evidence - non GBR; 24 inferred evidence; 55 contextual information</i></td></tr>
</table>

4.4 Indigenous engagement/participation within the body of evidence

From the gully studies reviewed there was significant Indigenous engagement with the projects undertaken in Cape York (Brooks et al., 2016; 2021; Shellberg & Brooks, 2013). Beyond that, no further direct Indigenous engagement was identified in any of the other research projects. Across the assessed streambank studies, none mentioned any involvement, participation or engagement with Indigenous groups. Many studies were not based in Australia, let alone the GBR.

4.5 Knowledge gaps

A summary of the knowledge gaps for Question 3.6 is presented in Table 13.

Table 13. Summary of knowledge gaps for Question 3.6.

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
Gully evolution conceptual models covering all potential permutations of how the key gully types have evolved over the last 150 yrs. This would need to encompass models for each of the primary gully types outlined in Thwaites et al. (2022).	Understanding the baseline erosion trajectory of a gully is a function of the evolutionary model, and is crucial for establishing a robust baseline against which effectiveness can be measured in all circumstances.	At present, the Gully toolbox assumes as a default that all gullies have a declining sediment yield trajectory – and yet this has been demonstrated not to be the case for many high yielding gullies. The result of this false assumption is that many gullies have had their baseline yields underestimated, and in other cases, overestimated.
Longer term effectiveness of gully remediation, include that associated with lower cost, higher risk treatments.	Need to monitor gullies over the long term that have had differing levels of investment and keep track of maintenance costs.	Need to understand the investment level below which it is false economy to proceed.
Standardised method for deriving cost-effectiveness.	Without a standardised strategy, it is not possible to compare effectiveness values between sites and other practices.	Critical knowledge base for informing investment.
Lidar-based methods for assessing gully sediment yields – in which "Limits of detection" are accurately quantified as a function of DEM resolution.	A rigorous method is required for determining the "limits of detection" for measuring gully and streambank erosion using Lidar DEM of Difference (DoD) data. At present, it is clear that 0.5 m data will significantly underestimate gully sediment yields at time intervals ~<10 years – depending on the rate of gully down wearing (sensu Daley et al., 2023), and rainfall received.	A more accurate record of sediment yield reductions, achieved through gully and riparian remediation.
Cost effective remediation techniques for non-alluvial (hillslope) gullies.	Understanding which approaches could be cost-effectively applied to hillslope gullies.	A more comprehensive approach towards cost-effective gully remediation.
Channel boundary sediment erodibility quantification.	Alluvial channel boundary sediment erodibility is the most sensitive variable of all parameters required to model channel erosion – varying by around six orders of magnitude (Klavon et al., 2017). A research program to quantify	Such a dataset will significantly improve our ability to model channel erosion. It will be best undertaken as a function of channel type.

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
	channel boundary erodibility is a high priority.	
A robust definition of the riparian zone that can be objectively defined across all GBR rivers.	Modelling channel stability requires knowledge of the functionally significant extent of riparian vegetation (i.e., not just a standard buffer width as a function of stream order). Developing a robust definition of the functional riparian zone that can be objectively defined.	Significantly improved ability to model the effective area of riparian vegetation, and hence the magnitude of channel erosion under different flow conditions.
Catchment-wide changes in streambank vegetation in recent years (e.g., last 30 years).	The extent of woody riparian vegetation is the best indicator of channel stability and resilience. In NSW coastal rivers Cohen et al. (2022), demonstrated that there has been a significant natural increase in riparian vegetation over the last 30 years.	It is currently unknown whether there are similar trends in the extent of riparian vegetation in the GBR catchment area. If such trends were evident, it could be reflected in sediment loads monitoring data. Such data will also provide a robust basis for river management prioritisation.
Magnitude of variability in end-of-system sediment and nutrient loads.	Need to understand the range of variability in end-of-system loads so that improved methods can be developed for detecting changes associated with practice change.	The ongoing support for the water quality program is dependent on being able to monitor the improvements. There is a justified lack of public trust in modelled outcomes.
Long-term outcomes from a range of different streambank rehabilitation works in the GBR catchment area, according to river type.	Development of optimal monitoring strategies for riparian zones, as a function of river type. This would include a combination of super reach water quality monitoring and high resolution topographic (lidar) monitoring.	Monitoring riparian improvements is critical to water quality program success.
Differences in streambank efficacy across major geoclimatic settings of the GBR catchment area (i.e., Wet Tropics, Dry Tropics, subtropics).	Quantitative monitoring strategies may need to be tailored to river type in the different regional ecosystems.	Provide greater confidence in the program success.
Measured production outcomes from gully remediation and streambank rehabilitation projects.	Understanding the production outcomes of a range of gully and streambank treatment options.	Provide greater understanding of private (versus public) benefits of remediation projects.

5. Evidence Statement

The synthesis of the evidence for **Question 3.6** was based on 88 studies (33 gully remediation and 55 streambank rehabilitation), undertaken in the Great Barrier Reef catchment area and other national and international locations, published between 1990 and 2022 with some earlier streambank studies. The synthesis includes a *Moderate* diversity of study types (58% observational, 19% reviews, 16% experimental and 7% modelling), and has a *Moderate* confidence rating (based on *Moderate* consistency for gullies and *Moderate* to *High* consistency for streambank studies and *Moderate* overall relevance of gully and streambank studies).

Summary of findings relevant to policy or management action

There are a small number of published studies undertaken in the Great Barrier Reef catchment area that assess the effectiveness and costs of gully remediation for reducing fine sediment export, and none that demonstrate a relationship between site-scale streambank stabilisation and downstream water quality. The large-scale remediation of alluvial[13] gullies has been demonstrated to be an effective strategy to significantly reduce fine sediment load delivered to the Great Barrier Reef. Gully remediation treatments can include major earth works and reshaping, soil treatment, installation of rock chute structures, earth bunds and water points, fencing and revegetation. A combination of these treatments can achieve over 90% fine sediment reduction within one to two years. In contrast, direct hillslope gully treatments appear less effective in reducing fine sediment exports (7 to 17% effectiveness). Destocking catchments may also reduce hillslope gully sediment yields by up to 60%, after ~25 years, however there is limited information on the practicality and costs of this approach. Streambank rehabilitation treatments include interventions to increase riparian vegetation, either directly through planting, or indirectly through the removal of disturbance pressures such as grazing to encourage natural colonisation, and in some cases bank reprofiling and stabilisation, which enables subsequent revegetation via planting and/or natural colonisation. Rehabilitation works cannot currently be evaluated due to limited measurement of treatment effectiveness, but studies have shown that bank erosion generally occurs at lower rates on vegetated streambanks than non-vegetated streambanks. There is a need to refocus efforts from site-scale management to whole-of-system approaches that seek to maximise recovery of riparian vegetation at the river reach to network scale, rather than focus on individual erosion sites. While streambank rehabilitation will assist in reducing sediment export in the Great Barrier Reef catchment area, estimates of return on investment are poorly understood.

Supporting points

- Apart from the studies published in the National Environmental Science Program Tropical Water Quality Hub (2014 to 2021), none of the gully and streambank projects undertaken in the Great Barrier Reef catchment area have quantitatively monitored sediment and particulate nutrient reductions as part of the evaluation of treatment options.
- Studies of gully remediation treatments undertaken in other parts of the world are of limited value for comparison to the Great Barrier Reef context due to the significant geographic and climatic differences, limited measurement of water quality and failure to differentiate between the fine and coarse sediment fractions.
- In the locations studied, a small number of high-yielding gullies (~2% of the total number) account for a substantial proportion of the sediment yield (30%). Alluvial gullies contribute a large proportion of the sediment yield from this top 2% of gullies and typically have high sediment delivery ratios. This highlights the need to prioritise and target gully remediation efforts to efficiently and cost-effectively reduce fine sediment exports to the Great Barrier Reef.

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[13] There are two major gully types; alluvial (or river associated) and colluvial (or hillslope gullies). This distinction is based on the material the gullies are eroding into: alluvium - sediments deposited overbank from rivers and streams; and colluvium -sediments derived from in-situ weathering on slopes and/or downslope processes on hillslopes.

While there are also large, high-yielding hillslope gullies in the Great Barrier Reef catchment area, there are no documented examples of these being remediated.

- While large, high-yielding gullies can be expensive to remediate (e.g., more than $500,000), they are a significant and spatially concentrated source of sediment, have shorter response times for fine sediment reductions, and can be treated at larger scales and in fewer locations. Evidence from alluvial gully remediation examples indicates that these treatments can be 26 - 60 times more cost-effective in achieving the same cumulative fine sediment reductions than lower-cost options for lower-yielding gullies, e.g., <$600 per tonne of sediment abated compared to >$13,000 per tonne of sediment abated.
- Although robust methods exist to calculate the cost-effectiveness of gully remediation projects, there is no consistency between projects and investment programs, and agreement on a standardised peer-reviewed method should be a priority. This is critical to assess and compare project viability, capture baseline data and monitor the effectiveness of gully remediation treatments ultimately leading to improved assessments of the cost-effectiveness of remediation design and implementation life.
- In most situations, particulate nutrient reductions from alluvial gully remediation typically track the reductions in fine sediment, however dissolved nutrients can increase where organic matter is added to improve soil condition. The use of organic products such as mulch or hay with a high carbon:nitrogen ratio is more likely to ensure a reduction in dissolved inorganic nitrogen runoff.
- The evidence of the water quality benefits of streambank rehabilitation from Australian and international literature is limited and focused on small scale (<150 ha) catchments. This evidence has limited applicability to the scale of the Great Barrier Reef river channel network. There are also a wide range of factors that influence river dynamics, posing additional challenges for evaluation.
- Maintenance of gully and streambank projects is critical to prevent further degradation and ensure treatments continue to be effective for many decades. The costs of ongoing maintenance are largely unknown but are required to quantify whole of life costs to inform future policy and management decisions.
- Undercapitalised treatment options are less effective and carry greater risk of future failure. At present it is not known whether the trade-off between initial capitalisation and ongoing maintenance costs will be more or less expensive across the life of the treatment.
- Obtaining quantitative monitoring data at a range of scales (site, subcatchment and catchment) is essential to evaluate the effectiveness, costs and production outcomes of gully and streambank projects and to maximise the benefits of remediation projects.

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 3.6

Theme 3: Sediments and particulate nutrients – catchment to reef

Primary Question 3.6 What is the effectiveness of gully and streambank restoration works in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?

Secondary Question 3.6.1 What is the benefit of vegetation restoration in 1) riparian zones and 2) hillslope and floodplain zones, in reducing sediment and particulate nutrient loss to the Great Barrier Reef?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Andrew Brooks	Griffith University	Fluvial geomorphology, catchment sediment budgets, gully remediation and river rehabilitation	Lead Author	All Sections
2.James Daley	Griffith University	Fluvial geomorphology, catchment sediment budgets, GIS, lidar analysis, gully remediation	Contributor	All Sections
3.Tim Pietsch	Griffith University	Fluvial geomorphology, catchment sediment budgets, GIS, lidar analysis, optical dating and geochemistry	Contributor	Writing and editing