2022 Scientific Consensus Statement

Question 4.8 What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality?

Megan Star[1,2], Syezlin Hasan[3], James C R Smart[3], Carla Wegscheidl[4]

[1]Star Economics, [2]Central Queensland University, [3]Griffith University, [4]Department of Agriculture and Fisheries

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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.

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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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

[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

evidence prior to starting the literature search. The Method recommended conducting a **systematic literature search** in at least **two online academic databases**. Searches were typically restricted to 1990 onwards (unless specified otherwise) following a review of the evidence for the previous (2017) SCS which indicated that this would encompass the majority of the evidence base, and due to available resources. In addition, the geographic **scope of the search for evidence** depended on the nature of the question. For some questions, it was more appropriate only to focus on studies derived from the GBR region (e.g., the GBR context was essential to answer the question); for other questions, it was important to search for studies outside of the GBR (e.g., the question related to a research theme where there was little information available from the GBR). Authors were asked to provide a rationale for that decision in the synthesis. Results from the literature searches were screened against **inclusion and exclusion** criteria at the title and abstract review stage (**initial screening**). Literature that passed this initial screening was then read in full to determine the eligibility for use in the synthesis of evidence (**second screening**). Importantly, all literature had to be **peer reviewed and publicly available.** As well as journal articles, this meant that grey literature (e.g., technical reports) that had been externally peer reviewed (e.g., outside of organisation) and was publicly available, could be assessed as part of the synthesis of evidence.

4. **Extract data and information from the literature**. To compile the data and information that were used to address the question, **Authors were asked to complete a standard data extraction and appraisal spreadsheet**. Authors were assisted in tailoring this spreadsheet to meet the needs of their specific question.
5. **Undertake systematic appraisal of the evidence base**. Appraisal of the evidence is an important aspect of the synthesis of evidence as it provides the reader and/or decision-makers with valuable insights about the underlying evidence base. Each evidence item was assessed for its spatial, temporal and overall relevance to the question being addressed, and allocated a relative score. The body of evidence was then evaluated for overall relevance, the size of the evidence base (i.e., is it a well-researched topic or not), the diversity of studies (e.g., does it contain a mix of experimental, observational, reviews and modelling studies), and consistency of the findings (e.g., is there agreement or debate within the scientific literature). Collectively, these assessments were used to obtain an overall measure of the level of confidence of the evidence base, specifically using the overall relevance and consistency ratings. For example, a high confidence rating was allocated where there was high overall relevance and high consistency in the findings across a range of study types (e.g., modelling, observational and experimental). Questions using the **SCS Evidence Review Method** had an **additional quality assurance step**, through the assessment of reliability of all individual studies. This allowed Authors to identify where potential biases in the study design or the process used to draw conclusions might exist and offer insight into how reliable the scientific findings are for answering the priority SCS questions. This assessment considered the reliability of the study itself and enabled authors to place more or less emphasis on selected studies.
6. **Undertake a synthesis of the evidence and complete the evidence synthesis template** to address the question. Based on the previous steps, a narrative synthesis approach was used by authors to derive and summarise findings from the evidence.

Guidance for using the synthesis of evidence

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

1. **Executive Summary**: This section brings together the evidence and findings reported in the main body of the document to provide a high-level overview of the question.
2. **Synthesis of Evidence:** This section contains the detailed identification, extraction and examination of evidence used to address the question.
   - ***Background***: Provides the context about why this question is important and explains how the Lead Author interpreted the question.

- ***Method:*** Outlines the search terms used by Authors to find relevant literature (evidence items), which databases were used, and the inclusion and exclusion criteria.
- ***Search Results:*** Contains details about the number of evidence items identified, sources, screening and the final number of evidence items used in the synthesis of evidence.
- ***Key Findings:*** The **main body of the synthesis**. It includes a summary of the study characteristics (e.g., how many, when, where, how), a deep dive into the body of evidence covering key findings, trends or patterns, consistency of findings among studies, uncertainties and limitations of the evidence, significance of the findings to policy, practice and research, knowledge gaps, Indigenous engagement, conclusions and the evidence appraisal.

3. **Evidence Statement:** Provides a succinct, high-level overview of the main findings for the question with supporting points. The Evidence Statement for each Question was provided as input to the 2022 Scientific Consensus Statement Summary and Conclusions.

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

Peer Review and Quality Assurance

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

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Executive Summary

Question

Question 4.8 What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality?

Background

To date the Australian and Queensland governments have invested in different policy and program mechanisms including incentives, extension and education, market-based instruments, regulation (*Great Barrier Reef Protection Amendment Bill 2009* (Queensland Government)) at a management practice level or gully and streambank remediation level, and conservation management land purchases.

More recently, greater focus has been placed on wetland restoration or the application of treatment systems including treatment (constructed) wetlands and bioreactors to reduce land-based anthropogenic pollutant runoff from entering the Great Barrier Reef (GBR).

Globally, wetlands have been restored and treatment systems have been constructed to help improve water quality from diffuse pollutants such as sediments, nutrients and pesticides from agriculture. In Australia and the GBR specifically, there is a very limited number of studies that have captured all the measured costs and that have been monitored over a number of years. Understanding the measured costs and cost drivers of wetland management and restoration actions is critical for informing new programs and projects seeking to achieve reductions in land-based pollutants.

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, ProQuest and Queensland Government's Wetland*Info*.
- The main source of evidence was international literature where long-term wetland policies and projects have been implemented. Of the 56 studies used in the synthesis, nine were from Australia, of which eight focused on the GBR catchment area.

In the context of measured costs and cost drivers, studies were placed into three key categories:

1) **Assessing the different costs associated with different types of wetland** restoration or construction, management, integration with Best Management Practices (BMP), or costs associated with a program design scale (paddock, catchment or subcatchment scale).
2) **Optimisation and prioritisation studies**, focused on allocation of resources to achieve a targeted pollutant reduction or number of wetlands at least cost.
3) **Policy and programs** required to achieve desired levels of adoption and pollutant reduction. These studies consisted of global reviews but also of adoption parameters and improved program and project design, through various policy mechanisms and approaches.

[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

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 two academic databases were searched.
- The review was restricted to peer reviewed literature including journal articles and publications from the major government programs in the GBR context.
- Only studies published post 1990 were included.

Key Findings

Summary of evidence to 2022

- A limited number of studies have fully assessed the cost-effectiveness of wetland systems (including natural/near natural wetlands, restored, treatment/constructed wetlands and other treatment systems) in the removal of pollutants in the GBR catchment area.
- Within the available studies, measured costs for treatment systems using best practice approaches have been reported. This includes measurement of upfront costs, ongoing costs and in some instances the opportunity costs, reported over a specified time using standard discount rates[6]. There is limited understanding of the variation in costs across different types of wetland treatment systems in the GBR.
- Currently, there are no long-term monitored assessments of the cost-effectiveness of nutrient removal from wetlands in the GBR region that are based on complete sets of measurements of both costs and nutrient removals, hindering comparison with other management actions. Measured costs for eight constructed wetlands completed in GBR catchments varied considerably, ranging from an annualised present value cost of $3,075 to $31,588 per hectare per year (in FY 2020/21 AUD) over a 25-year period.
- The actual costs of projects for different wetland types are driven by several factors including size, construction, opportunity costs, monitoring requirements and maintenance.
- International studies contained relevant information, but transferring the findings to the GBR can be challenging because of differing climatic and policy contexts.
- Overall, it was identified that cost-effective nitrogen reductions can occur when a wetland treatment system is designed at a landscape scale (i.e., subcatchment or catchment) taking into account broader landscape processes including hydrology and topography and the links between them. Many studies showed that the strongest driver of cost-effectiveness for wetland projects was the effectiveness of nitrogen removal based on initial placement in the landscape, landscape characteristics such as nutrient inputs, vegetation, rainfall, hydrology and topography, comprehensive planning and design, and ongoing maintenance of the project.
- International studies highlighted that long-term investments were most successful when there was a clear definition of investor's objectives and outcomes, which were reflected in policy and program design, and subsequent projects.
- Supporting points of direct relevance to the GBR:
  - Public and private investors have different objectives and expectations for investment outcomes. This will influence the minimum level of return on investment required for a wetland project designed for pollutant removal to be viable. Furthermore, different investors may seek different outcomes from wetland design and project implementation (e.g., different suites of co-benefits) which could influence the wetland attributes to be incorporated, impacting on project cost.
  - Measured costs of wetland projects need to be captured over a consistent timeframe and appropriate discount rate applied to evaluate the effectiveness of programs in present

[6] Discounting brings costs in future years back into current dollar terms. Discount rate is the rate at which this occurs and is typically 5-7%.

value. This includes costs during the pre-construction phase (e.g., conceptualisation, design, planning, landholder engagements, approvals), construction phase (e.g., earthworks, planting), and post-construction phase (e.g., monitoring, maintenance, repair).

- Opportunities to deliver co-benefits such as biodiversity outcomes from wetland restoration projects are well documented, particularly in large landscape-scale wetlands. The details of the co-benefits being sought must be included from the initial project design as well as the policy and program design. These may also require different monitoring and reporting, and potentially be influenced by different cost drivers that must be considered.
- Long-term international projects (in Denmark and Sweden) have demonstrated that average costs of nitrogen abatement for individual wetland projects typically increase (after correcting for inflation) as the number of willing landholders declines, and the locations where wetland treatment is likely to be most effective are already utilised. Furthermore, if implementation is undertaken at landscape scale (i.e., where a number of landholders are required to be involved to achieve the best outcomes), the transaction costs incurred in obtaining landholder participation will increase further.
- Internationally, management approaches undertaken in the edge of headlands or vegetated drains and buffer strips have been implemented as best management practices. However, such practices can also generate unintended negative impacts for landholders such as introduction of invasive species (e.g., pigs) or difficulty in headland management (e.g., less available space and increased water retention on headlands leading to getting bogged). Studies from Canada, the United States, Denmark and Sweden also indicate that burdensome management requirements (e.g., monitoring and reporting, labour intensive tasks such as hand pulling weeds) can deter farmers from signing up to wetland incentive programs.

Recent findings 2016-2022

The majority of GBR studies have been published since 2016 providing costs for a limited number of constructed wetlands and bioreactors.

Significance for policy, practice, and research

- Policy mechanisms and program design must be considered initially as this will drive what types of costs are critical to be captured. For example, the government will be seeking to understand different costs in an incentives program compared to an investor in a trading program. This would then allow development of a standard framework or guidelines for compilation, standardisation and reporting of cost data across projects. Currently, information on costs is limited and therefore there is scope to ensure that all measured costs are comparable.
- A whole of landscape approach is required to achieve the most cost-effective outcomes from a biophysical and hydrological perspective. Holistic approach to wetland management that include buffers and vegetated drains through to constructed wetlands or bioreactors should be adopted, starting from the initial planning stage through to post implementation stage.
- Over time, the price per tonne of pollutant reduction will increase as the number of willing landholders declines. This has been a key learning from the Baltic Sea catchments that is applicable to the GBR context. Although there are a small number of wetlands constructed for water quality outcomes in the GBR catchment to date, there is likely to be scope for cost-effective wetland project sites before this cost increase is realised if well-planned.
- Long-term opportunity costs and ongoing maintenance costs must be considered in assessing the cost-effectiveness of wetland projects. These are also important considerations in defining the length of funding programs and monitoring requirements, potentially (and most likely) extending beyond the life of the initial funding program.
- If co-benefits are being sought, the context of the type and subsequent design and implementation of wetland systems must be considered, along with the relevant policy mechanisms and the ability to stack benefits in trading programs. It must be noted that not all co-benefits can necessarily be achieved in the same timeframes or that specific water pollution

outcomes can be achieved from a specific wetland design; this highlights why co-benefits must be considered at the start of wetland planning for water quality improvements.

Key uncertainties and/or limitations

The small number of studies highlights some of the key costs and cost drivers, however given the diversity of these study sites and wetland system types, a comparison between costs cannot be completed. These limited studies do however provide an insight into the potential range of costs that may be experienced through wetland construction, restoration and treatment systems or bioreactors installation.

Although the international literature provides insights into policy and program design, the underpinning climate, agricultural land use, culture and policy context are different to the GBR which results in a degree of uncertainty regarding the specific costs such as opportunity costs, adoption and ongoing maintenance costs. However, the key findings that have been presented here have been assessed to be sufficiently relevant to be transferable to the GBR context.

Key knowledge gaps for further monitoring and research include:

- Comparable method (standard metric) for measured costs across all cost categories and water quality improvements in a range of GBR locations.
- Understanding at a landscape level where wetland systems could be situated to achieve efficient pollutant reductions and the subsequent actions and costs to achieve the reductions.
- Impacts of climate change on the construction and post-construction phase costs.
- Consideration of policy mechanisms and approaches over time to achieve the targeted reductions i.e., incentives or trading schemes.
- Stacked actions such as paddock scale management, establishment of vegetated drains or buffer strips and then wetland restoration, management or treatment systems.
- Capacity to achieve co-benefits and the mechanisms to achieve them.

Evidence appraisal

The relevance of the overall body of evidence was Moderate (5.1). The relevance of each individual indicator was Moderate (2.1) for overall relevance to the question (study approach/reporting results), Low (1.2) for spatial relevance, and Moderate (1.8) for temporal relevance.

The impact of the large number of international studies was that often the agricultural land use differed to those in the GBR and the spatial conditions were in temperate climates. The temporal relevance rating reflects that a few of the framework or adoption papers were less relevant due to the specific international context. The high variance in timeframe depending on the classification type (assessing costs, prioritisation and optimisation, and program review) of the paper resulted in a moderate score for temporal relevance.

Across the three classification types**,** consistency was assessed based on:

- How specific measures are implemented (Program and Project design).
- Scale (both spatial and temporal).
- Baseline situation.
- Land use types and management practices.

Overall, the consistency of cost types and classification within pre-construction, construction and post-construction was deemed to be High.

Uncertainty, timescales of effectiveness, and obtaining accurate cost estimates of measures over time are additional challenges in assessing the cost measures to reduce diffuse pollution from agriculture.

Given the high variability of biophysical characteristics, costs were not comparable, and this diversity therefore resulted in an inability to suggest the proportions of costs that could or should be allocated to specific drivers. The limited number of GBR specific studies and the range of wetland interventions and sites, along with the different types of cost information collected, means that they are not comparable.

However, for the constructed wetland studies there is high consistency of these costs where they were reported.

The quantity of studies in the GBR is Low with only three studies capturing costs and one study capturing costs across several sites. There are other studies which are not focused on measured costs or cost drivers but do note costs as an important factor. Internationally there is a large body of work and therefore an increase the diversity in study types and greater capacity to complete reviews after funding wetlands over a number of years.

The diversity ranges from very specific paddock scale cost drivers and measured costs through to reviews of adoption of landholder involvement in wetland management (and influence on driving costs), resulting in an overall rating of High. This diversity provides insights into the opportunities and challenges for implementing wetland programs and achieving land-based pollutant runoff changes.

Confidence

The overall score for the confidence assessment was rated as Moderate based on Moderate overall relevance and High consistency. The low number of GBR studies reflects the new interest in wetlands and the low monitoring to date relative to other countries such as Sweden, Denmark and the US. Therefore, due to the limited depth of understanding in the GBR, caution must be taken in transferring specific costs and values given the biophysical, climatic and land use differences. Key findings regarding overall program and policy outcomes, design and monitoring however provide insights for the GBR context.

1. Background

The declining health of the Great Barrier Reef (GBR) has been attributed to several factors, including pollutant runoff from land-based industries (Brodie et al., 2012; 2017; Kroon et al., 2016). The pressures on the GBR have led to a large number of policies and investments to improve water quality, many of which are focused on improving agricultural management practices (Australian Government, 2017). The Reef 2050 Water Quality Improvement Plan (WQIP) has a target of no net loss to the extent of natural wetlands, a 60% reduction in anthropogenic inorganic nitrogen load, and a 20% reduction of particulate nutrients and fine sediment by 2050 (Australian Government, 2017).

To date, the Australian and Queensland governments have invested in different policy and program mechanisms, including incentives (Rolfe & Windle, 2016), extension and education (Barbi et al., 2015; Rolfe et al., 2020), market-based instruments (Rolfe & Windle, 2011; Smart et al., 2016), regulation (*Great Barrier Reef Protection Amendment Bill 2009* (Queensland Government)) and conservation management land purchases. This is discussed further in Question 7.1 (Coggan et al., this Scientific Consensus Statement (SCS)).

More recently, treatment systems (such as treatment wetlands and denitrifying bioreactors) and natural wetlands have been investigated for their capacity to reduce land-based anthropogenic pollutant runoff entering the GBR. Globally, wetlands and treatment systems have been restored or constructed to help reduce losses of diffuse pollutants such as sediments, nutrients and pesticides from agriculture. The definition of wetlands (see DES, 2022) encompasses several ecosystems, of which palustrine and lacustrine wetlands have been the most studied for their capacity to reduce dissolved inorganic nitrogen (DIN), total suspended solids (TSS) and pesticide loads entering into the GBR from agricultural land uses.

For this reason, this question focuses on palustrine and lacustrine wetlands. Palustrine wetlands are vegetated, non-riverine or non-channel systems including billabongs, swamps, bogs, springs, and soaks and have more than 30% emergent vegetation (DES, 2022). Lacustrine wetlands are large, open-water-dominated systems with slow moving or still water (e.g., lakes). This definition also applies to modified systems (e.g., dams).

The primary question evaluated here is: *What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in GBR catchments for improving water quality*. Considerations were given to the spatial variability, wetland management, design and policy conditions under which costs were measured or considered a driver. A 'cost driver' is defined as any factor, index, event or coefficient that causes a change in the costs and which is the basis for cost allocation, and a measured cost has monitored and primary data for dollars per item or intervention associated with the management or improvement.

In the GBR catchments there are a number of stakeholders including both State and Australian government agencies, natural resource management (NRM) organisations, local government and industry groups that are responsible for various infrastructure, engagement and legislative obligations. These jurisdictions and responsibilities intersect (geographically and in terms of roles) in the context of wetland management, rehabilitation and construction. Policy frameworks for the GBR do not provide a specific framework for the assessments of cost, unlike in Europe, where the Water Framework Directive explicitly provides guidance regarding the assessment of costs and cost-effectiveness (Balana et al., 2011; Carvalho et al., 2019; Lam et al., 2011; Martin-Ortega, 2012), or the United States, where detailed cost-benefit assessments are required under the Clean Water Act (Keiser & Shapiro, 2018). Internationally, voluntary construction and/or restoration of wetlands to reduce non-point source runoff from agriculture is typically incentivised through economic mechanisms (Djodjic et al., 2022) and involves regionally specific program and government interactions.

In Europe, specifically Denmark and Sweden, blue-green algal blooms triggered by high nitrogen (N) and phosphorus (P) concentrations are major concerns for the Baltic Sea (HELCOM, 2021). The Helsinki Commission's Baltic Sea Action Plan established sea basin-specific targets to reduce N and P loads (HELCOM, 2021). Reduction of non-point source N and P runoff from agriculture is thus a prominent policy issue for Baltic littoral countries (Ollikainen et al., 2019). All except one (Russia) of the Baltic littoral countries are members of the European Union (EU). Thus, the EU's Water Framework Directive[7] is a major driver of water quality management throughout the Baltic drainage basin. The Water Framework Directive sets EU-wide requirements for inland and coastal water bodies to achieve 'good ecological status', but implementation mechanisms for achieving this objective can differ between national jurisdictions (Martin-Ortega, 2012).

Article 11 of the Water Framework Directive requires that cost-effectiveness analysis should be undertaken when considering implementation approaches, and selection of measures within those approaches, to ensure that water quality objectives are delivered at minimum overall cost. This has driven research interest in the cost-effectiveness of alternative approaches for improving water quality, with the construction or restoration of wetlands frequently included as a potential measure for reducing N and P runoff from agriculture (e.g., Czajkowski et al., 2021; Elofsson, 2003; Elofsson et al., 2003; Hasan et al., 2022; Hasler et al., 2014). Research on this topic from Sweden and Denmark is particularly prominent (Graversgaard et al., 2021). In Denmark there has been a strong focus on wetlands to reduce N runoff to receiving waters (Graversgaard et al., 2021). In Sweden wetland incentivisation programs have been geared towards biodiversity enhancement and more recently, broader ecosystem service supply, as well as N and P reduction (Graversgaard et al., 2021).

In the US, the Federal Clean Water Act does not regulate non-point source pollution from agriculture rather states, territories and delegated tribes are required to develop non-point source management programs which are funded and follow the cost management reporting of the Act (Soldo et al., 2022). Harmful algal blooms triggered by excess nutrient concentrations are major concerns for the Great Lakes, the Gulf of Mexico and Chesapeake Bay (DeBoe et al., 2017; Ribaudo et al., 2001; Sparks et al., 2015; Stephenson et al., 2021; Tyner & Boyer, 2020). Lacking a regulatory policy, voluntary uptake of improved management practices in arable cropping and livestock grazing is incentivised to reduce non-point source N and P loads to receiving waters. Practice-based cost-sharing subsidy schemes are the predominant approach for incentivising constructed wetlands as a component of improved management practice (Cheng et al., 2020). In combination, the Wetland Reserve Program and Conservation Reserve Program operated by the US Department of Agriculture have contributed more than $US 4.2 billion to wetland protection and restoration (Brinson & Eckles, 2010; Hansen et al., 2015). Subsidies to incentivise construction of wetlands for treatment of non-point source pollution are also offered by some state governments. 'Smart market' water quality credit trading has also been trialled as an incentive for wetland construction or recreation in the Big Bureau Creek catchment in Illinois (Raffensperger et al., 2017). These international frameworks have the potential to provide insights and learnings for GBR wetland management and policy.

1.1 Question

Primary question	**Q4.8** What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality?

Authors' interpretation:

Cost driver is defined as any factor, index, event or coefficient that causes a change in the costs and which is the basis for cost allocation, and a measured cost has monitored and primary data for dollars per item or intervention associated with the management or improvement. For the purposes of this review, "wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (consistent with RAMSAR, 2016). The scope is restricted to wetlands in, or receiving water from, agricultural lands. Questions 4.6 (Thorburn et al.,

[7] https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive

this SCS), 3.5 (Bartley & Murray, this SCS) and 5.3 (Davis et al., this SCS) cover the non-agricultural land uses.

The review focuses on palustrine and lacustrine wetlands that have been most studied in the GBR for their role in improving water quality, specifically by reducing loads of DIN, TSS and pesticides entering the GBR from agricultural land uses. Palustrine wetlands are vegetated, non-riverine or non-channel systems including billabongs, swamps, bogs, springs and soaks and have more than 30% emergent vegetation (DES*,* 2022) and lacustrine wetlands are large, open-water dominated systems (e.g., lakes). This definition also applies to modified systems (e.g., dams), which are similar to lacustrine systems (e.g., deep, standing or slow-moving waters).

In addition, the terms 'natural' or 'near natural' wetlands refer to wetlands that are not: 1) constructed by artificial means; or 2) geothermal wetlands (super-heated water and/or mud, hot springs, thermal streams). Wetlands constructed to 'offset impacts on, or restore, an existing or former natural wetland' are considered here as 'near natural' wetlands (Ministry for the Environment, 2021). These include wetlands that have been restored to enhance N or P retention.

For this review 'use' is referred to as implementing best management practice, systems repair or remediation/restoration/construction activities within or near agricultural land, that are associated with the aim of improving water quality passing through the system that then enters the GBR.

Treatment wetlands are engineered systems that replicate and enhance the physical, biological and chemical treatment processes occurring in natural wetlands to remove fine sediments, nutrients and other pollutants (e.g., pesticides, heavy metals). They differ from restored or natural wetlands in that they are designed and managed primarily to improve water quality (DES*,* 2022).

Water quality refers to 'the physical, chemical, and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species and/or to any human need or purpose' (ANZECC & ARMCANZ, 2000). Therefore, water quality treatment refers to the process of intercepting, slowing down and/or removing pollutants from water. This can be via chemical processes (e.g., volatilisation), biological processes (e.g., denitrification and plant absorption) and physical processes (e.g., sedimentation), as well as creating conditions for improvements in water quality, such as increasing concentrations of dissolved oxygen (DES, 2022). Water quality treatment will be measured as an *in situ* and/or downstream metric.

1.2 Conceptual diagram

The conceptual map (Figure 1) considers the costs drivers in wetland treatment systems as the biophysical features and policy setting. These include factors such as hydrology, scale, landscape position and agricultural land-use, along with the policy setting which impacts the costs through the program design specifications and performance objectives. The wetland is then constructed, restored or managed and the costs incurred specific to the wetlands which are measured including the pre-construction which includes design and project management. Construction includes installation and earthworks and post-construction costs capture monitoring and evaluation and maintenance.

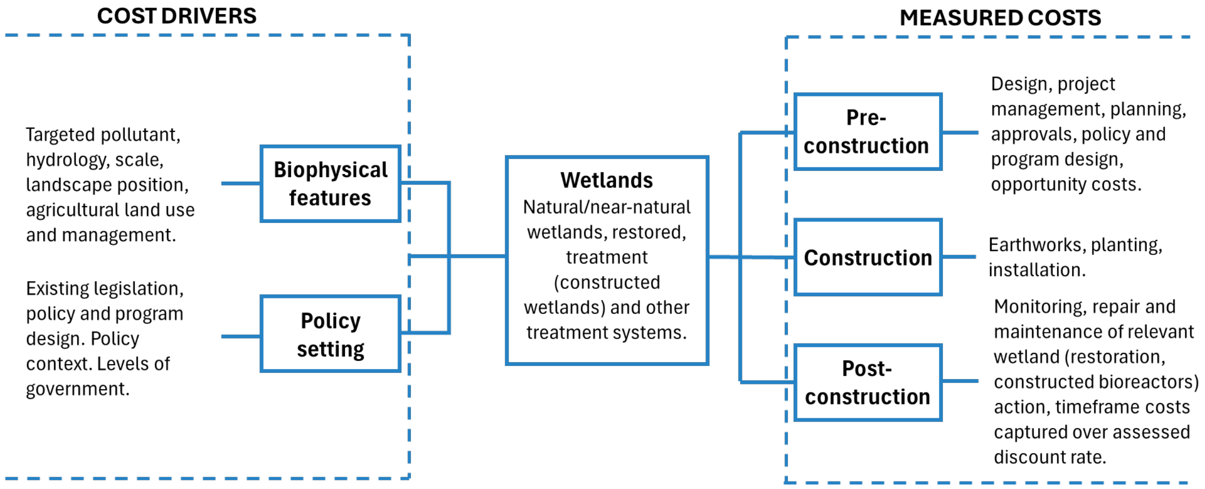


Figure 1. Concept map for cost drivers on the left and measured costs on the right.

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	**Q3.5** 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? **Q4.6** What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? **Q4.7** What is the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality (nutrients, fine sediments and pesticides)? **Q4.9** What role do Natural/near natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)? **Q5.3** What are the most effective management practices for reducing pesticide risk (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions?

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[8]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.

2.1 Primary question elements and description

The primary question is: ***What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality?***

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

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

Table 1. Description of primary question elements for Question 4.8.

Question S/PICO elements	Question term	Description
Subject/ Population	Measured Costs	**Cost of actions to restore and manage** natural/near natural wetlands, restored, treatment (constructed wetlands) and other treatment systems in agricultural landscapes. These costs will be monitored and not modelled to ensure they are measured and include private costs, opportunity costs, capital costs, and program costs (these costs may differ depending on the policy mechanism; regulation costs will be included in this component).
	Cost Drivers	A cost driver is any factor, index, event or coefficient that causes a change in the costs and which is the basis for cost allocation. Although not directly noted in the question, the land use that this question explores is agricultural land uses generating non-point source emission of pollutants. Therefore, dairy and intensive animal industries were excluded. Similarly, forestry was excluded.

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

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

Question S/PICO elements	Question term	Description
Intervention, exposure & qualifiers	Rehabilitate	Rehabilitation is an action, or actions to repair, enhance and/or replace ecosystem processes and/or components, to improve intrinsic values and/or ecosystem services.
	Restore	Restoration is an action, or actions to bring back a former, original, normal, or unimpaired condition[10]
	Construct	Construction/capital works in an area that was not a wetland in the recent past and that is isolated from existing wetlands (i.e., not directly adjacent).
	Manage	The removal of a threat to, or preventing decline of, wetland conditions by an action in or near a wetland i.e., weeds and pest management. Combinations of these interventions were considered.
Outcome & outcome qualifiers	Improved water quality	Improved water quality, removal or reduction of nutrients, sediments and pesticides measured by input versus output. Dissolved oxygen content measured as before/after. Removal efficiency. Efficacy in retaining or removing nutrients (nitrogen, nitrate, ammonium, phosphorus), fine sediments and pesticides.
Comparator	Wetland Type	Wetlands in this review will incorporate lacustrine, palustrine. Estuarine, riverine and marine wetlands will be excluded.
	Natural and near natural wetlands	Natural/near natural wetlands will exclude wetlands that are: 1) constructed by artificial means; and 2) geothermal wetlands. Wetlands constructed to 'offset impacts on, or restore, an existing or former natural wetland' are considered here as 'near natural' wetlands (Ministry for the Environment, 2021). These include wetlands that have been restored to enhance either N or P retention.

[10] Aquatic ecosystems rehabilitation background: https://wetlandinfo.des.qld.gov.au/wetlands/management/rehabilitation/rehab-background.html#citation-reference-1

Table 2. Definitions for terms used in Question 4.8.

<table>
<tr><th colspan="2">Definitions</th></tr>
<tr><td>Wetlands</td><td>Lacustrine, palustrine wetlands.
<table>
<tr><th>WETLAND SYSTEM</th><th>DEFINITION</th><th>EXAMPLES OF WETLAND TYPES</th></tr>
<tr><td>Palustrine</td><td>Palustrine wetlands are primarily vegetated non-channel environments with more than 30% emergent vegetation.</td><td>Grass, herb and sedge swamps; wet heath swamps (wallum); Melaleuca spp. and Eucalyptus spp. tree swamps; palm tree swamps; saline swamps; lignum swamps.</td></tr>
<tr><td>Lacustrine</td><td>Lacustrine wetlands are open, water-dominated systems (e.g. lakes). This definition also applies to modified systems (e.g. dams), which have deep, standing or slow-moving waters.</td><td>Floodplain lakes (including lagoons); perched sand lakes; window sand lakes; crater lakes; soil lakes; saline lakes; arid and semi-arid lakes; dams and reservoirs.</td></tr>
<tr><td>Riverine</td><td>Riverine wetlands are those systems that are contained within a channel and their associated streamside vegetation. The channels are naturally or artificially created, periodically or continuously contain moving water, or connect two bodies of standing water.</td><td>Rivers; streams; creeks; brooks; rivulets; canals; channels; watercourses; tributaries.</td></tr>
<tr><td>Intertidal</td><td>Intertidal wetlands are found between the high tide and low tide, experiencing fluctuating influences of sea and freshwater run-off from the land.</td><td>Sandflats; mudflats; saltmarsh and saltpans; mangroves; coral reefs; seagrass meadows; mollusc reefs; rocky reefs.</td></tr>
<tr><td>Subtidal</td><td>Subtidal wetlands on the sea floor remain continuously submerged from the low tide mark to 6 metres below the lowest astronomical tide.</td><td>Coral reefs; seagrass meadows; mollusc reefs; sand shoals; lagoon floor.</td></tr>
<tr><td>Subterranean</td><td>Subterranean wetlands are wetlands occurring below the surface of the ground that are fed by groundwater. These wetlands provide water to groundwater dependent ecosystems.</td><td>Unconsolidated aquifers (e.g. sand, gravel); porous sedimentary rock aquifers; fractured rock aquifers; karst systems (large void size).</td></tr>
</table>
Source: Queensland Museum (2022) Wetlands of Queensland, Queensland Museum Network, Brisbane</td></tr>
<tr><td>Natural/near natural wetlands</td><td>Wetlands that are not: 1) constructed by artificial means; or 2) geothermal wetlands. Wetlands constructed to ‘offset impacts on, or restore, an existing or former natural wetland’ are considered here as ‘near natural’ wetlands (Ministry for the Environment, 2021). These include wetlands that have been restored to enhance either N or P retention.</td></tr>
<tr><td>Water quality</td><td>Australian & New Zealand Guidelines for fresh & marine water quality definition: ‘the physical, chemical, and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species. Components may include volumes, variability in river discharges of nutrients and sediments; concentrations in flood plumes; regionally resolved annual mean water clarity, nutrient concentrations’ (ANZECC & ARMCANZ, 2000).</td></tr>
<tr><td>Rehabilitation</td><td>Actions to return an ecosystem to a close approximation of its condition prior to disturbance.</td></tr>
<tr><td>Construct</td><td>In the context of wetlands, construction/capital works in an area that was not a wetland in the recent past and that is isolated from existing wetlands (i.e., not directly adjacent).</td></tr>
<tr><td>Manage</td><td>In the context of wetlands, the removal of a threat to, or preventing decline of, wetland conditions by an action in or near a wetland i.e., weeds and pest management.</td></tr>
</table>

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:

- Scopus
- ProQuest
- Queensland Wetland*Info*.

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 4.8.

Question element	Search terms
Subject/Population	'cost', 'measured costs', 'cost drivers', 'private costs', 'opportunity costs', 'capital cost', 'maintained costs', 'program cost', 'cost effectiveness' 'management cost'
Exposure or Intervention	'rehabilitate', 'restore', 'construct', 'manage'
Comparator	'natural/near natural wetlands', 'restored wetland', 'treatment (constructed wetlands)', 'treatment systems', 'buffers'
Outcome	'improve', 'decrease', 'reduce', 'water quality'

c) Search strings

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

Table 4. Search strings used for electronic searches for Question 4.8.

Search strings
TITLE-ABS-KEY (*cost* AND (wetland* OR "treatment system*" OR bioreactor* OR buffer* OR swale* OR vegetated drain* OR recycle pit*) AND (improve* OR decrease* OR reduc* OR remov*) AND Nutrients OR Nitr* OR Phosph* OR pollut* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR fungicide* OR Salin* OR Sediment* OR "heavy metal*" OR "dissolved oxygen") AND (farm* OR agriculture*)

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 applied to the search returns for Question 4.8.

Question element	Inclusion	Exclusion
Subject/Population	Farm, row crops, agricultural stormwater, at a paddock, subcatchment or catchment scale.	Not agriculturally focused - industrial, forest, aquaculture, urban or point-sources from intensive animal industries.
	Measured costs, and cost drivers.	No cost related information. Costs are bundled with industrial and urban. Costs are at a laboratory scale.
Exposure or Intervention	Buffers, bioreactors, constructed wetlands, combinations of edge of field buffers and constructed wetlands, swales, management of wetlands, combination of agronomic and edge of field management approaches.	Re-use for irrigation, or other purposes. Multi-purpose studies (urban, industrial and agriculture). Non-wetland related studies.
Comparator	NA	NA
Outcome	Reduction in DIN, P, and/or sediments.	Primary outcomes of wetlands for biodiversity, birdlife, recreation or non-water quality related outcomes. Studies reporting on heavy metals as pollutants.
Language	English	Non-English
Study type	Reviews, optimisation, case studies, modelling approaches	Stated Preference studies - Choice modelling and willingness to pay studies which value benefits of the outcome.

3. Search Results

A total of 963 studies were identified through online searches for peer reviewed and published literature. Five studies were identified manually through expert contact and personal collections, which represented a 0.5% of the total evidence considered. 56 studies were eligible for inclusion in the synthesis of evidence (Table 6) (Figure 2). Three studies were unobtainable.

Table 6. Search results table, separated by A) Academic databases, B) Search engines (i.e., Google Scholar) 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 (d/m/y)	Search strings	Sources	
A) Academic databases		Scopus	ProQuest
15/12/22	Search string 1: (*cost* AND (wetland* OR "treatment system*" OR bioreactor* OR buffer* OR swale* OR vegetated drain* OR recycle pit*) AND (improve* OR decrease* OR reduc* OR remov*) A ND Nutrients OR Nitr* OR Phosph* OR pollut* OR light OR Irradiance OR Turbidity OR Pesticide OR Herbicide OR fungicide* OR Salin* OR Sediment* OR "heavy metal*" OR "dissolved oxygen") AND (farm* OR agricultur*)	60 of 963	6 (6) of 72
B) Search engines (e.g., Google Scholar)			
Not Conducted			
	Total items online searches	**963 (99.5 %)**	
C) Manual search			
Date	Source	Number of items added	
	Handsearch - Bioreactor Manual	1	
	WetlandInfo	1	
	Waltham, N. J., Canning, A., Smart, J. C. R., Hasan, S., Curwen, G., Waterhouse, J. (2020) Scoping land conversion options for high DIN risk, low-lying sugarcane, to alternative use for water quality improvement in Dry Tropics catchments.	1	
	Pfumayaramba, T., Wegscheidl, C., & Nothard, B. (2020). A preliminary cost-effectiveness analysis of denitrifying bioreactors in the Lower Burdekin. Townsville, State of Queensland	1	
	Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns (303pp.). Wegscheidl, C., Robinson, R & Manca, F (2021). Using denitrifying bioreactors to improve water quality on Queensland farms. Townsville: State of Queensland	1	
	Total items manual searches	**5 (0.5 %)**	

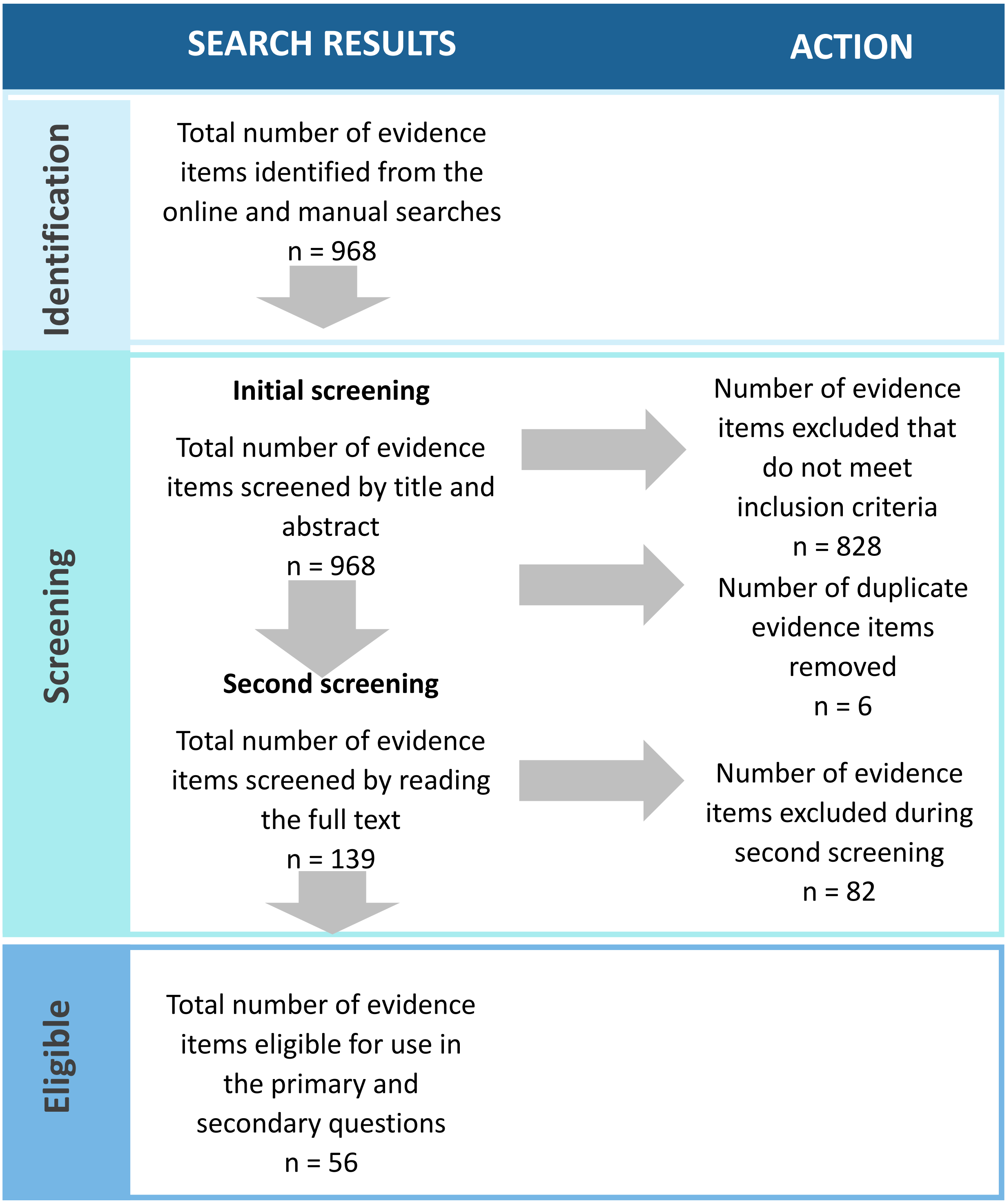


Figure 2. Flow chart of results of screening and assessing all search results for Question 4.8.

4. Key Findings

The key findings were globally spread with nine of the 56 studies included in the synthesis from Australia. These studies provide limited insights into costs due to the low number of field sites however, they have captured measured costs and cost drivers with high confidence. The international studies are over longer timeframes and although they generally have different climates, agricultural land use and policy contexts, they provide key insights for future considerations for wetland costs and cost drivers in the GBR catchment area.

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

Within the Australian studies, monitored costs were found in four of the studies with all four highlighting the potential capacity to stack outcomes and improve design to decrease costs, and one identifying the cost drivers that private landholders would incur.

Table 7. Summary of Australian studies used to address Question 4.8.

Study	Cost Driver and Measured Cost Focus
Canning et al. (2023)	Mock-landholder, considered representative of the participants, obtained from the costs incurred in constructing a representative scheme-subsidised lagoon on a medium-sized sugarcane farm. Construction and maintenance costs estimated. Included biodiversity and water quality benefits.
Kavehei et al. (2021)	Costs and nitrogen removal monitored and reported for eight constructed treatment wetlands (CW) and two vegetated drains (VD) in the GBR catchment, and four sewage treatment plant wetlands (STPWs) in Southeast Queensland, enabling cost-effectiveness to be calculated. Costs assessed include design, project management, construction, maintenance and repair.
Waltham et al. (2021a)	Transitioning low-lying, marginal sugarcane land to alternative land uses that require lower or no N inputs, such as treatment wetlands and ecosystem service wetlands which provide co-benefits of fish production. Costs assessed were reductions in annuity gross margins and land conversion cost.
Hagger et al. (2022)	Carbon focused but notes the opportunity costs of landholders and the capacity to stack benefits such as carbon, biodiversity and water quality.
White et al. (2022)	Bioreactor in blueberry farm, measures inflow and outflow of nutrients and construction cost captured.
Waltham et al. (2021b)	Transitioning low-lying, marginal sugarcane land to alternative land uses that require lower or no N inputs. Costs assessed were reductions in annuity gross margins and land conversion cost.
Wegscheidl et al. (2021)	Use of bioreactors on sugarcane farms, construction costs captured for different sites.
Pfumayaramba et al. (2020)	Detailed the actual costs for bioreactor construction and modelled cost-effectiveness under different size scenarios.
DES (2022)	WetlandInfo. Actions for wetland restoration and treatment systems construction.

Internationally, the search results highlight the key countries where wetland projects have been implemented and are of interest to improve water quality by reducing N or P concentrations (see Figure 3). The United States (US) dominated the literature with 23 studies primarily focusing on improving the water quality entering the Gulf of Mexico, Chesapeake Bay and the Great Lakes. Canada had three studies. Sweden, Denmark, and Germany have had 40 years of working to rehabilitate wetlands in catchments draining into the Baltic Sea and this was reflected in the 10 studies that included costs or cost drivers. A small number of studies conducted in Italy (1) and Spain (2) looked at decreasing N and/or P loads and improving water quality. New Zealand also had three studies that focused on wetlands. The UK had two studies that explored the cost drivers of wetland rehabilitation, and China had two studies. There was one global review of the application of bioreactors and the costs which highlighted the range of costs (Figure 3).

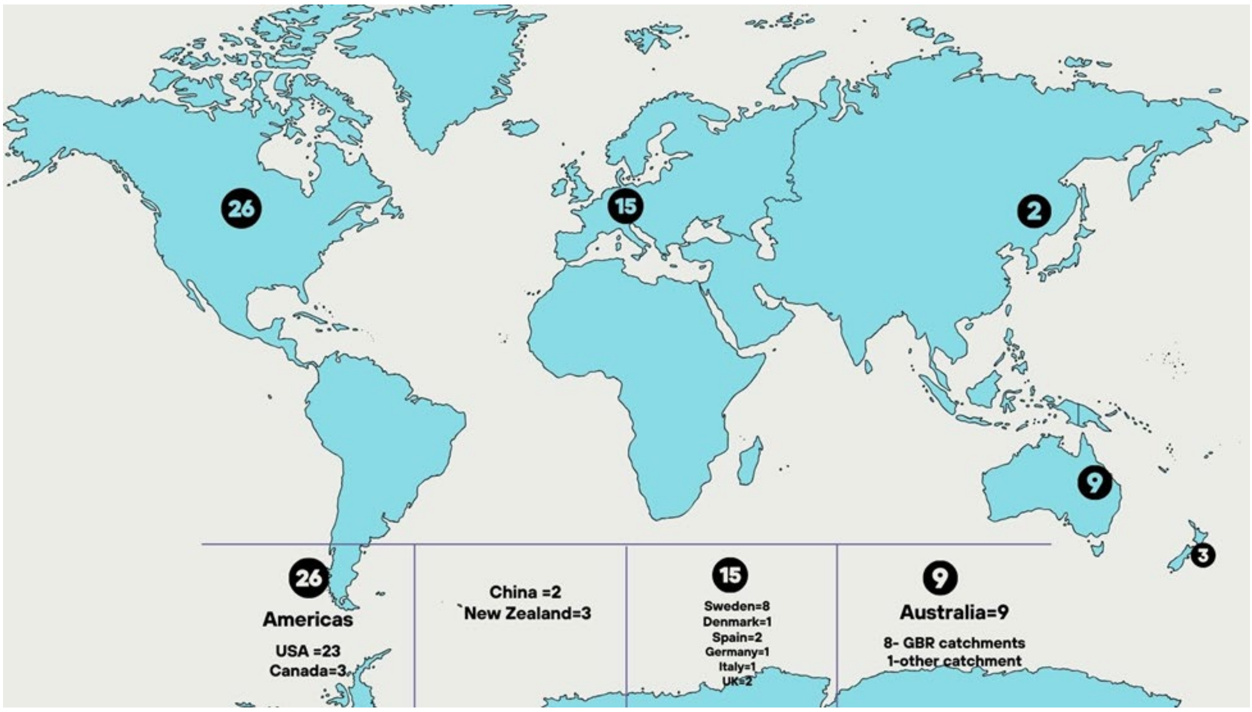


Figure 3. Countries where studies occurred.

The studies can be grouped in various ways however in the context of measured costs and cost drivers, the papers were placed into three key categories (Table 8).

1. Studies in the first category 'assessing costs' assessed the different costs associated with different types of wetland restoration or construction, management, integration with Best Management Practices (BMPs), or costs associated with a program design scale (paddock, catchment or subcatchment scale). There were 23 studies in this category.
2. Studies in the second category, 'optimisation and prioritisation', focused on allocation of resources to achieve a targeted pollutant reduction or number of wetlands. These studies often consisted of a portion of monitored data for government programs that were then linked with a model to understand the cost implications and progress towards achieving the target. There were 22 studies that sought to better optimise and prioritise funds to achieve pollutant targets or wetlands area targets.
3. The third category of papers reviewed the policy and programs required to achieve desired levels of adoption and pollutant reduction. These studies consisted of global reviews but also of adoption parameters and improved program and project design, through various policy mechanisms and approaches. There were 11 studies in this category.

Given the geographic spread of the body of evidence, the reviewed literature focused on different pollutants, from different agricultural industries with different types of wetlands and used different scales for assessing costs and cost drivers. In total, 34 studies focused on nitrogen, eight focused on phosphorus, seven considered both N and P, one considered sediment, N and P, and two considered nutrients as a bundle; typically these latter studies were exploring trading markets or program design. Finally, one study considered N removal as a potential co-benefit alongside carbon sequestration.

Similarly, a range of wetland types were explored, with rehabilitation being the primary focus in Sweden, Denmark and Germany resulting in 11 studies that focused on rehabilitation and restoration. Bioreactors were captured in seven studies. A combination of BMPs which consisted of edge of paddock buffer strips and vegetated drains were explored in 23 papers. Overall, 19 considered constructed wetlands. A number of papers captured a combination of wetland types.

Table 8. Classification of literature and relevant citations.

Category	Number	References
1. Assessing costs	23	Aggarwal et al., 2022; Byström, 1998; Canning et al., 2023; Christianson et al., 2013; 2018; Collins & Gillies, 2014; DeBoe et al., 2017; DES, 2022; Douglas-Mankin et al., 2021; Entry & Gottlieb, 2014; Kavehei et al., 2021; Pfumayaramba et al., 2020; Rao et al., 2012; Ribaudo et al., 2001; Roley et al., 2016; Sarris & Burbery, 2018; Stephenson et al., 2021; Tamburini et al., 2020; Waltham et al., 2021b; Wegscheidl et al., 2021; White et al., 2022; Yuan et al., 2022; Zimmerman et al., 2019
2. Optimisation and Prioritisation	22	Balana et al., 2015; Beukes et al., 2023; Byström, 2000; Cheng et al., 2020; Christianson et al., 2018; Comín et al., 2014; Geng et al., 2019; Getahun & Keefer, 2016; Gren et al., 1997; Hansen et al., 2021; Jacobsen & Hansen, 2016; López-Ballesteros et al., 2023; Lowe et al., 1992; Mewes, 2012; Rodriguez et al., 2011; Singh et al., 2019; Wang et al., 2019; Waltham et al., 2021b; Weeber et al., 2022; Yang et al., 2016; Zammali et al., 2021
3. Policy and Program review	11	Corrales et al., 2017; Djodjic et al., 2022; Graversgaard et al., 2021; Hagger et al., 2022; Hansson et al., 2012; Heberling et al., 2010; Lentz et al., 2014; Soldo et al., 2022; Strand & Weisner, 2013; Trenholm et al., 2017; van der Valk & Jolly, 1992

4.1.1 Summary of evidence to 2022

The three categories of assessing costs, optimisation and prioritisation, and policy and program review have the same cost drivers and measured costs, and therefore fall into the same conceptual diagram (Figure 1).

Cost Drivers

The different categories of papers highlight the different cost drivers for wetland systems for water quality outcomes and the different scales at which these drivers operate. Papers on cost drivers are categorised into papers that focused on drivers associated with biophysical features, or those associated with policy setting and adoption.

Biophysical features

- Cost-effective constructed or restored wetlands and treatment systems are those which have been selected, located and designed based on the components and processes of the landscape, such as hydrology, receiving water quality, pollutant, and topography of the landscape at a paddock and overall catchment scale (Byström, 1998; Cheng et al., 2020; DES, 2022; Djodjic et al., 2022; Hansen et al., 2021; Lowe et al., 1992; Manca et al., 2021; Rodriguez et al., 2011; Singh et al., 2019; van der Valk & Jolly, 1992; Wegscheidl et al., 2021; Zimmerman et al., 2019).
- Generally, cost-efficiency is poor when the constructed wetland area is large and incoming nutrient loads are low as this generates both a high cost and low nutrient reduction (Djodjic *et al.*, 2022).
- Cost is a function of bioreactor size (i.e., volume), and volume directly relates to residence time (DeBoe et al., 2017). The target residence time is a function of the inflow nitrate concentration and nitrate reduction objective (Wegscheidl et al., 2021).

- Stacking agronomic and edge of field management practices such as improved timing or reductions to in-field N application, edge of field buffer strips with wetland construction, rehabilitation or treatment systems (Bioreactors) resulted in more cost-efficient outcomes than individual measures (Balana et al., 2015; Christianson et al., 2018; Geng et al., 2019; López-Ballesteros et al., 2023). In addition, catchment scale collective approaches for edge of field mitigation placement become more cost effective than farm-based approaches when larger nutrient reductions are required (Weeber et al., 2022).
- The target reduction of a specific pollutant type is a key driver of cost. The dominant pollutant and/or water quality targets for a site will dictate system type, design and maintenance (Entry and Gottlieb, 2014). The maintenance costs can be significant, particularly where soil removal and vegetation re-establishment are required (Entry and Gottlieb, 2014). Maintenance costs are likely to be greater for P reduction as P cycles through the system and accumulates in the sediment requiring regular sediment removal, whereas N is permanently removed through the process of denitrification (Byström 1998; Byström, 2000; DES, 2022). Although a large number of studies were outside the GBR, the types of costs incurred need to be considered if projects were to be funded in the GBR solely for a pollutant reduction or if they include co-benefits.
- Co-benefits can be sought after and can generate a range of additional benefits, such as carbon sequestration, biodiversity gains, fisheries habitat and N reduction (Hagger et al., 2022; Strand & Weisner, 2013). Although providing co-benefits could increase the overall cost in some instances, securing payments for these additional ecosystem services could help cover the costs of on-ground works (Canning et al., 2023) and reduce the relative cost for water quality improvement. Conversely, Lentz et al. (2014) found that stacking benefits in a market-based trading scheme may or may not satisfy additionality. This highlights the importance of determining the mechanism and intent for the wetland outcomes from the planning and design phase.

Policy setting, mechanism and adoption

The mechanism used to incentivise wetland restoration or wetland/bioreactor construction varies between national and state jurisdictions depending on the water quality objective(s) and overarching policy context (see Section 4.2 – Contextual variables). Differences in policy context and the economic mechanism applied can influence the costs of wetland construction/restoration, either directly at project level by imposing conditions on wetland design, advisory or extension service, intended outcomes and monitoring requirements, or indirectly at program level by affecting the cohort of farmers who sign up to participate (Graversgaard et al., 2021; Mewes, 2012; Stephenson et al., 2021). Policy context can itself thus be a driver of wetland construction/restoration cost. Findings from the literature include:

- Differences in construction/restoration or location requirements under incentive mechanisms can influence wetland costs directly. These may be particularly relevant if wetland restoration aims to deliver multiple benefits (e.g., carbon sequestration and storage, water quality improvement, biodiversity enhancement, hunting opportunities) (Hagger et al., 2022; Soldo et al., 2022; Stephenson et al., 2021).
- Differences in the application requirements for incentive programs affect farmers' willingness to participate. Transaction costs associated with funding applications can be regarded as a significant disincentive from the landholder's perspective (Hansson et al., 2012; Stephenson et al., 2021).
- Differences in maintenance or monitoring requirements over time under incentive programs can influence compensation requirements and potential co-benefits (Hansson et al., 2012; Strand & Weisner, 2013).
- Findings from Soldo et al. (2022) in the US and Hansson et al. (2012) in Sweden suggest that programs aimed at supporting the construction of wetlands should emphasise the secondary benefits of wetlands (e.g., hunting opportunities, improved aesthetics) to the farmer, particularly since edge of field practices like buffers and wetland construction do not usually

provide on-farm benefits (Rao et al., 2012). It may be necessary to specifically target wetland construction on less productive land because many farmers believe that higher quality land is too productive for wetland conversion (Hansson et al., 2012; Soldo et al., 2022; Trenholm et al., 2017). Further to this Byström (2000) highlighted that the two limiting factors in Sweden to land conversion for the creation of constructed wetlands are the availability of suitable land and existing laws and infrastructure that constrain construction of larger areas for wetlands.

- A review and comparison of wetland incentive schemes in Denmark (1998-2021) and Sweden (1986-2021) by Graversgaard et al. (2021) indicated that in both countries the average payment ($\$ \text{ ha}^{-1}$) required to incentivise voluntary participation in wetland construction and/or restoration schemes has increased substantially through time (even after allowing for inflation). In Denmark incentive payments increased from 25,000 DKK ha^{-1} in 1998 to 117,000 DKK ha^{-1} in 2016; in Sweden (where only partial cover for costs is offered) incentive payments increased from 15,000 SEK ha^{-1} in 1989 to 50,000 – 60,000 SEK ha^{-1} in 1996 (Graversgaard et al., 2021). Graversgaard et al. (2021) also report that between 1998 and 2021 the threshold N removal effectiveness for entry to incentive schemes had to be reduced from 350 kg N ha^{-1} yr^{-1} in 1998 to 90 kg N ha^{-1} yr^{-1} to achieve the desired level of participation (Graversgaard et al., 2021). These outcomes suggest that compensation requirements may have to increase once an initial pool of environmentally motivated farmers and highly effective wetland locations have signed up.
- Schemes in which N credits from wetlands are traded on markets introduce buyers with evaluation criteria and outcome objectives that may differ from government who are typically the buyers of wetland outcomes that are funded via grants or incentives (Stephenson et al., 2021). These criteria include implementation costs (construction and maintenance, transaction/contracting costs (number of contracts required and the typical length of contract), regulatory risks (use of third-party contracts), certainty of N compliance (modelled or measured N removal outcomes), list of the pollutants reduced by the alternative and qualitative co-benefits (wildlife, aesthetics, flood control).
- A significant proportion of the literature on cost drivers and costs of constructed treatment wetlands comes from the US (Figure 3). In the US, the Federal Clean Water Act does not regulate non-point source pollution from agriculture (Soldo et al., 2022). Harmful algal blooms triggered by excess nutrient concentrations are major concerns for the Great Lakes, the Gulf of Mexico and Chesapeake Bay (Aggarwal et al., 2022; Soldo et al., 2022; Stephenson et al., 2021). Lacking a regulatory policy, voluntary uptake of improved management practices in arable cropping and livestock grazing is incentivised to reduce non-point source N and P loads to receiving waters. Practice-based cost-sharing subsidy schemes are the predominant approach for incentivising constructed wetlands as a component of improved management practice (Cheng et al., 2020).

Measured Costs

Project-level costs

Project-level cost is defined as the actual cost incurred at the scale of the individual wetland or treatment system. A treatment system such as bioreactors and constructed lagoons may comprise several distinct smaller treatment units situated in close proximity to each other in an agricultural farm that are designed to function as an integrated set to deliver the designed water quality treatment service.

A wetland project generally goes through three phases of measured progress and subsequent costs throughout its lifespan (Figure 4):

1) Pre-construction phase (e.g., conceptualisation, design, planning, landholder engagements, approvals).
2) Construction phase (e.g., earthworks, planting).
3) Post-construction phase (e.g., monitoring, maintenance, repair).

Pre-construction

Wetland establishment costs include design costs which involve surveying the site (Collins & Gillies, 2014; Douglas-Mankin et al., 2021) and consideration of the hydrology in the context of the required works which are critical factors as they identify the site specific actions and associated costs that will be required to achieve water quality outcomes for the targeted pollutant (Byström, 1998; Cheng et al., 2020; Djodjic et al., 2022; Hansen et al., 2021; Lowe et al., 1992; Manca et al., 2021; Rodriguez et al., 2011; Singh et al., 2019; van der Valk & Jolly, 1992; Zimmerman et al., 2019).

Costs for restored wetlands involve considerable and semi-irreversible structural work as well as long-term opportunity costs, with a number of studies highlighting the opportunity cost of production as a cost to be considered over the long term (Beukes et al., 2023; Douglas-Mankin et al., 2021; Heberling et al., 2010; Roley et al., 2016). Opportunity cost can be the main cost over time for constructed or rehabilitated wetlands as land area is permanently taken out of production (Ribaudo et al., 2001; Roley et al., 2016).

Yang et al. (2016) considered the transaction costs of administration associated with a project. These transaction costs included site assessment, negotiation, and paperwork, which were distributed over the number of wetlands within one farm. Transaction costs associated with funding applications can be regarded as a significant disincentive from the landholder's perspective (Hansson et al., 2012; Stephenson et al., 2021). Yang et al. (2016) also considered what they termed a nuisance cost, which represents the annual costs associated with inconveniences to agricultural production (e.g., machinery operations) when wetlands are present within farm fields.

In many studies, actual *in-kind contributions* are typically included in project costs, as upfront and/or ongoing costs, because such costs are seen as essential drivers for successful completion of wetland projects (Canning et al., 2023; Kavehei et al., 2021), however, in the long term, opportunity costs for the landholder can dominate the overall costs. Opportunity costs should therefore be captured from the time when agricultural production ceases (i.e., sometime during the pre-construction phase) through to the end of project lifespan (Roley et al., 2016).

This phase will also ensure that any legal restrictions and existing infrastructure are identified, and the relevant agencies can cooperate if required before construction begins. This may increase the process and subsequent costs (Byström, 1998; Hansen et al., 2021).

van der Valk and Jolly (1992) suggest the major technical issues that need to be resolved before effective and realistic guidelines can be developed for restoring wetlands to reduce non-point source pollution include: 1) the effects of contaminants, particularly sediments and pesticides, on restored wetlands; 2) the fate of organic contaminants in restored wetlands; 3) the development of site selection criteria; and 4) the development of design criteria. There are also many social, economic, and political barriers to using restored wetlands. Social and economic issues that need to be resolved include: 1) what is the most appropriate landscape unit for wetland restoration programs?; 2) where should wetlands be sited?; 3) who will make siting decisions?; 4) how can landowner cooperation for restoration programs be obtained?; 5) who will pay for wetland restoration?; and 6) how cost effective is this approach?

Construction

Construction costs occur initially and are based on the design aspects. They typically include soil and land conditioning, earth works such as use of excavator embankment construction, and construction and engineering of water-flow structures (Comín et al., 2014; Kavehei et al., 2021). These costs also include the planting of wetland specific plants and rhizomes (Aggarwal et al., 2022; Collins & Gillies, 2014; Comín et al., 2014). If land is acquired for construction then the cost pertaining to the acquisition is required to be captured in the construction costs. If this is the case the opportunity costs for the landholder of not producing off this land its negligible (Christianson et al., 2013). These costs generally occur in the first year of analysis for cost-effective studies and therefore are not impacted by discounting over time.

Construction costs will vary based on the type of wetland (e.g., natural, near natural or bioreactor) and design aspects will vary between sites based on hydrology and the biophysical features. These costs will also vary based on the location or access to heavy machinery, and or materials such as rocks and or woodchips (Weeber et al., 2022).

Post-construction

Following completion of on-ground wetland construction, recurrent or ongoing costs are incurred annually or periodically until the end of the project lifespan. Ongoing costs comprise of monitoring and evaluation costs, operating and maintenance costs, and repair costs. Beyond these wetland maintenance- and repair-related costs, the opportunity costs of not producing off the land continue to be incurred by the landholder. Opportunity costs should therefore be recorded during this phase.

Monitoring and evaluation costs (annual): Monitoring and evaluation activities are necessary to ensure targeted pollutants are being reduced and are effective either in terms of wetland functions (in the case of wetland restoration) or wetland extent and condition (in the case of new wetland installations) (Douglas-Mankin et al., 2021; Mewes, 2012; Strand & Weisner, 2013). If co-benefits are sought after, these also need to be monitored to ensure that these outcomes are being realised (Strand & Weisner, 2013).

Operating and maintenance costs (annual or periodical): The operating and maintenance works are undertaken to ensure that the restored or constructed wetlands remain effective at delivering water quality outcomes. These works may also include the areas close to the wetland such as buffer strips, or the actual wetlands (e.g., annual weed removal, mowing, periodic dredging of accumulated sediments) (Douglas-Mankin et al., 2021; Getahun & Keefer, 2016; Soldo et al., 2022; Tamburini et al., 2020). These costs obviously vary with the lifetime of the wetland, how it was designed and how it is is managed in the landscape.

Repair costs (as and when needed): Repair costs may be incurred post-wetland construction to account for unforeseen circumstances (e.g., mechanical failure, design oversight, flood damage) that have compromised wetland condition and function, and may involve minor or major repair works (e.g., revegetation, apron re-shaping). These were poorly documented in the literature which may reflect the temperate or alpine nature of international studies or the length of time studies were completed over.

Timeframe and Discount rate

The sum of upfront wetland construction base cost, the ongoing monitoring, evaluation, operating and maintenance costs (discounted), and repair cost (discounted) constitutes the actual measured costs of wetlands, expressed in present value (in $). The timeframes that wetland cost assessments were completed on also varied with some considering costs over 50 years (Christianson et al., 2013), 40 years (Strand & Weisner, 2013), 30 years (Zammali et al., 2021) and others 15 and 10 years (Roley et al., 2016; Yuan et al., 2022). The timeframe is dependent on the type of wetlands being assessed: for bioreactors, reflecting the lifespan; for buffer strips or BMP management approaches, reflecting management integration; and for natural or near natural wetlands, reflecting the ongoing management that would be required for having a wetland in the landscape.

Discount rates also varied between studies (Canning et al., 2023; Christianson et al., 2018; Collins & Gillies, 2014; Kavehei et al., 2021) reflecting the time period, with a 10-year analysis for a bioreactor with a 10.6% discount rate through to a 40-year timeframe for a bioreactor and management and a 4% discount rate (Christianson et al., 2013). The total present value of measured costs (in $) is then multiplied by the inverse of the annuity factor to arrive at the annualised present value of measured costs (in $/year) (Canning et al., 2023; Kavehei et al., 2021).

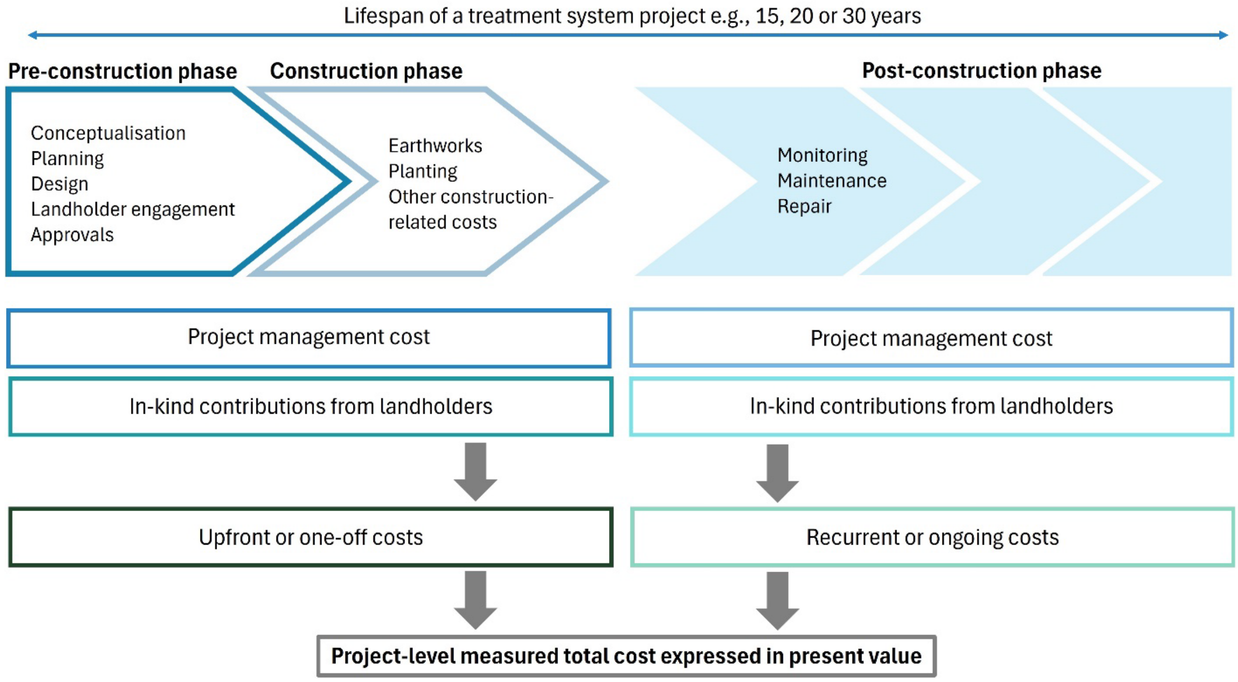


Figure 4. Types of costs over the lifespan of a wetland (adapted from Kavehei et al., 2021).

Given there is limited data that pertains to the biophysical conditions of the GBR, costs must be considered with caution. Table 9 has captured the actual costs reported in relevant Australian studies with these being difficult to compare as different pre-construction, construction and post-construction costs have been captured (Table 9). In addition, the type of wetland along with the location, different time periods for analysis, and discount rates have been applied. Table 1 highlights the different types of costs that have been captured and therefore although each study has reported a $ ha^{-1}, the difference in measured costs means they are not directly comparable.

Kavehei et al. (2021) captured the same costs across Queensland, with different wetland designs in different contexts and land uses. Each site had a different spatial footprint in regard to size. All but one site applied the same discount rate and timeframe, and reported both the annualised cost per hectare and the total cost per hectare. This consistency allows policy to consider and compare investment options over defined time periods.

Table 9. High-level summary of Queensland studies with reported cost types and values. Cost values are reported as annualised present value cost (APVC, in AU$ ha^{-1} $year^{-1}$) and its equivalent total present value costs (TPVC, in $ ha^{-1}).*

Study	Treatment system(s)	Region	Types of upfront measured cost included	Types of ongoing measured costs included	Opportunity cost of production	Time-frame(s) (years)	Discount rate(s) (% per annum)	Cost value
Kavehei et al. (2021)	Eight constructed treatment wetlands§	Wet Tropics, Burdekin and Mackay Whitsun day	Design, project management, and construction	Maintenance and repair	Not included	15, 20, 25	3, 5, 7	Reported APVC at 5% discount rate over 20 years ranged between AU$4,197 ha^{-1} yr^{-1} (TPVC at AU$52,304 ha^{-1}) and AU$43,076 ha^{-1} yr^{-1} (TPVC at AU$536,824 ha^{-1}) with mean and median costs of AU$11,886 ha^{-1} yr^{-1} (TPVC at AU$148,125 ha^{-1}) and AU$7,789 ha^{-1} yr^{-1} (TPVC at AU$97,064 ha^{-1}), respectively. (AU$ expressed in FY2020/21).
Canning et al. (2023) Environmental Management	Constructed lagoon	Wet Tropics- Tully-Murray	Construction	Maintenance	Opportunity cost net of yield improvement and higher value alternative land use across a representative farm	15	5	For a representative 0.3 ha lagoon, total (upfront) construction cost was AU$39,867, of which AU$9,867 (~25%) was contributed by landholders as in-kind and cash contributions. Maintenance costs ranged between AU$99 yr^{-1} and AU$990 yr^{-1}. (AU$ expressed in year 2019). On a per hectare basis and expressing costs in AU$ in 2020, total construction costs was AU$134,015 ha^{-1} and maintenance cost was between AU$333 ha^{-1} yr^{-1} and $3,328 ha^{-1} yr^{-1}.
Pfumayaramba et al. (2020) A preliminary cost-effectiveness analysis of denitrifying bioreactors in Lower Burdekin	Denitrifying bioreactor[Ŧ]	Lower Burdekin	Construction	Ongoing measured costs not available	No	N/A	N/A	Total construction cost for 34 m^3 bioreactor was AU$20,951. (AU$ expressed in year 2020). Construction cost comprised fixed cost component (AU$11,600 per bioreactor) and variable cost component (AU$275.04 per m^3, AU$9,351 for 34 m^3).

§ Vegetated drains are not included because the construction, maintenance and repair costs are not measured actual costs i.e., they were derived and/or estimated from other studies.

Ŧ Costs of two denitrifying bioreactors were provided: 34 m^3 trialled bioreactor bed and 100 m^3 hypothetical bioreactor; only the cost for the actual 34 m^3 bioreactor is reported in this table.

*Costs reported here are expected to be higher due to the supply chain issues and increased costs that occurred post pandemic.

Table 10. Reported cost types and measured cost values for individual constructed treatment wetlands (CW) as reported in Kavehei et al. (2021). Cost values are reported as annualised present value cost (APVC, in AU\$ ha^{-1} $year^{-1}$) and its equivalent total present value costs (TPVC, in \$ ha^{-1}).# The range of APVCs is based on combinations of timeframe and discount rates used in the study; corresponding TPVCs are calculated by dividing APVC by the annuity factor. Measured costs for CW8 wetland is reported for a 20-year timeframe at 5% per annum discount rate because APVC for this wetland is not provided for other timeframes and discount rates.

Treatment system	Size (ha)	Region	Characteristics	Cost value (in FY2020/21 AU\$)#
CW1	1.6	Wet Tropics	Groundwater dominated, converted drain on a sugarcane farm. Very high length-to-width ratio. Vegetation cover is >50%.	$APVC_{25yrs\_3\%}$ = 6,369 AU\$ ha^{-1} yr^{-1} $APVC_{15yrs\_7\%}$ = 11,269 AU\$ ha^{-1} yr^{-1} $TPVC_{25yrs\_3\%}$ = 110,901 AU\$ ha^{-1} $TPVC_{15yrs\_7\%}$ = 102,633 AU\$ ha^{-1}
CW2	1.2	Wet Tropics	A square-shaped wetland on a banana farm with a sediment basin at the inlet. Low length-to-width ratio. Vegetation cover is <25%.	$APVC_{25yrs\_3\%}$ = 31,588 AU\$ ha^{-1} yr^{-1} $APVC_{15yrs\_7\%}$ = 57,665 AU\$ ha^{-1} yr^{-1} $TPVC_{25yrs\_3\%}$ = 550,046 AU\$ ha^{-1} $TPVC_{15yrs\_7\%}$ = 525,204 AU\$ ha^{-1}
CW3	8.5	Wet Tropics	A large landscape wetland with two inlet points draining sugarcane farms. Vegetation cover is >50%.	$APVC_{25yrs\_3\%}$ = 3,075 AU\$ ha^{-1} yr^{-1} $APVC_{15yrs\_7\%}$ = 5,629 AU\$ ha^{-1} yr^{-1} $TPVC_{25yrs\_3\%}$ = 53,538 AU\$ ha^{-1} $TPVC_{15yrs\_7\%}$ = 51,273 AU\$ ha^{-1}
CW4	10	Wet Tropics	Sugarcane paddock converted to wetland. Water level is regulated via manually operated gates. Vegetation cover is >50%.	$APVC_{25yrs\_3\%}$ = 7,874 AU\$ ha^{-1} yr^{-1} $APVC_{15yrs\_7\%}$ = 12,915 AU\$ ha^{-1} yr^{-1} $TPVC_{25yrs\_3\%}$ = 137,115 AU\$ ha^{-1} $TPVC_{15yrs\_7\%}$ = 117,632 AU\$ ha^{-1}
CW5	2.5	Wet Tropics	Treatment system draining a banana farm. Designed for a retention time of two days. Very high length-to-width ratio. Vegetation cover is <25%.	$APVC_{25yrs\_3\%}$ = 5,244 AU\$ ha^{-1} yr^{-1} $APVC_{15yrs\_7\%}$ = 8,705 AU\$ ha^{-1} yr^{-1} $TPVC_{25yrs\_3\%}$ = 91,306 AU\$ ha^{-1} $TPVC_{15yrs\_7\%}$ = 79,283 AU\$ ha^{-1}
CW6	1.8	Dry Tropics, Mackay Whitsunday	A square-shaped wetland draining sugarcane farm. Low length-to-width ratio. Comprise two internal berms to increase residence time, a sediment basin, two inlets and an outlet wall. Vegetation cover is >50%.	$APVC_{25yrs\_3\%}$ = 5,232 AU\$ ha^{-1} yr^{-1} $APVC_{15yrs\_7\%}$ = 8,928 AU\$ ha^{-1} yr^{-1} $TPVC_{25yrs\_3\%}$ = 91,112 AU\$ ha^{-1} $TPVC_{15yrs\_7\%}$ = 81,312 AU\$ ha^{-1}
CW7	2.1	Dry Tropics, Mackay Whitsunday	A treatment train system draining sugarcane land comprising multiple ponds. High length-to-width ratio. Vegetation cover is between 25-50%.	$APVC_{25yrs\_3\%}$ = 5,775 AU\$ ha^{-1} yr^{-1} $APVC_{15yrs\_7\%}$ = 9,997 AU\$ ha^{-1} yr^{-1} $TPVC_{25yrs\_3\%}$ = 100,555 AU\$ ha^{-1} $TPVC_{15yrs\_7\%}$ = 91,054 AU\$ ha^{-1}
CW8	1.3	Dry Tropics, Mackay Whitsunday	A treatment train system draining sugarcane land comprising multiple ponds. High length-to-width ratio. Vegetation cover is between 25-50%.	APVC AU\$ ha^{-1} $year^{-1}$: 7,963 (20 years at 5%) TPVC AU\$ ha^{-1} : 99,237 (20 years at 5%)

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

The few studies that have been completed in the GBR catchment area have occurred in the past six years. These have focused on a range of constructed wetlands and bioreactors and guidelines have been developed for the implementation of bioreactors which also provides specific examples of construction costs. Although the number of studies that have been completed in Australia is very small, there is high confidence in the measured costs that have been captured (Kavehei et al., 2021; Waltham et al., 2021; Wegscheidl et al., 2021). There has not been a study in Australia that has captured all types of costs across the pre-construction, construction and post-construction phase, partly because this is a relatively new area of research. To allow reviews over time, there is a need to implement a standard approach to collecting such data (Aklilu & Elofsson, 2022; Graversgaard et al., 2021; Strand & Weisner, 2013).

International projects (Denmark and Sweden) have demonstrated that average costs of nitrogen abatement typically increase over time (after correcting for inflation) as the number of willing participants and effective wetland locations are exhausted (Aklilu & Elofsson, 2022; Graversgaard et al., 2021; Strand & Weisner, 2013). Therefore, initial landscape design accounting for landscape processes, hydrology and topography is critical to achieving cost-effective outcomes (Cheng et al., 2020; DeBoe et al., 2017; Hassett & Steinman, 2022; Roley et al., 2016). If the wetland is also to achieve other co-benefits, then these must be identified at the design phase (Canning et al., 2023; Hagger et al., 2022).

Wetland management options can be stacked management approaches such as buffers and grassed drains with bioreactors or wetland construction to achieve more cost-effective outcomes. In the US and Canada, farming BMPs capture buffer strips and then consider bioreactors and wetland construction. This highlights that a whole of system approach is required to ensure water quality outcomes however it must be considered that such practices can also generate unintended negative impacts on landholders such as invasive species (i.e., pigs) or difficulty in headland management (Entry & Gottlieb, 2014; Getahun & Keefer, 2016; Hansen et al., 2021; Rao et al., 2012; Ribaudo et al., 2001; Sarris & Burbery, 2018).

Policy mechanisms and program design is a key driver of costs and adoption with public and private investors having different objectives and expectations for investment outcomes. This will influence the minimum level of return on investment required. Furthermore, different investors may seek different outcomes from wetland design and project implementation (e.g., different suites of co-benefits). This could require different wetland attributes to be incorporated, impacting on wetland cost (Lentz et al., 2014; Soldo et al., 2022; Stephenson et al., 2021; Trenholm et al., 2017).

4.1.3 Key conclusions

Overall, it was identified that cost-effective nitrogen reductions can occur when a wetland treatment system is designed at a landscape scale (i.e., subcatchment or catchment) taking into account broader landscape processes including hydrology and topography and the links between them. Many studies showed that the strongest driver of cost-effectiveness for wetland projects was the effectiveness of nitrogen removal based on initial placement in the landscape, landscape characteristics such as nutrient inputs, vegetation, rainfall, hydrology and topography, comprehensive planning and design, and ongoing maintenance of the project.

Currently, there are no long-term monitored assessments of the cost-effectiveness of nutrient removal from wetlands in the GBR region that are based on complete sets of measurements of both costs and nutrient removals, hindering comparison with other management actions. Measured costs for eight constructed wetlands completed in the GBR catchments varied considerably ranging from an annualised present value cost of $3,075 to $31,588 per hectare per year (in FY 2020/21 AUD) over a 25-year period. The actual costs of projects for different wetland types are driven by several factors including size, construction, opportunity costs, monitoring requirements and maintenance.

These studies highlight the need for planning to consider hydrological and biophysical contexts to achieve the most cost-effective outcomes. Although GBR studies are limited by the number of field sites, they provide context for the types of costs that will be realised in the pre-construction, construction, and post-construction phases. They also provide context for requirements for future studies to enable costs to be considered across analysis and approaches.

International studies contained relevant information, but transfer of the findings to the GBR can be challenging because of differing climatic and policy contexts. International studies highlighted that long term investments were most successful when there was a clear definition of investor's objectives and outcomes, which were reflected in policy and program design, and subsequent projects.

Supporting points of direct relevance to the GBR:

- Public and private investors have different objectives and expectations for investment outcomes. This will influence the minimum level of return on investment required for a wetland project designed for pollutant removal to be viable. Furthermore, different investors may seek different outcomes from wetland design and project implementation (e.g., different suites of co-benefits) which could influence the wetland attributes to be incorporated, impacting on project cost.
- Measured costs of wetland projects need to be captured over a consistent timeframe and discount rate to evaluate the effectiveness of programs. This includes costs during the pre-construction phase (e.g., conceptualisation, design, planning, landholder engagements, approvals), construction phase (e.g., earthworks, planting), and post-construction phase (e.g., monitoring, maintenance, repair).
- Opportunities to deliver co-benefits such as biodiversity outcomes from wetland restoration projects are well documented, particularly in large landscape-scale wetlands. The details of the co-benefits being sought must be included from the initial project design as well as the policy and program design. These may also require different monitoring and reporting, and potentially be influenced by different cost drivers that must be considered.
- Long-term international projects (in Denmark and Sweden) have demonstrated that average costs of nitrogen abatement for individual wetland projects typically increase (after correcting for inflation) as the number of willing landholders declines, and the locations where wetland treatment is likely to be most effective are already utilised. Furthermore, if implementation is undertaken at landscape scale (i.e., where a number of landholders are required to be involved to achieve the best outcomes), the transaction costs incurred in obtaining landholder participation will increase further.
- Internationally, management approaches undertaken in the edge of headlands or vegetated drains and buffer strips have been implemented as best management practices. However, such practices can also generate unintended negative impacts for landholders such as introduction of invasive species (e.g., pigs) or difficulty in headland management (e.g., less available space and increased water retention on headlands leading to getting bogged). Studies from Canada, the United States, Denmark and Sweden also indicate that burdensome management requirements (e.g., monitoring and reporting, labour intensive tasks such as hand pulling weeds) can deter farmers from signing up to wetland incentive programs.

4.1.4 Significance of findings for policy, management and practice

The policy mechanism and program design must be considered initially as this will drive the types of costs that are critical to be captured. For example, the government will be seeking to understand different costs in an incentives program compared to an investor in a trading program. This consistency and early consideration of policy mechanisms and program design would then allow a standard framework for costs to be developed and captured across projects and programs. Currently, there is limited information on costs and therefore there is scope to ensure that all measured costs are comparable.

There is a need for policy and planning to adopt a whole of landscape approach to achieve the most cost-effective outcomes from a biophysical and hydrological context. The grouping of wetland management from buffers and vegetated drains through to constructed wetlands or bioreactors must also be considered, from the initial planning stage, particularly in the context that over time, the price per tonne of pollutant reduction will increase as the number of willing landholders declines. This has been a key learning from the Baltic Sea catchments that is applicable to the GBR context. Although with the small number of wetlands constructed for water quality outcomes in the GBR catchment area to date, there is likely to be scope for cost-effective wetland project sites before this cost increase is realised if planned sufficiently.

Given the context of the wetland type and restoration, and the different time periods over which the wetlands are managed on an ongoing basis, the long-term opportunity costs and ongoing maintenance costs must also be considered. These are also an important consideration in program length and monitoring requirements, potentially (and most likely) beyond the life of the initial funding program.

If co-benefits are being sought, the context of the type and subsequent design and implementation of wetland management must be considered, along with the relevant policy mechanisms and the ability to stack benefits in trading programs. It must be noted that not all co-benefits can necessarily be achieved in the same timeframes or that specific water pollution outcomes can be achieved from a specific wetland design; this highlights why co-benefits must be considered at the start of wetland planning for water quality improvements.

4.1.5 Uncertainties and/or limitations of the evidence

The small number of studies highlights some of the key costs and cost drivers, however given the diversity of these study sites and wetland types, a comparison between costs cannot be completed. These limited studies do however provide an insight into the potential range of costs that may be experienced through wetland construction, rehabilitation or bioreactors.

Although the international literature provides insights into policy and program design, the underpinning climate, agricultural land use, culture and policy context vary compared to the GBR presenting a degree of uncertainty regarding the specific costs such as opportunity costs, adoption and ongoing maintenance costs. However, the key findings that have been presented here have been assessed to be sufficiently relevant to be transferable to the GBR context.

4.2 Contextual variables influencing outcomes

Table 11. Summary of contextual variables considered in Question 4.8.

Contextual variables	Influence on question outcome or relationships
Location/ biophysical attributes	• Most of the research has been completed in temperate row crop or mixed farming enterprises with a very small amount completed in the GBR catchments. The variance in hydrology and biophysical factors make it difficult to compare results as the specific dollar values are difficult to transfer and the proportion of cost types are not comparable (Byström, 1998; Cheng et al., 2020; DeBoe et al., 2017; Hassett & Steinman, 2022; Lowe et al., 1992; Roley et al., 2016; van der Valk & Jolly, 1992). • The range over time in regard to data collection and period of analysis also varied significantly making it difficult to transfer costs to the GBR catchment area (Irwin et al., 2018; Weeber et al., 2022; Zammali et al., 2021). However, it does provide insights into the cost drivers as do the small number of specific studies to the GBR catchments which provide insights into the types of construction costs when implemented into sugarcane farming systems (Pfumayaramba et al., 2020; Wegscheidl et al., 2021).
Wetland Type	• The type of wetland that was being assessed influenced the measured costs and cost drivers, with buffers being a part of best management practices in the US and Canada (Yuan et al., 2022; Zammali et al., 2021). Constructed wetlands had different site variables and construction approaches based on the biophysical context (Pfumayaramba et al., 2020; Strand & Weisner, 2013; Weeber et al.,

Contextual variables	Influence on question outcome or relationships
	2022) and rehabilitation of natural or near natural wetland have large timeframes so they have often not been monitored over the same timescale (Graversgaard et al., 2021).
Policy and Program	• Policies provide the framework for wetland adoption, design, construction and maintenance to occur. Policy and subsequent program design are therefore a large key driver of costs with the studies in Sweden and Denmark that have the EU Water Directive Framework to work within and the US that has a separate Clean Water Act. These provide the architecture for program design which would then vary in Australia and the GBR specifically (Aklilu & Elofsson, 2022; Graversgaard et al., 2021; Mewes, 2012; Stephenson et al., 2021).

4.3 Evidence appraisal

Relevance

The relevance of the overall body of evidence was Moderate (5.4). The relevance of each individual indicator was Moderate (2.2) for overall relevance to the question (study approach/reporting results), Low (1.3) for spatial relevance, and was Moderate (1.9) for temporal relevance.

The impact of the large number of international studies was that often the agricultural land use differed to those found in the GBR catchment area and the spatial conditions were in temperate climates. The temporal relevance rating reflects that a few of the framework or adoption papers were less relevant due to the specific international context. The high variance in timeframe depending on the classification type (assessing costs, prioritisation and optimisation, and program review) of the paper resulted in a moderate score for temporal relevance.

In the context of this question, relevance was considered within the three categories of assessing costs, prioritisation and optimisation, and program review. For relevance there were two parts to the score. First was regarding the agricultural land use and policy approach. Second, was the analysis used to assess the costs in the context of pre-construction, construction and post-construction and the effectiveness if it was captured in a dollars per unit of pollutant reduced. For the prioritisation and optimisation approach, the agricultural land use and the analysis used to assess the costs and the policy mechanisms were considered, and for the program design the underpinning settings such as the EU's Water Framework Directive were considered along with integration with data and review over time.

For example, Kavehei et al. (2021) captured the construction costs of wetlands in the Mackay Whitsunday region and pre-construction costs of design and project management. The study assessed construction costs and post-construction costs of maintenance and repair, assessing the economic outcomes over 15, 20, 25 years with discount rates of 3, 5, 7%. This was assigned a score of 3 for overall relevance. Conversely, Djodjic et al. (2022) modelled costs using past actual data to assess the appropriate method for the placement of constructed wetlands at a landscape level in Sweden, which had a different agricultural land-use and different policy framework, resulting in a score of 2. Finally, if the study was a review or only captured the costs as a total value, it was given a score of 1.

Given the small number of Australian studies, two had measured costs from agriculture and were assessed over time regarding native fish habitat and carbon sequestration (Canning et al., 2023; Hagger et al., 2022) both of which received a score of 3 for contextual relevance and the remaining one received a 1 as there was only one cost not discounted over time for a bioreactor and was in a blueberry production system (White et al., 2022).

The review of bioreactors received a 3 for relevance (Christianson et al., 2021) as it included studies from Australia and other countries along with cost-effectiveness estimations and different program approaches. The remaining overseas studies scored 2 and this is based on the cost aspects being captured but the land use applications and policy frameworks varying. The large amount of international literature resulted in the average score of 1.

In the context of the question, the spatial aspects of relevance were considered a 3 if measured costs at a paddock scale were then applied to a catchment scale study, or were measured across a number of paddock scale sites. A score of two was given to studies where spatial modelling was applied and costs were applied from other studies, and 1 was given if the study did not identify the location or did not apply spatial considerations; these papers were often landholder adoption papers. Across these studies, spatial considerations were scored with an average of 1.2.

Temporal relevance in measured costs and cost drivers across the types of studies was assessed according to the type of study. Studies which were review studies ranged in timeframes from 20 to 40 years particularly for the construction of wetlands. Bioreactors had a shorter time span which reflected the useful life of bioreactors and analyses were completed over a 10-year period, and paddock scale studies varied regarding the cropping system with row crop captured over a three-year cropping rotation. Review studies are backward looking and therefore it is expected they will have the capacity to capture more data, whereas prioritisation studies are often across the catchment or subcatchment and are typically forward-looking or forecasting. Therefore, often the analysis period in prioritisations is predictive and forecasting of costs. Finally, adoption focused papers or program design are not temporal features and therefore these have been classified as N/A. Overall an average score of 1.8 was obtained for temporal relevance.

Consistency, Quantity and Diversity

Across the three classifications that literature was assigned to, consistency was assessed on the costs that were highlighted as depending on:

- How specific measures are implemented (Program and Project design) (Byström, 2000; Corrales et al., 2017; Djodjic et al., 2022; Graversgaard et al., 2021; Heberling et al., 2010; van der Valk & Jolly, 1992; Zammali et al., 2021).
- Scale (both spatial and temporal) (Corrales et al., 2017; Douglas-Mankin et al., 2021; Mewes, 2012; Ribaudo et al., 2001; Rodriguez et al., 2011; Roley et al., 2016; Singh et al., 2019; Strand & Weisner, 2013; Tamburini et al., 2020).
- Baseline situation (Balana et al., 2015; Christianson et al., 2013; 2018; Gren et al., 1997; Hansen et al., 2021; Jacobsen & Hansen, 2016; Strand & Weisner, 2013; Waltham et al., 2021a; Wang et al., 2019; Yuan et al., 2022).
- Land use types and management practices (Hansson et al., 2012; Mewes, 2012; Rodriguez et al., 2011; Singh et al., 2019; Trenholm et al., 2017; Waltham et al., 2021a; Weeber et al., 2022; Zimmerman et al., 2019).

Overall, the consistency of cost types and classification within pre-construction, construction and post-construction was deemed to be High.

Uncertainty, timescales of effectiveness, and obtaining accurate cost estimates of measures over a period of time are additional challenges in assessing the cost measures to reduce diffuse pollution from agriculture (Aggarwal et al., 2022; Aklilu & Elofsson, 2022; DeBoe et al., 2017; Graversgaard et al., 2021; Yuan et al., 2022).

Given the high variability of biophysical characteristics, costs were not comparable, and this diversity therefore resulted in an inability to suggest the proportions of costs that could or should be allocated to specific drivers. The limited number of GBR specific studies and the range of wetland interventions and sites, along with the different types of cost information collected, means that they are not comparable. However, for the constructed wetland studies there was high consistency of these costs where they were reported.

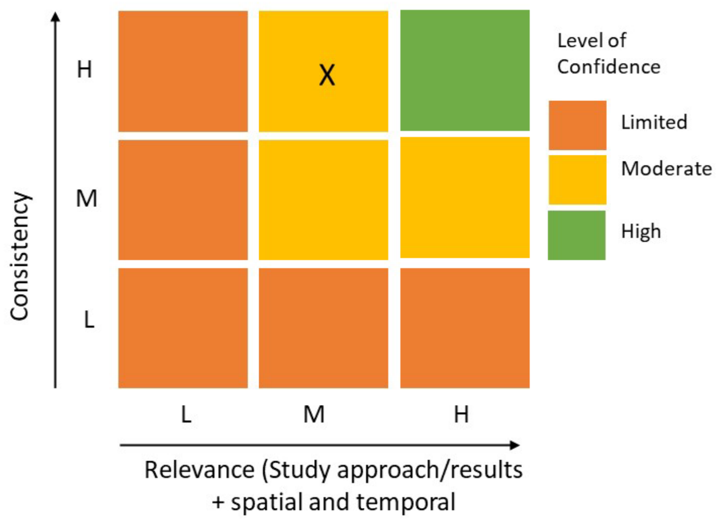
The quantity of studies in the GBR is Low with only three studies capturing costs and one study capturing costs across a number of sites. There are other studies which did not focus on measured costs or cost drivers but noted costs as an important factor. Internationally there is a large body of work and therefore increased diversity in study types and capacity to complete reviews after funding wetlands over a number of years.

This diversity results in studies that document very specific quantified paddock scale cost drivers and measured costs, through to reviews of the cost drivers of landholder adoption of wetland management, resulting in an overall rating of High. This diversity provides insights into the opportunities and challenges for implementing wetland programs and achieving land-based pollutant runoff changes.

Confidence

The overall rating for the confidence assessment was Moderate (5.1), based on Moderate overall relevance and High consistency (Table 12). The low number of GBR studies reflects the new interest in wetlands and the low monitoring to date relative to other countries such as Sweden, Denmark and the US.

Table 12. Summary of results for the evidence appraisal of the whole body of evidence used in addressing Question 4.8. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	Moderate	
-To the Question	Moderate	
-Spatial	Low	
-Temporal	Moderate	
Consistency	High	
Quantity	Low for GBR specific (8 GBR studies + 1 wider Australia) Moderate International (47 studies)	
Diversity	High (41% modelling, 39% reviews and 20% observational)	

4.4 Indigenous engagement/participation within the body of evidence

No Indigenous participation was identified.

4.5 Knowledge gaps

Table 13. Summary of knowledge gaps for Question 4.8.

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
Measured costs across all cost categories and measured water quality improvements in GBR locations in a comparable way (standard metric).	What are the measured costs across all cost categories and measured water quality improvements in GBR locations?	Understanding the cost effectiveness and the potential total cost for implementing a wetlands strategy.
Understanding at a landscape level of where wetlands could be situated to achieve efficient pollutant reductions and the subsequent actions and costs to achieve the reductions.	Where in the landscape could a series or different types of wetlands be most efficient at achieving pollutant reductions and what is the subsequent cost?	Optimisations of funds and actions long term.
Impacts of climate change on the construction and post-construction phase costs.	What was the weather sequence which resulted in making amendments to the wetland at either construction or post-construction phase?	Targeting across the landscape to limit risk due to extreme weather outcomes.
Consideration of policy mechanisms and approaches over time to achieve the targeted reductions i.e., incentives or trading scheme.	What policies over time are required to achieve the outcomes based on costs and adoption?	Optimisations of funds and actions long term.
Stacked actions such as paddock scale management, drains buffers and then wetland management.	What are the ongoing combinations of different wetland management actions that achieve the best outcomes in the shortest timeframes?	Understanding the cost effectiveness of wetlands in the GBR catchment area.
Capacity to achieve co-benefits and the mechanism to achieve them.	Would we like to see co-benefits achieved with water quality improvements? If so, what are they? And what are the design modifications that are required to achieve these outcomes over time? What policies will be applied and will these be stacked?	Co-benefits realised.

5. Evidence Statement

The synthesis of the evidence for **Question 4.8** was based on 56 studies undertaken mostly internationally (only 9 were from Australia) and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (41% modelling, 39% reviews and 20% observational), and has a *Moderate* confidence rating (based on *High* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

A limited number of studies have fully assessed the cost-effectiveness of wetland systems (including natural/near natural wetlands, restored, treatment/constructed wetlands and other treatment systems) in the removal of pollutants in the Great Barrier Reef catchment area. Within the available studies, measured costs have been reported for treatment systems using best practice approaches. These measured costs include upfront costs, ongoing costs and in some instances the opportunity costs, reported over a specified time using standard discount rates[11]. There is limited understanding of the variation of costs across different types of wetland treatment systems in the Great Barrier Reef. International studies contained relevant information, but transfer of the findings to the Great Barrier Reef can be challenging because of differing climatic and policy contexts. Overall, it was identified that cost-effective nitrogen reductions can occur when a wetland treatment system is designed at a landscape scale (i.e., subcatchment or catchment) taking into account broader landscape processes including hydrology and topography and the links between them. Many studies showed that the strongest driver of cost-effectiveness for wetland projects was the effectiveness of nitrogen removal based on initial placement in the landscape, landscape characteristics such as nutrient inputs, vegetation, rainfall, hydrology and topography, comprehensive planning and design, and ongoing maintenance of the project. International studies highlighted that long term investments were most successful when there was a clear definition of investor's objectives and outcomes, which were reflected in policy and program design, and subsequent projects.

Supporting points

- Currently, there are no long-term monitored assessments of the cost-effectiveness of nutrient removal from wetlands in the Great Barrier Reef region that are based on complete sets of measurements of both costs and nutrient removals, hindering comparison to other management actions. Measured costs for eight constructed wetlands completed in Great Barrier Reef catchments varied considerably ranging from an annualised present value cost of $3,075 to $31,588 per hectare per year (in FY 2020/21 AUD) over a 25-year period.
- Measured costs and cost drivers for wetland projects designed for pollutant removal can be categorised into studies that assess costs, focus on optimisation and prioritisation or discuss implications for policy and program design.
- The actual costs of projects for different wetland types are driven by several factors including size, construction, opportunity costs, monitoring requirements and maintenance.
- Public and private investors have different objectives and expectations for investment outcomes. This will influence the minimum level of return on investment required for a wetland project designed for pollutant removal to be viable. Furthermore, different investors may seek different outcomes from wetland design and project implementation (e.g., different suites of co-benefits) which could influence the wetland attributes to be incorporated, impacting on project cost.

[11] Discounting brings costs in future years back into current dollar terms. Discount rate is the rate at which this occurs and is typically 5-7%.

- Cost drivers of the cost-effectiveness of projects are typically biophysical or associated with policy setting and adoption:
  - Biophysical cost drivers include consideration of whole-of-system landscape processes (such as hydrology, receiving water quality, and topography of the landscape at a paddock and overall catchment scale), the current land use, the quantity of nutrient inputs in relation to wetland size, residence times, pollutant type and whether or not there are opportunities for co-benefits.
  - Policy setting and adoption cost drivers include specific requirements under incentive programs such as inclusion of certain locations, period of management, maintenance and/or monitoring requirements, complexity of application processes, and opportunities for secondary benefits.
- Measured costs of wetland projects need to be captured over a consistent timeframe and discount rate to evaluate the effectiveness of programs. This includes costs during the pre-construction phase (e.g., conceptualisation, design, planning, landholder engagements, approvals), construction phase (e.g., earthworks, planting), and post-construction phase (e.g., monitoring, maintenance, repair).
- Long-term opportunity costs and ongoing maintenance costs must be considered in assessing the cost effectiveness of wetland projects. These are also important considerations in defining the length of funding programs and monitoring requirements, potentially (and most likely) extending beyond the life of the initial funding program.
- Opportunities to deliver co-benefits such as biodiversity outcomes from wetland restoration projects are well documented, particularly in large landscape-scale wetlands. The details of the co-benefits being sought must be included from the initial project design as well as the policy and program design. These may also require different monitoring and reporting, and potentially be influenced by different cost drivers that must be considered.
- Long-term international projects (in Denmark and Sweden) have demonstrated that average costs of nitrogen abatement for individual wetland projects typically increase (after correcting for inflation) as the number of willing landholders declines, and the locations where wetland treatment is likely to be most effective are already utilised. Furthermore, if implementation is undertaken at landscape scale (i.e., where a number of landholders are required to be involved to achieve the best outcomes), the transaction costs incurred in obtaining landholder participation will increase further.
- Internationally, management approaches undertaken in the edge of headlands or vegetated drains and buffer strips have been implemented as best management practices. However, such practices can also generate unintended negative impacts for landholders such as introduction of invasive species (e.g., pigs) or difficulty in headland management (e.g., less available space and increased water retention on headlands leading to getting bogged). Studies from Canada, the United States, Denmark and Sweden also indicate that burdensome management requirements (e.g., monitoring and reporting, labour intensive tasks such as hand pulling weeds) can deter farmers from signing up to wetland incentive programs.

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.

Body of Evidence

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 4.8

Theme 4: Dissolved nutrients – catchment to reef

Question 4.8 What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Megan Star	Star Economics/ Central Queensland University	Agricultural Economics	Lead Author	All Sections
2. Syezlin Hasan	Griffith University	Wetlands and Environmental Economics	Contributor	Searches data collation and data extraction, narrative synthesis and overall report.
3. James C R Smart	Griffith University	Wetlands and Environmental Economist	Contributor	Narrative synthesis and final revision of overall report
4. Carla Wegscheidl	Queensland Department of Agriculture	Technical Wetlands	Contributor	Narrative synthesis and final revision of overall report

Appendix 2: Wetland Ecosystem Services (Waltham et al., 2021)

Table 1. Final ecosystem services estimated to be provided by wetlands created as part of the Riversdale-Murray Scheme. Class and codes are from the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2012). Pedigree scores indicate confidence in service provision estimates, ranging from 1 (low confidence) to 4 (total confidence), in line with those proposed by Costanza et al. (1992).

Section	Class	Code	Application in Riversdale-Murray scheme	Pedigree
Provisioning (Biotic)	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	1.1.5.1	Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person	1
	Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)	1.1.5.2	Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person	1
	Wild animals (terrestrial and aquatic) used for nutritional purposes	1.1.6.1	Farmers and their family reported fishing in lagoons in interviews. Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person and in interviews	4
	Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)	1.1.6.2	Indigenous community harvest (purpose unknown) observed by some farmers and relayed to us in person. Potential could include crocodile hide	1
Regulation & Maintenance (Biotic)	Visual screening.	2.1.2.3	Farmers mentioned (in person) trees from wetland riparian screening unsightly land.	2
	Control of erosion rates	2.2.1.1	Riparian vegetation may be reducing bank erosion	1
	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)	2.2.1.3	Change in farm inundation frequency observed in Appendix A2.5 Drainage, and hydrological modelling changes modelled and published by Karim et al (2012)	3
	Wind protection	2.2.1.4	Tall Eucalyptus trees were observed in the riparian vegetation at some lagoon, and these may be protecting crops from wind, though yet to be quantified	1
	Pollination (or 'gamete' dispersal in a marine context)	2.2.2.1	Wetland riparian vegetation may be supporting insect vectors that assist crop pollination. Not quantified.	1
	Maintaining nursery populations and habitats (Including gene pool protection)	2.2.2.3	Field surveys caught Barramundi across many wetlands of various sizes, indicating habitat support (Godfrey et al. 2016; Appendix A2.3 Fisheries provision)	3
	Regulation of the chemical condition of freshwaters by living processes	2.2.5.1	The wetlands likely provide some level of nutrient and sediment removal. Indirect estimates of *potential* denitrification rates in ideal conditions (likely over-estimating actual rates) are provided in Appendix A2.4.	2

Section	Class	Code	Application in Riversdale-Murray scheme	Pedigree
	Regulation of chemical composition of atmosphere and oceans	2.2.6.1	The wetlands will likely store carbon in deposited sediments and riparian vegetation. This is not quantified.	1
	Regulation of temperature and humidity, including ventilation and transpiration	2.2.6.2	Open water and forested vegetation typically have a much lower albedo than crops and soil, which is likely to reduce ambient temperature. Wetlands can also increase humidity as retained water evaporates. The specific effect of this from these wetlands has not been quantified.	1
Cultural (Biotic)	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	3.1.1.1	Multiple farmers have mentioned using the wetlands for fishing, kayaking, boating, skiing and walking in person and in interviews.	3
	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions	3.1.1.2	Multiple farmers have mentioned visiting wetlands to enjoy the nature and to relax. They also mentioned personal satisfaction from completing the restoration.	3
	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	3.1.2.1	Several scientific papers have arisen from examining these wetlands (Pearson et al. 2013; Godfrey et al. 2016; Karim et al. 2012).	4
	Characteristics of living systems that enable education and training	3.1.2.2	Farmers have gained considerable knowledge from restoring and observing these wetlands.	2
	Characteristics of living systems that are resonant in terms of culture or heritage	3.1.2.3	Indigenous people have been observed collecting from the lagoons, and this may resonate with their heritage/culture.	1
	Characteristics of living systems that enable aesthetic experiences	3.1.2.4	Numerous farmers have mentioned in person and in interviews the pleasure they get from wetlands improving farm aesthetics.	3
	Characteristics or features of living systems that have an existence value	3.2.2.1	The wetlands support a diverse array of freshwater fish (Pearson et al. 2013; Appendix A2.2 Fish biodiversity).	3
	Characteristics or features of living systems that have an option or bequest value	3.2.2.2	Farmers mentioned during visits and in interviews the satisfaction they get from providing a resource for their grandchildren to enjoy in the future.	3
Provisioning (Abiotic)	Surface water used as a material (non-drinking purposes)	4.2.1.2	Some farmers have used stored water for irrigation. The extent to which this occurs has not been quantified.	1