# 2022 Scientific Consensus Statement

## **Question 4.7** 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)?

### **Question 4.7.1** What are the key factors that affect the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality and how can these be addressed at scale to maximise water quality improvement?


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# Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

## What is the Scientific Consensus Statement?

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

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

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

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

## Method used to address the 2022 SCS Questions

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

In recent years there has been an emergence of evidence synthesis methods that involve some modifications of Systematic Reviews so that they can be conducted in a more timely and cost-effective

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

manner. This suite of evidence synthesis products are referred to as **'Rapid Reviews'**[2]. These methods typically involve a reduced number of steps such as constraining the search effort, adjusting the extent of the quality assessment, and/or modifying the detail for data extraction, while still applying methods to minimise author bias in the searches, evidence appraisal and synthesis methods.

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

Two methods were developed for the 2022 SCS:

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

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

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

1. **Describe the final interpretation of the question.** A description of the interpretation of the scope and intent of the question, including consultation with policy and management representatives where necessary, to ensure alignment with policy intentions. The description is supported by a conceptual diagram representing the major relationships relevant to the question, and definitions.
2. **Develop a search strategy**. The Method recommended that Authors used a S/PICO framework (Subject/Population, Exposure/Intervention, Comparator, Outcome), which could be used to break down the different elements of the question and helps to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[4].
3. **Define the criteria for the eligibility of evidence for the synthesis and conduct searches.** Authors were asked to establish **inclusion and exclusion criteria to define the eligibility of evidence** prior to starting the literature search. The Method recommended conducting a **systematic literature search** in at least **two online academic databases**. Searches were typically restricted to 1990 onwards (unless specified otherwise) following a review of the evidence for the previous (2017) SCS which indicated that this would encompass the majority of the evidence

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

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

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

base, and due to available resources. In addition, the geographic **scope of the search for evidence** depended on the nature of the question. For some questions, it was more appropriate only to focus on studies derived from the GBR region (e.g., the GBR context was essential to answer the question); for other questions, it was important to search for studies outside of the GBR (e.g., the question related to a research theme where there was little information available from the GBR). Authors were asked to provide a rationale for that decision in the synthesis. Results from the literature searches were screened against **inclusion and exclusion** criteria at the title and abstract review stage (**initial screening**). Literature that passed this initial screening was then read in full to determine the eligibility for use in the synthesis of evidence (**second screening**). Importantly, all literature had to be **peer reviewed and publicly available.** As well as journal articles, this meant that grey literature (e.g., technical reports) that had been externally peer reviewed (e.g., outside of organisation) and was publicly available, could be assessed as part of the synthesis of evidence.

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

## Guidance for using the synthesis of evidence

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

1. **Executive Summary**: This section brings together the evidence and findings reported in the main body of the document to provide a high-level overview of the question.
2. **Synthesis of Evidence:** This section contains the detailed identification, extraction and examination of evidence used to address the question.
    - ***Background***: Provides the context about why this question is important and explains how the Lead Author interpreted the question.
    - ***Method:*** Outlines the search terms used by Authors to find relevant literature (evidence items), which databases were used, and the inclusion and exclusion criteria.
    - ***Search Results:*** Contains details about the number of evidence items identified, sources, screening and the final number of evidence items used in the synthesis of evidence.

- ***Key Findings:*** The **main body of the synthesis**. It includes a summary of the study characteristics (e.g., how many, when, where, how), a deep dive into the body of evidence covering key findings, trends or patterns, consistency of findings among studies, uncertainties and limitations of the evidence, significance of the findings to policy, practice and research, knowledge gaps, Indigenous engagement, conclusions and the evidence appraisal.

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

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

## Peer Review and Quality Assurance

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

# Contents

## Acknowledgements

We acknowledge the Traditional Owners of the lands on which we work and pay respect to their leader's past, present and emerging. Thanks to Rob Richards (Evidentiary), Jane Waterhouse ($C_2O$ Consulting) and Mari-Carmen Pineda ($C_2O$ Consulting) for guidance in preparing this document and early review comments. We thank Aimee Brown for assistance with data extraction from the literature.

# Executive Summary

## Questions

**Primary Question 4.7 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)?**

**Secondary Question 4.7.1 What are the key factors that affect the efficacy of natural/near-natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality and how can these be addressed at scale to maximise water quality improvement?**

In the context of this document the term 'wetlands' includes natural and near-natural wetlands, restored and treatment (constructed) wetlands and other treatment systems. 'Water quality' refers to nutrients, sediments, pesticides and other pollutants.

## Background

Wetlands in the coastal zone can play a critical role in providing many ecosystem services such as water quality improvement, biodiversity, cultural, societal-recreational, and economic services, as well as climate change mitigation possibilities. Since the European settlement (~1850), land-use changes within catchments and major modifications to floodplains have contributed to the degradation and loss of wetland habitats. In the Great Barrier Reef (GBR) catchments, between 78% and 97% of wetlands that existed prior to European settlement remain, however, this varies between Natural Resource Management (NRM) Regions and basins, and the losses are more substantial for some wetland types in certain locations. These losses are primarily the result of changed land management through clearing, draining or infilling of wetlands. The rate of wetland loss has generally slowed in the last few decades with slight increases in wetland extent observed in some catchments due to the construction of artificial wetlands (e.g., farm dams, ponded pasture). However, declines in the area of natural wetlands has continued with a net loss of 7,688 ha of natural wetlands in the GBR catchment area between 2001 and 2017 (i.e., excluding artificial/highly modified); the greatest losses were recorded in riverine wetlands. As a result of these losses in wetland extent, the capacity for wetlands to process and assimilate contaminants has reduced, placing greater pressure on the remaining wetlands.

Of particular interest globally is the capacity of wetland ecosystems to improve water quality by reducing pollutant concentrations and loads through their biotic and abiotic functions. This is of specific relevance to the GBR catchments, due to the number and increasing severity of anthropogenic and climatic stressors, including increased nutrient and sediment loads and pesticide concentrations, which can negatively impact aquatic ecosystems in the region.

Wetlands are dynamic, transitional ecosystems that vary over spatial and temporal scales. Wetland hydrology is highly variable – driven by seasonal rainfall and land-based activities that also influence their biological function and ability to improve water quality. This review collates and summarises published evidence from studies around the world where they have investigated the efficacy of wetlands in improving water quality. The results are used to provide guidance on what kind of wetlands in the GBR catchments may best remediate reduce the amount of sediment, nutrients (nitrogen, phosphorus) and pesticides entering GBR waters.

## 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

[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

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 Review method was used.

- Search locations included Web of Science and Scopus, in addition to a review of the grey literature websites including United States Department of Agriculture (USDA), Queensland Government (Wetland*Info*, the Queensland Department of Environment and Science, the Australian Government's Department of Climate Change, Energy, the Environment and Water) and Pandora.
- From the initial keyword search, Scopus returned 2,300 results across the three search strings (2,329 before duplicates were removed) and Web of Science returned 1,160 (2,587 before duplicates with Scopus outputs removed). After initial screening by title, 483 potentially relevant items were identified from Scopus, and 296 potentially relevant items from Web of Science. After further screening by scanning the full text for relevance, 236 items contained relevant information to be incorporated into the Evidence Review. To this set, two studies were manually added. A total of 238 evidence items contributed to this Evidence Review and 25 studies provided contextual background information.

### Method limitations and caveats to using this Evidence Review

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

- Only studies written in English from 1990 to 2022 were included.
- The Evidence Review focused on studies in tropical and subtropical locations from overseas, as well as studies specifically in the GBR (studies from temperate locations were excluded from this Evidence Review).
- Non-agricultural (including urban studies) were excluded from this review and are addressed in Questions 4.6 (Thorburn et al., this SCS) and 5.3 (Davis et al., this SCS).
- Subtidal and subterranean wetlands were excluded from this review.
- The definition of wetlands and the scope of this review were set in collaboration with the SCS Coordination Team, policy representatives and the authors.
- The distribution and variability of nutrients and pesticides in wetland benthic sediment were not considered.
- Constructed/treatment wetlands and bioreactors were reviewed in the context of pastoral and arable agriculture only.

## Key Findings

### Summary of evidence to 2022

- Global evidence has revealed that wetlands can process, retain and in some cases export nutrients (dissolved and particulate) and sediments from multiple land uses, with a wide-ranging capacity for pollutant retention.
- Wetlands are highly dynamic ecosystems, and efficacy can be variable, affected by local conditions such as soils, topography, hydrology, climate, land use and vegetation communities. Critical factors for optimising the efficacy of water quality improvement include: the presence and maintenance of vegetation communities; hydrological characteristics including the wetland size relative to the contributing catchment area, flow rate, loss pathways and water residence time; and the type and input concentration of the targeted pollutant.
- Research on the efficacy of wetlands in terms of water quality improvements has largely occurred in the United States (49% of total studies examined) and China (18%), with very few studies in Australia (6%, n = 15), of which 13 were from the GBR catchment area. The parameters assessed also vary: 72% of studies measured nutrient concentrations, 8% pesticide concentrations and 2.5% sediments; the remainder examined various combinations of these pollutants.

- While local studies have measured denitrification rates in wetland soils and plant nutrient processing rates, it is not possible to derive long-term nitrogen removal from these data or assess wetland performance without knowledge of the wetland hydrology (mainly residence time). There are no studies that measure the pesticide/herbicide removal efficacy of wetlands in the GBR catchment area, only studies that measure in situ concentrations.
- The evidence demonstrates high variability in nutrient, sediment and pesticide removal efficiency between wetland types and locations within agricultural landscapes. This is illustrated by the range of efficiencies for parameters including total suspended sediments: -4-94%; total nitrogen: -4-97%; total phosphorus: 1.8-97.6% and pesticides: 14.3-100%. These differences are strongly driven by the vegetation community (extent and maintenance; reported in 36% of studies) and hydrology (control and residence time; reported in 20% of studies). The mean efficacy and variability between wetland types is also highlighted (note that those with less than 5 studies have low confidence):
  - For natural wetlands: total nitrogen reduced by 63.5% (5 studies, range 27-96.4%), total phosphorus reduced by 74.5% (3 studies, range 59-97.6%), total suspended sediment reduced by -45% (2 studies, range -1-91%) and pesticide reduced by 98.5% (2 studies, range 97-100%).
  - For near natural wetlands: total nitrogen reduced by 33.5% (6 studies, range 11.6-83%), total phosphorus reduced by 54.6% (6 studies, range 6-93%) and there were no results for total suspended sediments or pesticides.
  - For restored wetlands: total nitrogen reduced by 38% (1 study), total phosphorus reduced by 52.4% (2 studies, range 25.7-59%), total suspended sediments reduced by 34.9% (2 studies, range -4-73.8%) and there were no results for pesticides.
  - For treatment wetlands: total nitrogen reduced by 46.4% (40 studies, range -4-97%), total phosphorus reduced by 49.3% (38 studies, range 1.8-96.5%), total suspended sediments reduced by 57.1% (10 studies, range 1.1-94%) and pesticide reduced by 69.2% (16 studies, range 3.6-100%).
  - For bioreactor systems: total nitrogen reduced by 80% (1 study), there were no results for total phosphorus or total suspended sediments, and pesticide removal was 47% (2 studies, range 14.3-100%).
- There is no standard approach for monitoring and evaluating the efficacy of wetlands for water quality improvement in the GBR catchment area. Studies have had different research questions, experimental approaches, equipment use, water quality variables of interest, and the frequency and duration of monitoring. Site-based performance reporting should be presented relative to the catchment load, providing greater context when considering whole-of-catchment water quality improvement.
- Since the 2017 SCS there has been increased research effort to quantify the efficacy of wetlands as a tool for water quality improvement. This research, in conjunction with the development of the Queensland Government's values-based framework, provides a positive foundation for understanding the values and ecological function of wetlands, and increasing confidence in pollutant removal efficiencies.
- More research is needed to decipher which wetland types are likely to be most beneficial for water quality improvement in different settings (i.e., land uses, groundwater contribution, climates, and soils), configuration of multiple systems in the landscape, the spatial and temporal drivers of variability, quantification of delivery pathways (surface and groundwater), pesticide removal efficiencies (particularly those found to impact Great Barrier Reef ecosystems), improved characterisation of nutrient processing, long-term changes in wetland nutrient and sediment stores, and evidence of the timescales over which management interventions are likely to be effective.

## Recent findings 2016-2022

- Prior to the 2017 SCS, four studies had been conducted within the GBR catchment area, relating to the water quality improvement efficiency of wetlands, only two of which measured and modelled water and nutrient balances in GBR wetlands.

- Since the 2017 SCS, there has been an increased research effort following a values-based approach, developed by the Queensland Government, to recognise the components and processes of wetland systems, and where restoration or engineering efforts have occurred or are most beneficial.
- Since the 2017 SCS, there have been nine additional publications relating to the water quality improvement efficiency of GBR wetlands. Only two of the nine studies published after 2017 measured and modelled the water and nutrient balance in GBR wetlands.

## Significance for policy, practice, and research

This Evidence Review has focused on published (journals and grey literature) studies quantifying wetland efficacy in the improvement of water quality. The findings reveal that the efficacy of wetlands is highly variable, with wetland vegetation and hydrology among the most important considerations to effectively ensure wetlands can improve water quality. It is also acknowledged that while wetlands may improve water quality, there are other ecosystem services they provide (see Question 4.9, Waltham et al., this SCS), and indeed trade-offs that challenge managers when considering their use and/or design.

From this Evidence Review, the greatest proportion of published studies on wetlands for water quality treatment were from the United States and China. Studies in Australia and the GBR are far fewer in total, supporting the need for this review to draw on studies from abroad. There are not yet enough data to assess spatial and temporal trends in wetland efficacy in the GBR, particularly as some published studies from overseas are supported by data collected over several decades. By comparison, water quality studies in GBR wetlands have been ongoing for only a few years, which is far shorter than the average duration of studies (2.9 years) based on the review of the literature here.

Further evidence is required to increase confidence in the potential pollutant removal efficiencies of wetland treatment systems in agricultural landscapes in the Great Barrier Reef catchment area. This review has identified several major knowledge gaps for further research that could contribute to improved confidence in the knowledge base. These include:

- Improving our understanding of the spatial (wet and dry tropics) and temporal drivers of variability in water quality improvement efficiency reported in overseas studies, within the context of the GBR catchment. This includes better/more frequent data collection/data resolution and modelling of the hydrology and water cycle in wetlands.
- Better characterisation of organic nutrients in wetlands.
- The characterisation of long-term changes in wetland sediment nutrient stores will allow more robust estimates of the timescales over which management interventions are likely to be effective.
- Quantification of the changes to catchment hydrology, as a result of land use change, infrastructure including drainage and barriers to flow, and landscape modification including floodplain development, and the impacts of these changes on biological processes and water quality improvement in wetlands.
- Need to include hydrology modelling in all wetland projects, to understand the potential processing of nutrients and sediments in wetlands.
- While treatment wetlands can provide water quality improvement prospects, there is a need to understand how the site-based water quality improvements translate to the overall catchment load.

There is also a need for ongoing monitoring of the efficacy of wetlands and their contribution to pollutant removal in the landscape (i.e., inflow versus outflow), which should align with the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) and the GBR Marine Monitoring Program for Inshore Water Quality (MMP WQ). Such a program would provide managers with a deeper understanding of the efficacy of wetlands in Queensland and would assist with designing experimental research and monitoring programs to fill any obvious gaps in knowledge.

## Key uncertainties and/or limitations

A summary of the key uncertainties and/or limitations in the evidence base is presented below:

- The number of studies relating to wetlands and water quality improvement efficacy is limited in the GBR, particularly when compared to other wetlands globally (e.g., the Everglades and Mississippi delta and catchment in the United States, and the Yellow River and floodplain, alongside regional and coastal areas of China).
- There are a wide range of approaches to monitoring water quality outcomes from wetland systems, including a range of sampling equipment (e.g., flow gauges, auto-samplers, loggers, grab samples and piezometers), sampling frequencies, study duration, time of year (i.e., wet or dry season), wetland size, and additional important information (e.g., vegetation cover or hydroperiod). The inclusion of all these details in publications, as supplementary material, would assist with comparisons and provide greater context for managers to consider when planning projects.
- While the Paddock to Reef (P2R) Wetland Condition Monitoring commenced in 2018, it is not yet spatially and temporally comparable to monitoring efforts overseas. This is different to nearshore and inshore water quality monitoring undertaken as part of the Marine Monitoring Program, which has operated for over 15 years. Such long-term datasets would allow researchers to establish baselines, provide insight into the importance of wetland age and maturation, provide a better understanding of the influence of long-term climatic change and understand when management intervention is required and likely to be most effective.
- The approach of collecting water quality samples at the defined inlet and outlet to wetlands, and building a water balance model for wetland sites, is not very common and is often carried out in a piecemeal way. Studies that do not include relevant methodological details or model the water balance over a reasonable period (several years) make interpretation of the water quality improvement efficacy difficult. Further, consideration and evaluation of additional water sources in wetlands, particularly groundwater, are rarely considered or included, which further limits the interpretation of water quality data and the ability to assess the full water and nutrient balance.
- Designing a treatment wetland that is appropriate for the feeding catchment size is rarely considered or examined. Moreover, elements of wetland design such as vegetation, deep water zones, and maintenance requirements are generally overlooked.

## Evidence appraisal

Overall, the relevance of the body of evidence was rated as Moderate (score 5/9). This scoring is derived from three metrics: 1) relevance of the body of evidence to the question (score = 2.1, i.e., 'Moderate'); 2) the body of evidence's spatial relevance to the question (score = 1.7, i.e., 'Moderate'); and 3) the temporal relevance of the body of evidence to the question (score = 1.6, i.e., 'Moderate'). The number of studies was scored as 'High', with 238 papers comprising the body of evidence, the Diversity also scored as 'High', due to the diversity of study types featured and the number of countries covered within the body of evidence, and the consistency was scored as 'Moderate', with some variability in the factors found to determine water quality improvement efficiency.

Of the 238 studies, 36% (n = 86) had High relevance of the study approach to the question, 40% Moderate (n = 96), and 23.5% (n = 56) scored Low. However, only 12% (n = 30) and 15% (n = 36) were rated highly as spatially and temporally generalisable to the question, respectively. These studies are diverse in their approaches, data sources and authorship, featuring a mixture of primary and secondary data collection, as well as several conceptual, theoretical and review studies. Experimental and observational studies were the most featured within the body of evidence, comprising 75% of the studies used. There is also a high degree of consistency among studies, with 92 of the 206 studies relevant to the secondary question 4.7.1 finding vegetation and hydrology to be the two most important variables influencing the water quality improvement efficiency of wetlands. The overall internal reliability of the body of evidence was High, with 88% of studies rated as 'High' internal validity and 12% rated as 'Low'. Of the 238 studies featured within the body of evidence, 119 studies ranked with a moderate-to-high overall relevance and had high reliability. Where possible, these studies have formed the focus of this Evidence Review.

# 1. Background

Coastal wetlands hold immense value due to the range of ecosystem services they provide, from biophysical (e.g., nutrient cycling), biological (e.g., biodiversity) and environmental (e.g., flood control and foreshore stabilisation), to economic (e.g., tourism) and cultural (e.g., aesthetic; Findlay & Fischer, 2013; Fisher et al., 2011; Gopal, 2013; Sah & Heinen, 2001). The water within wetlands can be permanent or temporary, which is a function of the hydrology, weather conditions and human water use. Water quality in wetlands can be highly variable which is also a function of hydrology, weather, human use, and runoff from adjacent land uses. Depending on the land use immediately surrounding or nearby wetlands, and modifications to natural processes, wetland water quality conditions can change or be altered from natural cycling conditions to alternative modified states.

Since European settlement (~1850), land-use changes within catchments and major modifications to floodplains have contributed to the degradation and loss of wetland habitats. In the Great Barrier Reef (GBR) catchments, between 78% and 97% of wetlands that existed prior to European settlement remain, however, this varies between Natural Resource Management (NRM) Regions and basins, and the losses are more substantial for some wetland types in certain locations. These losses are primarily the result of changed land management through clearing, draining or infilling of wetlands. The loss of wetlands within the GBR catchment area and subsequent changes in land use and catchment hydrology not only negatively impacts water quality within the wetlands, but also the quality of water flowing from catchment to the GBR (DEHP, 2016). The rate of wetland loss has generally slowed in the last few decades with slight increases in wetland extent observed in some catchments due to the construction of artificial wetlands (e.g., farm dams, ponded pasture) (Australian & Queensland Government, 2022). However, declines in the area of natural wetlands has continued with a net loss of 7,688 ha of natural wetlands in the GBR catchment area between 2001 and 2017 (i.e., excluding artificial/highly modified). Riverine wetlands experienced the greatest loss—accounting for 6,255 ha (or 81%) of the reduced area of natural wetlands, followed by estuarine salt flats and saltmarshes (605 ha), and coastal and subcoastal tree swamps (*Melaleuca* spp. and *Eucalyptus* spp.) on non-floodplains (569 ha) and floodplains (537 ha) (DES, 2017). As a result of these losses in wetland extent, the capacity for wetlands to process and assimilate contaminants has reduced, placing greater pressure on the remaining wetlands (DEHP, 2016). This is discussed further in Question 4.9 (Waltham et al., this Scientific Consensus Statement (SCS)).

Aside from the ongoing decline in the extent of natural wetlands, the main threats to water quality in GBR wetlands, and their ability to continue providing services that are essential to life, are pesticides, excess nutrients (nitrogen and phosphorus) and sediments that are washed into local creeks, estuaries, and nearshore areas following rainfall (Mitsch & Gosselink, 1993). These contaminants have the potential to alter and affect the natural balance of local, sensitive, downstream receiving habitats such as seagrass meadows, mangroves, and coral reefs, as well as unvegetated habitat settings such as intertidal channels and sandy beaches (refer to Questions 3.2 Collier et al., 4.2 Diaz-Pulido et al., and 5.1 Negri et al., this SCS). This transportation from the land to the coastal zone is usually untreated and unprocessed (Batson et al., 2012), placing increased pressure on already modified and stressed coastal ecosystems. Other than directly controlling these contaminants at the source, through land-based management action (such as the actions described in Questions 3.5 Bartley & Murray, 3.6 Brooks et al., 4.6 Thorburn et al., and 5.3 Davis et al., this SCS), alternative ways to assist in the treatment of these contaminants are needed before they reach receiving habitats.

One solution is the use of wetlands and directly channelling land runoff through either natural or engineered treatment wetlands that are capable of processing land-based contaminants (Agaton & Guila, 2023; Batson et al., 2012; Moustafa et al., 2011). Wetlands are hydraulic low points in the landscape that receive water from surface and subsurface pathways (Mitsch & Gosselink, 1993), and channel this flow to lower catchment and nearshore areas. Wetlands may provide an effective means of processing and storing land-based nutrients, sediments, and pesticides, among other contaminants; but this service diminishes with poorly managed or designed systems, such that wetlands can become a point source of contaminants to downstream habitats (Adame et al., 2021; Moustafa et al., 2011). For example, under low dissolved oxygen conditions and long residence time, wetlands process available nutrients and store them as biomass in sediments or plant material which can enter aquatic food webs, or off-gas to the atmosphere via denitrifying bacteria (Mitsch & Gosselink, 1993). Under conditions that are not conducive to these processes, much of the available nutrients can flow through a wetland unprocessed, and remain available in the system, flowing further downstream (McJannet et al., 2012b). There have been several international research studies that have modelled and measured the rate of nutrient processing in wetlands as a way of advocating their application in improving water quality (Zhao et al., 2023). The results are generally variable, and a function of water flow (residence time), wetland size, maintenance, water temperature and nutrient supply – among others. Some common requirements to assist with increasing efficacy need to be incorporated in future designs.

Wetlands are also places in the landscape that may trap and store particulates including sediment and organic material that washes in from the surrounding landscape (Fennessy & Craft, 2011). For particulates, they can contain organic material that can break down and become locked up in wetlands or that can be processed and available for uptake in dissolved forms (e.g., dissolved inorganic nitrogen). Sediments can also accumulate in wetlands, particularly coarser size fractions that are denser and will settle and accumulate when wetlands have low flow velocity. For the finer sediment particles, these can move through wetlands unprocessed, and flow downstream to nearshore and offshore areas. The rate of accumulation in wetlands is a function of flow velocity and the size of the particle (Johnston, 1991; Mitsch et al., 2014). Wind events and intense rainfall high-flow events can also remobilise sediments accumulated in wetlands, transporting them downstream.

Wetlands can also provide a treatment role for pesticides and other contaminants that are transported via flow pathways in the landscape. In the United States, there has been a lot of research into the response of wetlands to pesticides, particularly in agricultural catchments where these contaminants are mobilised during rainfall. Wetlands can also provide an opportunity to process pesticides/herbicides in coastal areas (Vymazal & Březinová, 2015).

This review examines the efficacy of natural/near-natural wetlands, restored wetlands, treatment (constructed) wetlands and other treatment systems in GBR catchments in improving water quality (nutrients, sediments, and pesticides). This review also examines the key factors that affect the efficacy of these types of wetlands in improving water quality and how these can be addressed at scale to maximise water quality improvement. The use of wetlands as treatment systems in non-agricultural land uses is reviewed in Questions 3.5 (Bartley & Murray, this SCS), 4.6 (Thorburn et al., this SCS) and 5.3 (Davis et al., this SCS).

## 1.1 Questions

Primary and secondary questions are outlined below.

| | |
|---|---|
| Primary question | **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?) |
| Secondary question | **Q4.7.1** What are the key factors that affect the efficacy of natural/near-natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality and how can these be addressed at scale to maximise water quality improvement? |

The questions here have been interpreted as referring to the efficacy or degree to which wetlands **within an agricultural landscape** in the GBR perform, or could be expected to perform, in improving water quality (defined as nutrients, sediments, and pesticides). This review has also considered how GBR wetlands can be improved to maximise the objective of water quality improvement. While the bounds of this question relate to the Great Barrier Reef World Heritage Area (GBRWHA), including the catchment and floodplains, a broad approach to the published literature has been taken to provide background context of wetland efficacy in improving water quality, and in doing so, capturing the key factors that affect their efficacy. By identifying what factors improve water quality and how it changes for each wetland type, it is expected that this review will provide useful information for better design and management strategies to maximise water quality improvement in the GBR.

For the purposes of this review, natural/near-natural wetlands include lacustrine, palustrine, estuarine, and riverine wetlands, i.e., non-marine wetlands, thereby excluding coral reefs, seagrass meadows and pelagic and benthic plankton communities. Treatment/constructed wetlands and systems are defined as: 'engineered systems that replicate and enhance the physical, biological, and chemical treatment processes occurring in natural wetlands. They differ from restored or natural wetlands in that they are designed and managed primarily to improve water quality' (DEHP, 2016; Queensland Government, 2022). Treatment systems include bioreactors, floating wetlands, denitrification ponds, vegetated drains, recycle pits, swales, buffer strips and sediment basins. Within this Evidence Review, only treatment and constructed wetlands within an arable and/or pastoral agricultural setting are included.

Here, the efficacy of wetlands in improving water quality is measured as the difference between the quantity/concentration of nutrients, pesticides, and sediment entering and leaving the wetland. For natural/near-natural wetlands where it is difficult to identify inlet and outlet points, efficacy will also consider measurements of denitrification and other nitrogen processes such as denitrification, anammox and dissimilatory nitrate reduction to ammonium.

## 1.2 Conceptual diagram

The conceptual diagram below (Figure 1) graphically summarises some of the key processes influencing the water quality improvement efficiency of various wetland types. These include internal drivers such as vegetation, hydrology and wetland soils/sediments, and external drivers such as landscape context, climate, management, and environmental factors.

## 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 but the primary question linkages are listed below.

| | |
|---|---|
| Links to other related questions | **Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?<br>**Q4.5** What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time?<br>**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? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?<br>**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?<br>**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)?<br>**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? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? |

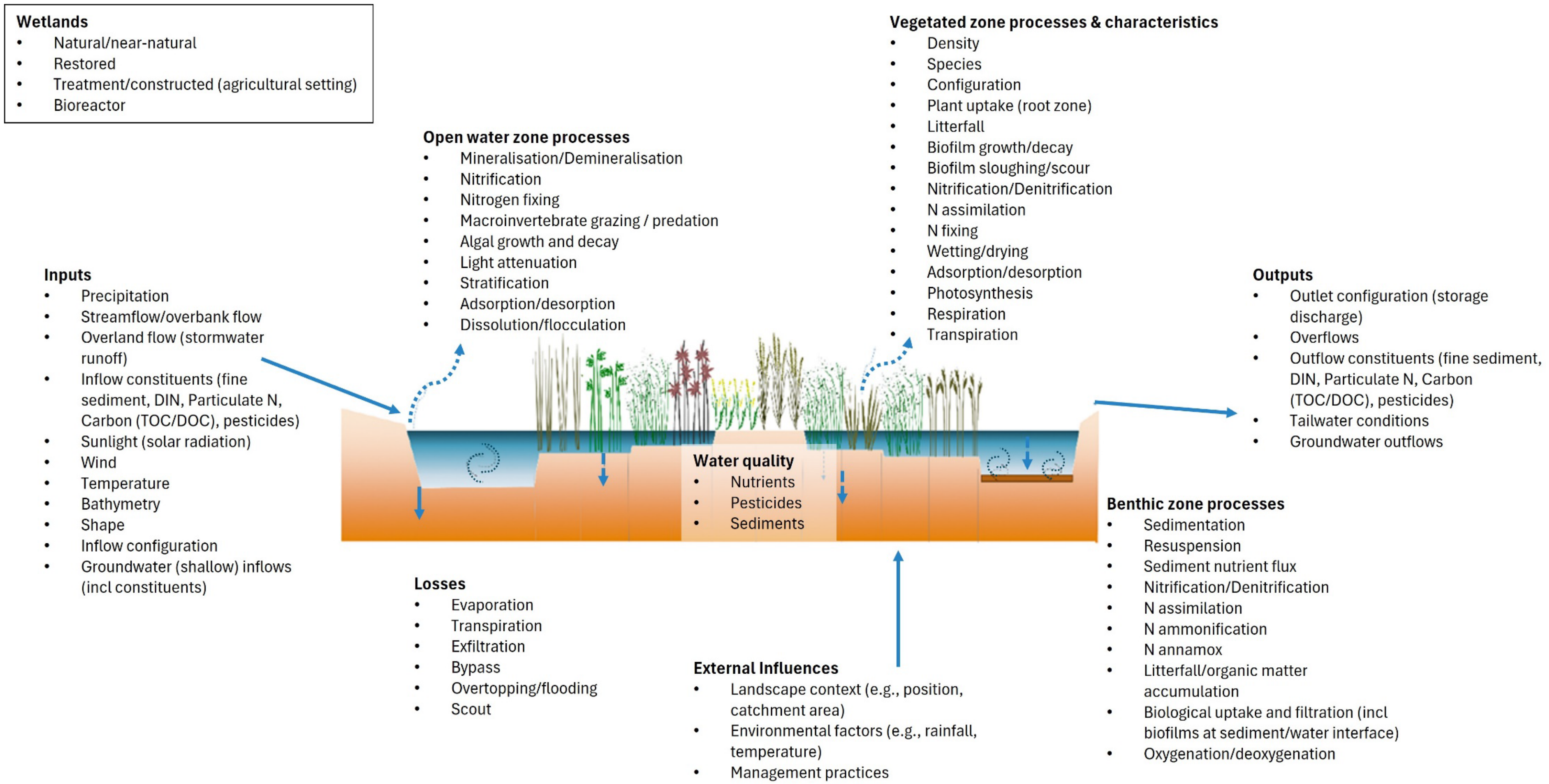



*Figure 1. Conceptual diagram illustrating: 1) the types of wetlands addressed in 4.7 and 4.7.1; 2) the water quality parameters of interest; and 3) key wetland processes affecting the water quality improvement efficiency of wetlands (Adapted from Alluvium, JCU, Griffith University, 2022).*

# 2. Method

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

## 2.1 Primary question elements and description

The primary question is: ***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, sediments and pesticides)?***

The secondary question is: ***What are the key factors that affect the efficacy of natural/near-natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier reef catchments in improving water quality and how can these be addressed at scale to maximise water quality improvement?***

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[7] but other variations are also available.

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

*Table 1. Description of question elements for 4.7 and 4.7.1.*

| Question S/PICO elements | Question term | Description |
|---|---|---|
| Subject/Population | Water Quality | **Subject - Water quality:**<br>Nutrients: nitrogen, nitrates, phosphorus, phosphates<br>Sediments: suspended sediments/solids, particulate<br>Pesticides: herbicide, fungicide, insecticide |
| Intervention, exposure & qualifiers | Wetlands and other treatment systems | **Intervention** - natural/near-natural wetlands, restored wetlands, treatment/constructed wetlands, treatment systems, bioreactors. |

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

[7] 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 |
|---|---|---|
| | Key factors | Wetland: palustrine, lacustrine, riverine, melaleuca, marsh, mangrove.<br><br>Treatment/constructed wetlands: floating wetland, vegetated drain, recycle pit, swale, buffer strip, sediment basin, vegetated buffer, algae treatment, algae pond.<br><br>Bioreactor: Bioreactor<br><br>**Qualifiers:**<br><br>Key factors - biotic and abiotic factors influencing the efficacy of wetlands to remove, retain or process nutrients, sediments and pesticides including:<br>- Landscape context (e.g., position, catchment area, land use)<br>- Environmental factors (e.g., rainfall, temperature)<br>- Vegetation (e.g., type, abundance)<br>- Wetland type<br>- Soil<br>- Management practices<br>- Hydrology (e.g., water inflow, depth, residence time)<br>- Water Quality (e.g., sediment and nutrient concentration). |
| Comparator | Great Barrier Reef catchments | Great Barrier Reef (GBR)<br><br>GBR catchments: catchments that flow into the Great Barrier Reef World Heritage Area.<br><br>Treatment systems: farming (arable and pastoral) context. |
| Outcome & outcome qualifiers | Improved water quality<br><br><br><br><br>Efficacy | **Outcome:** Improved water quality - Removal (including processing and retention) of nutrients, sediments, and pesticides.<br><br>Improved water quality: removal, retention, denitrification, anammox, nitrate reduction, sedimentation, mitigation, deposition.<br><br>**Outcome qualifier**: Efficacy. Efficacy of removal (including processing and retention) of nutrients, pesticides, and sediments.<br>Efficacy: Efficacy, Efficiency, Effective |

*Table 2. Definitions for terms used in Questions 4.7 and 4.7.1.*

| Definitions | |
|---|---|
| **Great Barrier Reef (GBR)** | Great Barrier Reef World Heritage Area (includes ports). |

<table>
<tr><th colspan="2">Definitions</th></tr>
<tr><td>Catchments / GBR catchments</td><td>Catchments: The natural drainage area upstream of a point that is generally on the coast. It generally refers to the ‘hydrological’ boundary and is the term used when referring to modelling outputs in this document. There may be multiple catchments in a basin.<br><br>GBR Catchments: Catchments that flow into the Great Barrier Reef World Heritage Area. Great Barrier Reef catchment area includes the 35 mainland river basins draining into the GBR (DEHP 2016).</td></tr>
<tr><td>Wetlands</td><td>‘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’.<br><br>
<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>
<br>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, 2) geothermal wetlands. Wetlands constructed to ‘offset impacts on, or restore, an existing or former natural wetland’ are considered here as ‘near-natural’ wetland (Ministry for the Environment, 2021).</td></tr>
</table>

| Definitions | |
|---|---|
| | For this review, **natural and near-natural wetlands** refer to lacustrine, palustrine, estuarine, and riverine wetlands, excluding subtidal and subterranean wetlands, thereby excluding coral reefs, seagrass meadows, oyster reefs and aquifers.<br><br>**Natural wetlands** refer specifically to wetlands without any anthropogenic structural or hydrological change to the wetland, or within its catchment.<br><br>**Near-natural wetlands** refer to wetlands without any anthropogenic structural change to the wetland, but with anthropogenic structural or hydrological change occurring within the broader catchment. |
| **Restored Wetlands** | **Restored or rehabilitated wetlands** refer to wetlands where ecological and/or hydrological processes have been recovered where natural wetlands previously existed. These may have been drained in an agricultural landscape, for example, and can include the construction of levées and dykes.<br><br>**Restored wetlands** are considered treatment wetlands when engineering interventions go beyond the construction of levées and dykes. |
| **Treatment (or constructed) wetlands and other treatment systems** | **Treatment (or constructed) wetlands**, and related treatment systems for improving water quality, are engineered and designed to intercept, slow down, and remove sediments, nutrients, and other pollutants (e.g., pesticides) from water.<br><br>"Treatment (or constructed) wetlands are engineered systems that replicate and enhance the physical, biological, and chemical treatment processes occurring in natural wetlands. They differ from restored or natural wetlands in that they are designed and managed primarily to improve water quality" (Queensland Government, 2022). Other names for treatment wetlands are constructed wetlands, landscape wetlands, embellished wetlands, surface flow wetlands, free-water wetlands.<br><br>Treatment systems include floating wetlands, vegetated drains, recycle pits, swales, buffer strips and sediment basins. |
| **Nutrients** | "Nutrients are the natural chemical elements and compounds that plants and animals need to grow. There are several of them, but six are particularly important: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulphur."<br><br>"There is strong evidence for several effects of nutrients in the Great Barrier Reef including increased outbreaks of coral-eating crown-of-thorns starfish, lower coral diversity, algal blooms (that reduce light and add their own nutrients), increased susceptibility to coral bleaching and some coral diseases. While most effects occur in the wet season, some effects may continue for many years, for example crown-of-thorns starfish outbreaks."<br><br>"Rainfall and irrigation can wash nutrients, pesticides and sediment into waterways and coastal wetlands. Nutrients and pesticides can also drain through agricultural soils into groundwater and then reach downstream waters." (Queensland Government, 2019b). |
| **Fine sediments** | "Fine sediment, measured as total suspended solids, is any sediment fraction in water that measures less than 16 µm. Fine sediment is one of the parameters for which Reef water quality targets are set in the Reef 2050 Water Quality Improvement Plan. |

| Definitions | |
|---|---|
| | Given its small size, fine sediment is transported the furthest in the marine environment, leading to increased turbidity and reduced light availability. When compared to other sediment fractions, fine sediments pose the greatest risk to the Reef" (Queensland Government, 2019a). |
| **Pesticides** | "Pesticides kill, repel, or control forms of animal and plant life considered to damage or be a nuisance in agriculture and domestic life." Pesticides include herbicides, insecticides, and fungicides (National Institute of Environmental Health Sciences, 2023). |
| **Water Quality** | "Water quality refers to the chemical, physical, biological, and radiological characteristics of water. It is a measure of the condition of water relative to the requirements of one or more biotic species and/or to any human need or purpose." (Queensland Government, 2019a).<br><br>For treatment systems, this review will be focusing on water quality improvements within an agricultural setting, as this is highly relevant to GBR catchments.<br><br>Systems treating sewage, urban or wastewater were not investigated in this review as these systems are covered in Question 4.6 (Thorburn et al., this SCS). |
| **Efficacy** | Mass removal (including processing and retention) of nutrients (nitrogen, phosphorus), fine sediments or pesticides from the water body per unit area.<br><br>Removal efficiency: Percentage of input load of nutrients, sediments or pesticides removed (including processing and retention).<br><br>For natural/near-natural wetlands where it is difficult to identify inlet and outlet points, efficacy will also consider measurements of denitrification and other nitrogen processes such as denitrification, anammox and dissimilatory nitrate reduction to ammonium. |
| **Hydrology** | Hydrology encompasses the occurrence, distribution, movement, and properties of water on and beneath a planet's surface and its atmosphere, and the relationship between water and the environment within each phase of the hydrologic cycle (U.S. Geological Survey, 2019). |

## 2.2 Search and eligibility

### a) Search locations

Searches were performed using two literature search databases and several specialist websites. These included:

- Web of Science
- Scopus
- National Environmental Science Programme (NESP) Tropical Water Quality Hub
- Specialist websites – United States Department of Agriculture (USDA), Queensland Government's Wetland*Info*, and the Department of Environment and Science, the Australian Government's Department of Climate Change, Energy, the Environment and Water and Pandora.

### b) Search terms

A list of the search terms used to conduct the online searches is provided in Table 3.

*Table 3. Search terms for S/PICO elements of Questions 4.7 and 4.7.1.*

| Question element | Search terms |
|---|---|
| Subject/Population | "Water Quality", Nutrient*, Nitr*, Phosph*, Pesticide*, Herbicide*, Fungicide*, Sediment*, "suspended solids", "particulate" |
| Exposure or Intervention | Natural/near-natural: wetland*, palustrine, lacustrine, riverine, melaleuca, marsh*, mangrove<br><br>Not: sewage, urban, wastewater<br><br>Treatment systems: "floating wetlands", "vegetated drain", "recycle pit", swale, "buffer strip", "sediment basin", "vegetated buffer", "algae treatment", "algae pond"<br><br>Bioreactor: bioreactor |
| Comparator (if relevant) | Treatment systems: Farm*, agricultur*, crop*<br><br>Bioreactors: Great Barrier Reef, GBR, Tropical Australia, Queensland |
| Outcome | Removal, retention, denitrification, anammox, "nitrate reduction", sedimentation, mitigation, deposition, efficacy, efficiency, effective* |

### c) Search strings

A set of search strings were defined by the authors and confirmed with the SCS Coordination Team. The list of search strings used to conduct the online searches is presented in Table 4.

*Table 4. Search strings used for electronic searches for Questions 4.7 and 4.7.1.*

| Search strings |
|---|
| **Natural, near natural, restored wetlands**<br>*Limited to studies 1990–2022, in English and only published journal articles.*<br><br>"water quality" AND<br><br>(nutrient*OR nitr* OR phosph* OR pesticide* OR herbicide* OR fungicide* OR sediment* OR "suspended solids" OR "particulate") AND<br><br>(wetland* OR palustrine OR lacustrine OR riverine OR melaleuca OR marsh* OR mangrove) AND<br><br>(removal OR retention OR denitrification OR anammox OR "nitrate reduction" OR sedimentation OR mitigation OR deposition OR efficacy OR efficiency OR effective*) AND<br><br>NOT (sewage OR urban OR wastewater) |
| **Treatment Systems**<br>*Limited to studies 1990–2022, in English and only published journal articles.*<br><br>("water quality" OR nutrient* OR nitr* OR phosph* OR pesticide* OR herbicide* OR fungicide* OR sediment* OR "suspended solids" OR "particulate") AND<br><br>("floating wetland*" OR "vegetated drain*" OR "recycle pit*" OR swale* OR "buffer strip*" OR "sediment basin*" OR "vegetated buffer*" OR "algae treatment*" OR "algae pond*") AND<br><br>(removal OR retention OR denitrification OR anammox OR "nitrate reduction" OR sedimentation OR mitigation OR deposition OR efficacy OR efficiency OR effective*) AND |

| Search strings |
|---|
| (farm* OR agricultur* OR crop*) |
| **Bioreactors**<br>*Limited to studies 1990–2022, in English and only published journal articles.*<br>("water quality" OR nutrient* OR nitr* OR phosph* OR pesticide* OR herbicide* OR fungicide* OR sediment* OR "suspended solids" OR "particulate") AND<br>Bioreactor* AND<br>(removal OR retention OR denitrification OR anammox OR "nitrate reduction" OR sedimentation OR mitigation OR deposition OR efficacy OR efficiency OR effective*) AND<br>("Great Barrier Reef" OR GBR OR (tropical AND Australia) OR Queensland) |

## d) Inclusion and exclusion criteria

A set of search inclusion and exclusion criteria were defined by the authors and confirmed with the SCS Coordination Team. The list of the search criteria is presented in Table 5.

*Table 5. Inclusion and exclusion criteria applied to the search returns.*

| Question element | Inclusion | Exclusion |
|---|---|---|
| Subject/Population | Studies investigating the efficacy of natural, near-natural, restored, bioreactors and treatment (constructed) wetlands in improving water quality.<br>Nitrogen (N) and Phosphorus (P) in all forms.<br>Total suspended solids, sediments, fine sediments.<br>Pesticides: including insecticides, herbicides, fungicides. | All strings:<br>Not water-quality related.<br>Related to water quality measures other than nutrients, fine sediments, pesticides (e.g., exclude genotoxins, Nitrous oxide emissions, pathogens, selenium, heavy metals, carbon, acid mine drainage, *E. coli*, Faecal coliform etc.)<br>Exclude studies only looking at surface or *in situ* water quality, not following residence time in or processing through the wetland.<br>Urban-related studies, mariculture, and aquaculture, e.g., systems to treat point source pollution, such as sewage, stormwater etc., and natural/near-natural/restored wetlands with municipal waste re-directed through them. |
| Exposure or Intervention | All strings:<br>Measure wetland efficiency – e.g., inflow water quality versus outflow water quality<br>Look specifically at in-water treatment, not within sediments.<br>Treatment string:<br>Wetlands in tropical (0–23.5° latitude) and subtropical climates (23.5–40° latitude).<br>Studies investigating the efficacy of floating wetlands, vegetated drains, recycle pits, swales, buffer strips, sediment basins, vegetated buffers, algal treatments, and | All strings:<br>Exclude studies that only look at sediment retention – (nutrients/pollutants will eventually leach from sediments and affect water quality).<br>Studies in temperate, boreal, or polar climates including Russia, Sweden, Canada, Finland, Greenland, Norway, Alaska.<br>Treatment & bioreactor string: |

| Question element | Inclusion | Exclusion |
| --- | --- | --- |
| | ponds, as well as studies introducing substances and/or chemicals to catalyse N and P removal (within an agricultural setting) in improving water quality.<br><br>Include studies with mixed catchment uses – e.g., agriculture, urban and industrial. Extract as much agricultural information as possible and note that multiple uses/pollutant/nutrient sources are present.<br><br>Natural/near-natural/restored string:<br><br>Palustrine, lacustrine, riverine, melaleuca, marsh wetlands, etc. | Non-agricultural studies, or studies looking at agriculture other than arable and pastoral uses.<br><br>Natural/near-natural/restored string:<br><br>Wetlands that do not meet natural/near-natural/restored wetlands definition (unless applicable to treatment or bioreactor strings).<br><br>Subtidal and subterranean wetlands, i.e., coral reefs, seagrass meadows, oyster lagoons and aquifers.<br><br>Exclude riparian buffer strips that are not wetlands. |
| Comparator | - | - |
| Outcome | - | Not related to the function, activity, or efficiency of wetlands in improving water quality. |
| Language | All strings:<br><br>Studies written in English. | All strings:<br><br>Studies not written in English. |
| Study type | All strings:<br><br>Peer reviewed and published studies.<br><br>Grey literature (peer reviewed and publicly available studies)<br><br>Experimental, observational, and/or modelling studies – so long as the model is appropriately built, i.e., trained with real-world data.<br><br>Include pilot studies.<br><br>Studies at all size wetlands (excluding watershed scale, unless looking at individual wetlands – likely to include mix of wetland types, cannot separate out natural versus treatment etc.).<br><br>Studies including a water balance.<br><br>Studies where statistics are not described in the abstract but are believed to be in the manuscript's results – include in second screening for checking.<br><br>Natural/near-natural string:<br><br>Include experimental mesocosms (simulating natural wetland conditions), but note reduced relevance/reliability in simulating natural wetland conditions | All strings:<br><br>Studies conducted before 1990 (unless essential).<br><br>Modelling studies not trained on real-world data.<br><br>Non-quantitative studies.<br><br>Exclude studies at watershed/catchment scale (unless include and discuss multiple wetlands within).<br><br>Treatment strings:<br><br>Constructed wetlands established for less than 12 months. |

## 3. Search Results

A total of 236 studies were identified through online searches for peer-reviewed and published literature after screening. A single published study was identified manually through expert contact and personal collection, and one item of grey literature satisfied the inclusion criteria, representing 0.8% of the total evidence. 238 studies were therefore eligible for inclusion in the review of evidence (Table 6; Figure 2). 27 studies were unobtainable.

*Table 6. Search results table, separated by A) Academic databases and B) Manual searches. The search results for A 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 | Web of Science |
| *24/01/2023* | ***Natural string:*** *"water quality" AND*<br>*(nutrient*OR nitr* OR phosph* OR pesticide* OR herbicide* OR fungicide* OR sediment* OR "suspended solids" OR "particulate") AND*<br>*(wetland* OR palustrine OR lacustrine OR riverine OR melaleuca OR marsh* OR mangrove) AND*<br>*(removal OR retention OR denitrification OR anammox OR "nitrate reduction" OR sedimentation OR mitigation OR deposition OR efficacy OR efficiency OR effective*) AND*<br>*NOT (sewage OR urban OR wastewater)* | *103 (8) of 1,872* | *78 (1,082 duplicates with Scopus output) of 2,039* |
| *24/01/2023* | ***Treatment string:*** *("water quality" OR nutrient* OR nitr* OR phosph* OR pesticide* OR herbicide* OR fungicide* OR sediment* OR "suspended solids" OR "particulate") AND*<br>*("floating wetland*" OR "vegetated drain*" OR "recycle pit*" OR swale* OR "buffer strip*" OR "sediment basin*" OR "vegetated buffer*" OR "algae treatment*" OR "algae pond*") AND*<br>*(removal OR retention OR denitrification OR anammox OR "nitrate reduction" OR sedimentation OR mitigation OR deposition OR efficacy OR efficiency OR effective*) AND*<br>*(farm* OR agricultur* OR crop*)* | *43 (21) of 446* | *10 (333) of 540* |
| *24/01/2023* | ***Bioreactor string:*** *("water quality" OR nutrient* OR nitr* OR phosph* OR pesticide* OR herbicide* OR fungicide* OR sediment* OR "suspended solids" OR "particulate") AND*<br>*Bioreactor* AND*<br>*(removal OR retention OR denitrification OR anammox OR "nitrate reduction" OR sedimentation OR mitigation OR deposition OR efficacy OR efficiency OR effective*) AND*<br>*("Great Barrier Reef" OR GBR OR (tropical AND Australia) OR Queensland)* | *2 (0) of 11* | *0 (5) of 3* |

| Date (d/m/y) | Search strings | Sources |
|---|---|---|
| ***Total items from online searches*** | | 236 of 4,911 (total search returns) (99.2%) |
| B) Manual search | | |
| Date | Source | Number of items added |
| *07/02/2023* | *Department of Climate Change, Energy, the Environment and Water* | *1* |
| *07/02/2023* | *Nathan Waltham – personal collection* | *1* |
| ***Total items manual searches*** | | 2 (0.84%) |

A Google Scholar search was not conducted due to the volume of papers (3,462) retrieved from Scopus and Web of Science database searches. The 'Natural' string for both Scopus and Web of Science databases included multiple outputs relevant to the 'Treatment' string.

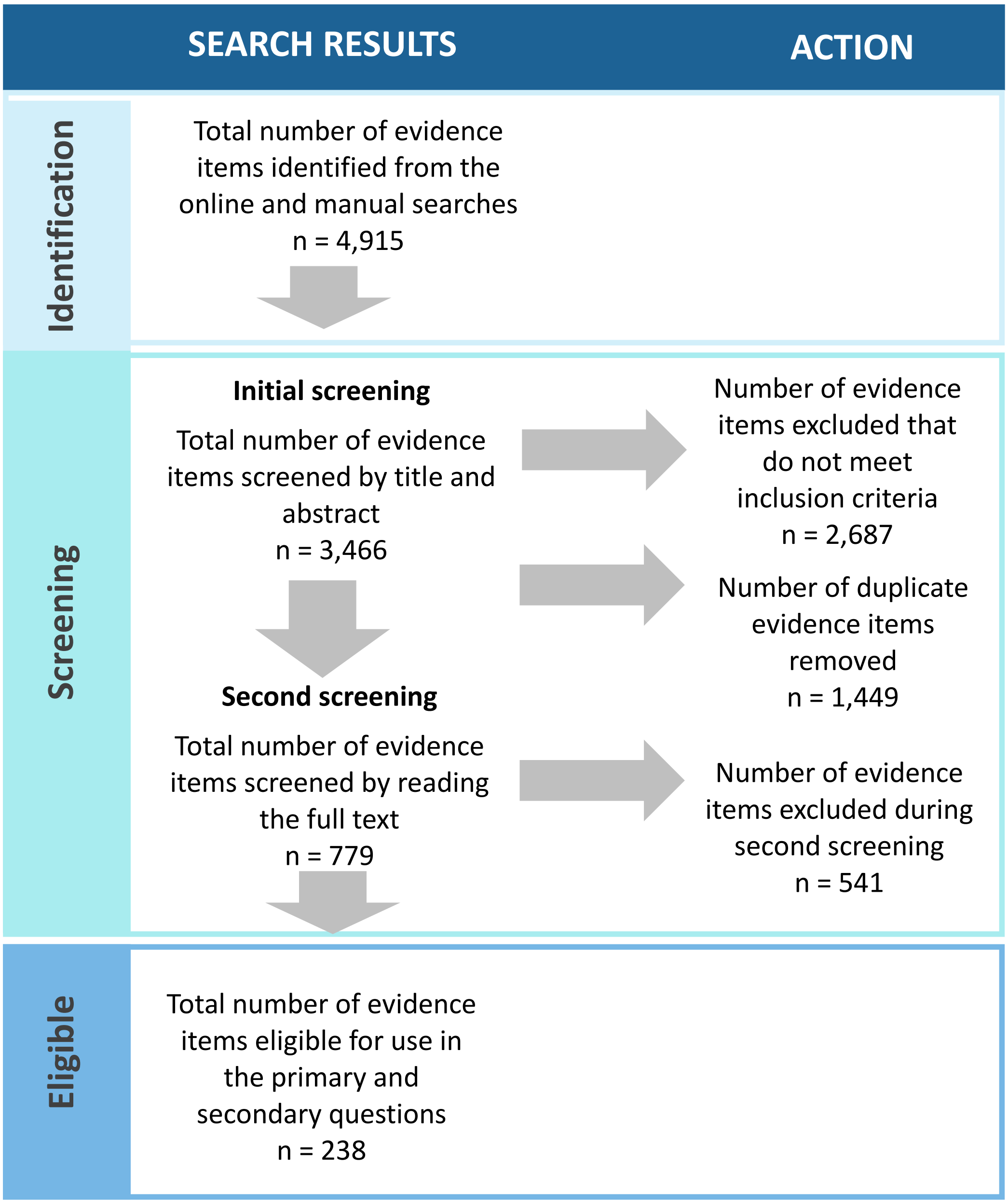



*Figure 2. Flow chart of results of screening and assessing all search results.*

# 4. Key Findings

## 4.1 Narrative synthesis

### 4.1.0 Summary of study characteristics

A total of 24 studies addressed the primary question exclusively, 73 studies addressed only the secondary question 4.7.1, and 141 studies addressed both question elements. Characteristics are summarised in Table 7 below. Overwhelmingly, most of the studies included in this review were on wetlands in the United States (49%, n = 117) and China (18%, n = 44), with far fewer studies in Australia and the GBR by comparison (6%; Table 7). The remaining research has been conducted in the following countries: Argentina, Botswana, Brazil, Chile, Costa Rica, the Democratic Republic of Congo, Ethiopia, Greece, Iran, Israel, Japan, Kenya, Tanzania, Korea, Lesotho, Malaysia, Mexico, New Zealand, Portugal, Singapore, South Africa, South Korea, Spain, and Taiwan (see summary in Figure 3).

The body of evidence predominantly contains studies focusing on treatment and constructed wetlands (56%), followed by natural and near-natural wetlands (27%), and restored wetlands (7.5%). Studies specifically focusing on the use of bioreactors within agricultural settings constituted only 2.5% of the literature.

From this review, it is apparent that the interest and research focus on the role of wetlands and their ability to provide a water quality improvement service is widescale, with more than 2,000 studies included in the initial screening and review. If this review was not just focused on tropical and subtropical locations and included temperate studies, the number of papers included would have been far higher.

*Table 7. Overview of the locations and pollutant types featured within the body of evidence. 'N' = Nitrogen, 'S' = Sediments, 'P' = Pesticides. NA refers to studies that did not specifically address nutrients, sediments, or pesticides, but that informed the secondary question 4.7.1. 'Other' refers to studies conducted within the following countries: US, China, Argentina, Botswana, Brazil, Chile, Costa Rica, the Democratic Republic of Congo, Ethiopia, Greece, Iran, Israel, Japan, Kenya, Tanzania, Korea, Lesotho, Malaysia, Mexico, New Zealand, Portugal, Singapore, South Africa, South Korea, Spain, and Taiwan.*

| Wetland type | Location (No. of studies) | | Pollutant type (No. of studies) | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *GBR* | *Other* | *N* | *S* | *P* | *S & N* | *P & N* | *S & P* | *All* | *NA* | |
| Natural / near-natural | 6 | 58 | 49 | 5 | 1 | 6 | 0 | 0 | 0 | 3 | 64 |
| Restored | 3 | 15 | 12 | 0 | 0 | 4 | 0 | 0 | 0 | 2 | 18 |
| Treatment/constructed | 3 | 131 | 96 | 1 | 15 | 16 | 4 | 1 | 0 | 1 | 134 |
| Bioreactor | 1 | 5 | 5 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 6 |
| Combination of wetland types | 0 | 10 | 7 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 10 |
| NA (e.g., experimental mesocosm) | 0 | 6 | 2 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 6 |
| **Total** | *13* | *225* | *171* | *6* | *20* | *28* | *5* | *1* | *1* | *6* | **238** |

Most studies (n = 108, 45%) had an experimental or mesocosm design approach, 28% (n = 67) were observational studies (i.e., collected data to monitor or evaluate wetland performance), while the remaining were modelling approaches, reviews or had a theoretical base in the study approach (Table 8). For natural/near-natural wetlands, the most common study type used was observational (n = 24, ~38%), followed by modelling (n = 17, ~27%). For treatment/constructed wetlands, the most common study type used was experimental (n = 80, ~60%), followed by observational (n = 31, 23%).

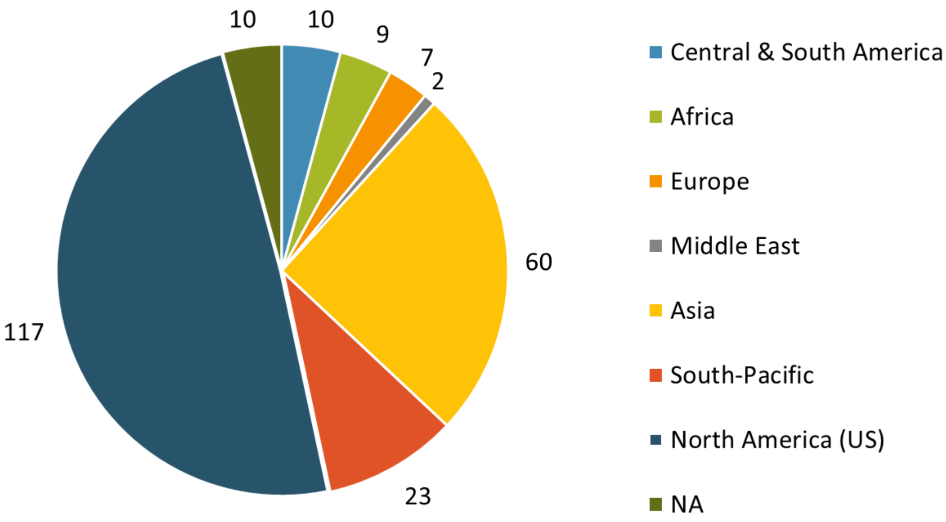



*Figure 3. Global distribution of studies within the body of evidence used to answer questions 4.7 and 4.7.1 (n = 238).*

Riverine habitats had the highest number of studies (27%), followed by lacustrine (7%), palustrine (5%) and estuarine (2%) wetlands. Seven percent of studies investigated a combination of wetland types. Surprisingly, 19% of studies did not provide clear information to decipher the habitat setting. For the remainder of studies, (e.g., treatment and constructed wetlands), habitat was not relevant. This highlights the need for publications to provide as much site detail as possible to provide important context for comparisons and to understand the key conclusions presented by the authors.

Among treatment/constructed wetlands, the most common systems studied were the use of vegetation (n = 22), buffer strips (n = 20), and non-specific constructed wetlands (n = 15). Treatment wetlands also included the addition of chemicals to enhance water quality improvement efficiency (Ann et al., 1999; Bachand et al., 2019) and the use of on-farm irrigation tanks (Shao et al., 2013). Among restored wetlands, the most common means of restoration studied were hydrological restoration (n = 3), planting of vegetation (n = 3), and weed removal (n = 2; e.g., Bruland et al., 2003).

Within the body of evidence, nutrients were the most studied pollutant, with 171 studies (~72%; Table 7) investigating the removal efficiency of nutrients in all wetland types, followed by the combination of sediments and nutrients (n = 28, ~12%) and pesticides (n = 20, 8%; see Table 9 for the list of pesticides featured within the body of evidence). Only one study focused on all three pollutants (pesticides, nutrients, and sediments), investigating contaminant removal efficiencies within natural wetlands and bioreactors (Kao et al., 2002). Within the body of evidence, the nutrient removal efficiency of treatment/constructed wetlands (n = 96, 40%) and natural/near-natural wetlands (n = 49, ~21%) represented the highest proportion of studies.

*Table 8. Study types of the body of evidence, by wetland type. 'C' = conceptual, 'E' = experimental, 'M' = modelling, 'O' = observational.*

| Wetland type | C | E | M | O | O & E | O & M | O, E, M | Review | Theoretical | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Bioreactor | | 4 | | 2 | | | | | | 6 |
| Combination | | 0 | 2 | 5 | 1 | | | 1 | 1 | 10 |
| NA | | 5 | | | | | | 1 | | 6 |
| Natural/near -natural | 1 | 10 | 17 | 24 | 0 | 1 | 1 | 0 | 10 | 64 |
| Restored | | 9 | 2 | 5 | | | | 1 | 1 | 18 |
| Treatment/ Constructed | 1 | 80 | 12 | 31 | 1 | 1 | | 3 | 5 | 134 |
| **Total** | **2** | **108** | **33** | **67** | **2** | **2** | **1** | **6** | **17** | **238** |

*Table 9. The pesticides featured within the body of evidence.*

| Pesticide | References |
|---|---|
| Acetamiprid | Satkowski et al., 2018 |
| Ametryn | Navaratna et al., 2012 |
| Atrazine | Kao et al., 2001; 2002; Lizotte et al., 2009; Locke et al., 2011; Marecik et al., 2012; Tyler et al., 2013 |
| Azinphos-methyl | Stehle et al., 2016 |
| Azoxystrobin | Boutron et al., 2011 |
| Bifenthrin | Bennett et al., 2005 |
| Carbaryl | Stehle et al., 2016 |
| Chlorpyrifos | Moore et al., 2002; Pavlidis et al., 2022b; Werner et al., 2010 |
| Cis-permethrin | Moore et al., 2009 |
| Clomazone | Moore & Locke, 2020 |
| Clothianidin | Satkowski et al., 2018 |
| Cyfluthrin | Moore & Locke, 2020 |
| Dimethoate | Satkowski et al., 2018 |
| Diazinon | Moore et al., 2008 |
| 2,4-Dichlorophenoxyacetic | Yorlano et al., 2022 |
| Difenoconazole | Pavlidis et al., 2022b |
| Dimethomorph | Pavlidis et al., 2022a; 2022b |
| Dinotefuran | Satkowski et al., 2018 |
| Diuron | Boutron et al., 2011 |
| Fipronil | Lizotte et al., 2009 |
| Fluometuron | Locke et al., 2011 |
| Glyphosate | Jacklin et al., 2020 |
| Imidacloprid | Pavlidis et al., 2022a; 2022b; Phillips et al., 2021; Satkowski et al., 2018 |
| Isoproturon | Boutron et al., 2011 |
| KOCIDE 3000 | Simonin et al., 2018 |
| Lambda-Cyhalothrin | Bennett et al., 2005 |
| Lindane (γ-BHC) | Stehle et al., 2016 |
| Malathion | Stehle et al., 2016 |
| Metalaxyl | Satkowski et al., 2018 |
| Methoxyfenozide | Stehle et al., 2016 |
| Metryn | Borges et al., 2009 |
| Myclobutanil | Pavlidis et al., 2022a; 2022b |
| Organophosphates | Anderson et al., 2011 |
| Permethrin | Phillips et al., 2021; Werner et al., 2010 |
| Propanil | Moore & Locke, 2020 |
| Pyrimethanil | Stehle et al., 2016 |
| Pyrethroid | Anderson et al., 2011 |
| S-metolachlor | Lizotte et al., 2009 |
| Tebuconazole | Boutron et al., 2011 |
| Thiacloprid | Pavlidis et al., 2022a; 2022b; Satkowski et al., 2018 |
| Thiamethoxam | Satkowski et al., 2018 |
| Trans-permethrin | Moore et al., 2009 |
| Zoxamide | Stehle et al., 2016 |

### 4.1.1 Summary of evidence to 2022

#### Reported efficacy of wetlands in contaminant removal and factors influencing efficacy

Data were extracted to the best of the authors' on the efficacy of wetlands from the studies examined here (Figure 4) and the factors affecting nutrient, sediment and pesticide removal efficiencies (Table 10). There were considerable differences in the way data were reported and on many occasions it was difficult to extract the details required – either the details were not provided in the publication or the details and sampling procedure had not been adequately designed during experimental planning.

Information was extracted on the reported efficacy of wetlands in improving water quality (nutrients, sediments and pesticides) between the inlet and outlet. From the body of evidence, roughly 67% of studies were used to extract this information across all contaminants, with the remaining papers focused on sediment chemistry or other water quality parameters which were outside the scope of this review. A summary of the data can be found in Table 11 which presents the average of the range of reported efficacy values for water quality parameters, with minimum and maximum reported values in parentheses, for each nutrient and total suspended sediment parameter for each wetland type included in this review. Due to the limited number of studies investigating pesticide removal efficiencies and the wide range of pesticides studied, different pesticides and their removal efficiencies have been aggregated. To generate this table, the average reported value was extracted from publications — acknowledging that in some cases some wetlands and at some times were performing at a higher and lower rate than used in the calculations here. It is important to also note here that while the rates reported in Table 11 outline the range in percentage treatment, how this equates to overall export catchment load is not shown, and quite possibly only represents a small fraction of the total load exported downstream from catchment areas.

Information on the factors influencing the nutrient, pesticide and sediment removal efficiency of natural/near-natural, restored, treatment/constructed wetlands and bioreactors is presented in Figure 4. In most cases, while several factors were identified (such as hydrology), there was limited detail on what aspects of those factors were the most critical to efficacy. In many cases, this detail would also vary with location and site-specific characteristics so the categories remain relatively broad.

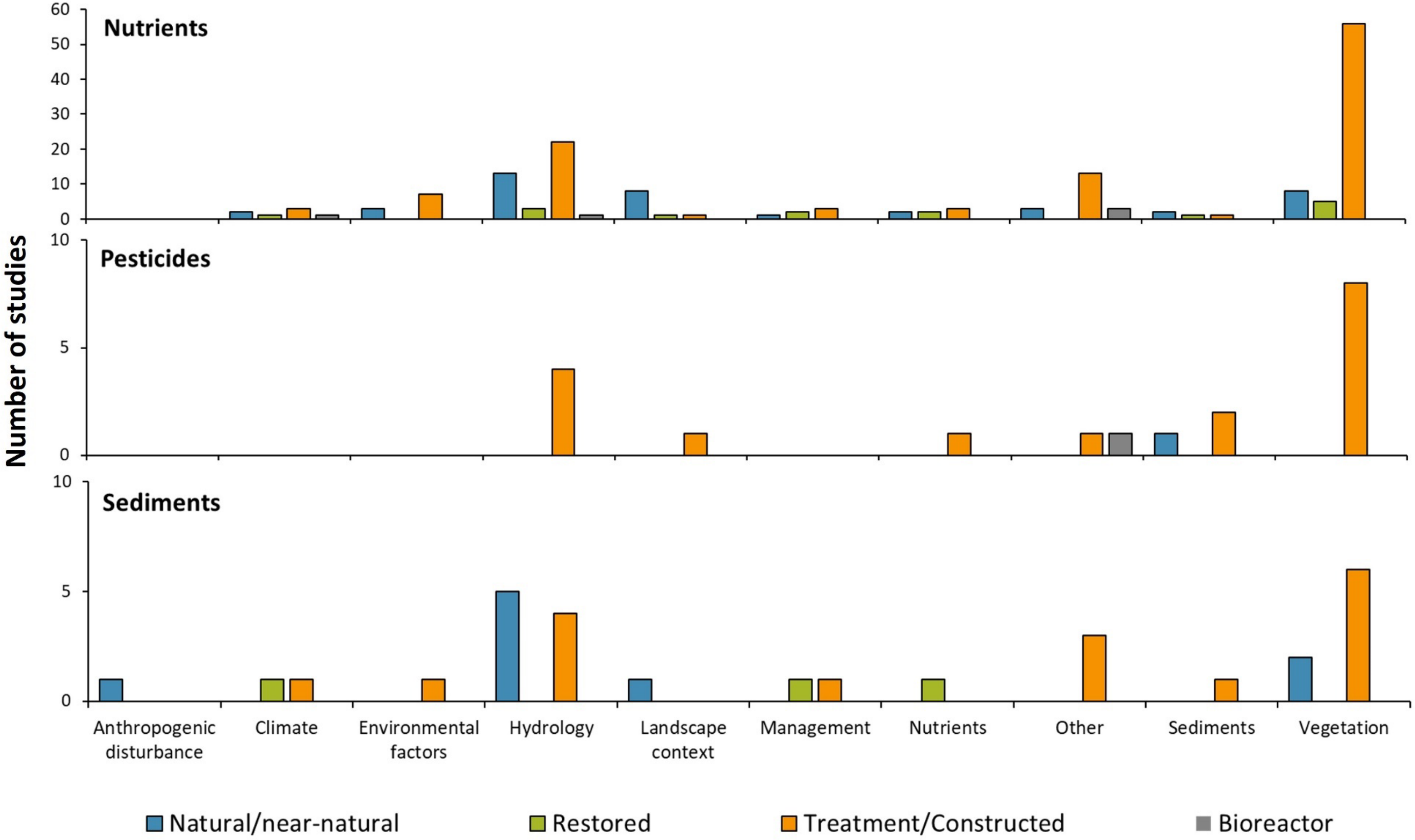



*Figure 4. Factors affecting the nutrient, pesticide and sediment removal efficiency of natural/near-natural, restored, treatment/constructed wetlands and bioreactors. Note the different y-axis values by pollutant type.*

*Table 10. Factors found to affect nutrient, pesticide and sediment removal efficiencies of natural, near-natural, restored and constructed/treatment wetlands from the body of evidence (some studies appear in multiple rows).*

| Factor affecting removal efficiency | Reference |
|---|---|
| Anthropogenic disturbance | Bagalwa, 2006 |
| Climate | Bowes et al., 2022; Chen et al., 2015; David et al., 2015; García-García et al., 2009; Ham et al., 2010; Jordan et al., 2003; Niu et al., 2016; Schmidt et al., 2019 |
| Environmental factors | Ann et al., 1999; Cai et al., 2017; Hunt et al., 1999; Kröger et al., 2007; 2011; Lu et al., 2017; McKergow et al., 2004; Min et al., 2015; Neubauer et al., 2019; Raisin & Mitchell, 1995; Zhao et al., 2019 |
| Hydrology | Appelboom et al., 2008; Ardón et al., 2010; Arora et al., 2010; Bason et al., 2017; Bennett et al., 2005; Birgand et al., 2016; Chescheir et al., 1991; Cui et al., 2020; DeLaune et al., 2005; Díaz et al., 2012; Ebadi & Hisoriev, 2018; Etheridge et al., 2017; Forbes et al., 2012; Groh et al., 2015; Hernández-Crespo et al., 2016; Hunt et al., 2008; Jiao et al., 2002; Jones et al., 2014; Kahara et al., 2022; Kao & Wu, 2001; Kavahei et al., 2021; Kovacic et al., 2000; Kröger et al., 2008; Lerch et al., 2017; Littlejohn et al., 2014; Locke et al., 2011; McJannet et al., 2012a; 2012b; Mu et al., 2020; Nnadi & Addasi, 1999; Nsenga Kumwimba et al., 2018; O'Geen et al., 2007; Oromeng et al., 2021; Reddy et al., 1996; Rutherford & Nguyen, 2004; Ryder & Fares, 2008; Tanner et al., 2005; Turner et al., 2004; Wallace et al., 2022; Welsh et al., 2019; Werner et al., 2010; Xu, 2006a; 2006b; 2013; Yu et al., 2001; Zainol & Akhir, 2022; Zhang et al., 2015 |
| Landscape context | Axt & Walbridge, 1999; Bird & Day, 2014; Cao et al., 2019; Greiner & Hershner, 1998; Lindau et al., 2008; Lizotte et al., 2014; Lu et al., 2020; Moore et al., 2014; Stanley & Ward, 1997; Stehle et al., 2016; Surratt & Aumen, 2014; Xu et al., 2014; Zhao & Li, 2001 |
| Management | Alemu et al., 2017; Brockmeyer et al., 1996; Cao et al., 2018; Khare et al., 2019; Kim et al., 2020; Martins et al., 2008; Shukla et al., 2011; Waltham et al., 2020a |
| Nutrients | Buelow & Waltham, 2020; Chen et al., 2010; Ma et al., 2019; Satkowski et al., 2018; Shao et al., 2013; Shenker et al., 2005; Shoemaker et al., 2017; Zhao & Piccone, 2020 |
| Other | Bachand et al., 2019; Bhomia & Reddy, 2018; Chance et al., 2020; Du et al., 2016; Janse et al., 2001; Jia et al., 2019; Kao et al., 2002; Liang et al., 2020; Lin et al., 2015; Liu et al., 2014; Manca et al., 2021; Navaratna et al., 2012; Phillips et al., 2021; Shahid et al., 2018; Shen et al., 2022; Sim et al., 2008; Takeda & Fukushima, 2006; Tanner & Kadlec, 2013; Uuemaa et al., 2018; Wilcock et al., 2012; Zhang et al., 2021a |
| Sediments | Faridmarandi et al., 2020; Ho & Chambers, 2019; Hogan et al., 2004; Kao et al., 2001; Masscheleyn et al., 1992; Maynard et al., 2009; Moore et al., 2002; Tyler et al., 2013 |
| Vegetation | Adame et al., 2019a; 2019b; 2021; Aust et al., 2012; Borges et al., 2009; Bouldin et al., 2004; Brisson et al., 2020; Chen et al., 2017; 2019; Cui et al., 2020; Del Toro et al., 2019; Dong et al., 2020; Franklin et al., 2019; Gall et al., 2018; George et al., 2021; Gu & Dreschel, 2008; Han et al., 2013; He et al., 2021; Hou et al., 2019; Hume et al., 2002; Ibekwe et al., 2007; Jacklin et al., 2020; Kadlec, 2006; Kato et al., 2007; Kröger et al., 2009; 2012; Li et al., 2011; Liu et al., 2013; Lu et al., 2014; Lv & Wu, 2021; Marecik et al., 2012; Martin et al., 2003; Martínez et al., 2018; Matheson et al., 2002; McGill et al., 2010; McKergow et al., 2004; Menon & Holland, 2013; Messer et al., 2012; Moore & Locke, 2020; Moore et al., 2002; 2008; Moore & Kröger, 2011; Moustafa, 1999; Moustafa et al., 2011; 2012; Nifong & Taylor, 2021; Pavlidis et al., 2022a; 2022b; Pierce et al., 2021; Rigotti et al., 2021; Rodrigo et al., 2018; Salazar et al., 2015; Sasikala et al., 2009; Schnabel et al., 1997; She et al., 2018; Singh et al., 2019; Stewart et al., 2008; Sun et al., 2021; Tomimatsu et al., 2014; Tyler et al., 2012a; 2012b; Veitch et al., 2007; Vellidis et al., 2003; Waltham et al., 2020b; Wang et al., 2019; 2022b; White et al., 2004; Xu et al., 2019; Yamasaki et al., 2022; Yang et al., 2019; Yen et al., 2012; Yi et al., 2010; Yorlano et al., 2022; Zamorano et al., 2018; Zeng et al., 2017; Zhang et al., 2016; 2017; 2020a; 2020b; 2022; Zhao et al., 2012; 2016 |

*Table 11. Overview of the efficiency (% reductions in concentrations) reported by studies included in this review. All data presented are the average removal efficiencies (%) (number of studies, minimum and maximum) of all reported water quality variables. For sites/studies where multiple results or a range are presented, the average value has been extracted for this analysis, suggesting that efficacy could be higher or lower depending on how the data were generated and presented in published studies. TN = Total Nitrogen, DIN = Dissolved Inorganic Nitrogen, $NO_3^-$ = Nitrate, $NH_4^+$ = Ammonium, TP = Total Phosphorus, $PO_4^{3-}$ = Phosphate, TSS = Total Suspended Sediment. Shaded cells indicate average values derived from less than 5 studies and therefore low confidence in the averages provided.*

| Wetland | TN | DIN | $NO_3^-$ | $NH_4^+$ | TP | $PO_4^{3-}$ | TSS | Pesticide |
|---|---|---|---|---|---|---|---|---|
| Bioreactor system | 80.0 (1, 80–80) | | 82.2 (1, 82.2–82.2) | | | | | 47.0 (2, 14.3–100) |
| Combination | 19.0 (1, 19–19) | | 93.0 (1, 93–93) | | 45.0 (4, 24–94) | | 50.0 (1, 50–50) | |
| Natural wetland | 63.5 (5, 27–96.4) | | 78.0 (2, 76–80) | 79.5 (2, 73–86) | 74.5 (3, 59–97.6) | | 45.0 (2, -1–91) | 98.5 (2, 97–100) |
| Near-natural | 33.5 (6, 11.6–83) | | 60.8 (3, 6–96.5) | 64.0 (1, 64–64) | 54.6 (6, 6–93) | | | |
| Restored wetland | 38.0 (1, 38–38) | | 48.9 (3, 25.7–77.9) | 48.2 (2, 48–48.3) | 52.4 (2, 25.7–59) | | 34.9 (2, -4–73.8) | |
| Treatment wetland | 46.4 (40, -4–97) | 44.2 (5, 6.6–60.5) | 57.9 (18, 1.8–129) | 64.6 (11, -14–99) | 49.3 (38, 1.8–96.5) | 38.0 (5, -15.1–59.5) | 57.1 (10, 1.1–94) | 69.2 (16, 3.6–100) |

### Natural and near-natural wetlands

In natural wetlands it is difficult to identify inlet and outlet points hence there are proportionately fewer studies considering wetland efficiency in removing nutrients, sediments, and pesticides than in treatment/constructed wetlands. However, within the body of evidence, most studies in natural/near-natural wetlands have been conducted in the United States (n = 30) and China (n = 10), followed by Australia (n = 6). Studies of natural/near-natural wetlands varied from modelling the water quality improvement efficiency of redirecting polluted waters through natural wetlands (Lane et al., 2003), to monitoring the spatial and temporal variability in river-floodplain interactions (Primost et al., 2022), monitoring water quality improvement efficiency and nitrous oxide generation in seepage wetlands (Zaman et al., 2008), and studies re-routing agricultural drainage water through a forested wetland (Lindau et al., 1997).

From those natural and near-natural studies, as shown in Table 11 that reported on annual loading and removal rates of total nitrogen (TN) (n = 5 and n = 6 respectively), there was an average removal efficiency of 63% and 33% respectively. For total phosphorus (TP) the average removal efficiency of natural wetlands was ~74% (n = 3) and for near-natural wetlands was ~54% (n = 2). For total suspended sediments (TSS), natural wetlands had an average removal efficiency of 45% (i.e., accretion) (n = 2). From the body of evidence, natural and near-natural wetlands were reported to remove $NH_4^+$ the most efficiently (73% and 86%) and TSS the least, with two studies ranging from -1% to 91% (n = 2, natural wetlands only).

Figure 4 shows that in natural/near-natural wetlands, the removal effectiveness of nutrients is influenced by hydrology (n = 13), landscape context (n = 8), and vegetation (n = 8). One study provided information on the factors influencing pesticide removal efficiency of natural/near-natural wetlands, finding that removal efficiencies were influenced by sediments. Of the few studies investigating sediment removal efficiencies in natural/near-natural wetlands, five studies found removal efficiencies were influenced by hydrology, while two studies reported vegetation to be influential.

### Restored wetlands

Within the body of evidence, most wetland restoration studies have been conducted in the United States (n = 11) and Australia (n = 3). Studies of restored wetlands varied from regenerative stormwater conveyance (Thompson et al., 2018), ditch-filling and planting (Bruland et al., 2003), modelling the water quality impacts of 8,000 km$^2$ of wetland restoration (Evenson et al., 2021), to restoring wetland hydrology (Kahara et al., 2022) and adding carbon to increase nitrate removal of restored wetlands (Yang et al., 2019).

From the single study that provided annual loading and removal rates of TN, the removal efficiency was 38%. For TP the removal efficiency of restored wetlands for two studies was 26% and 52%, and for TSS, restored wetlands had removal efficiencies of -4% and 78% (n = 2). From the body of evidence, restored wetlands were reported to remove TP the most efficiently (52%) and TSS the least (35%), however this was based on limited studies.

Figure 4 shows that in restored wetlands, removal effectiveness of nutrients is influenced by hydrology (n = 3) and vegetation (n = 5). No studies investigated the pesticide removal efficiency of restored wetlands. Of the three studies providing information on the factors influencing sediment removal efficiencies in restored wetlands, climate (n = 1), management (n = 1), and nutrients (n = 1) were key.

### Treatment/constructed wetlands

For treatment/constructed wetlands, most studies have been conducted in the United States (n = 67) and China (n = 30). Studies of treatment/constructed wetlands varied from modelling the efficiency of treatment wetlands in reducing runoff from agricultural hillsides (Zhang et al., 2020a), to the water quality improvement efficiency of subsurface horizontal flow systems (de Caballos et al., 2001), constructed tidal marshes (Etheridge et al., 2015), riparian buffer strips and drainage ditches (Iseyemi et al., 2016; Schoonover et al., 2010) and identifying optimal sampling strategies for constructed wetlands (Moustafa & Havens, 2001). Only seven of the studies featured within the body of evidence looked at floating treatment wetlands (FTWs, e.g., Chance et al., 2020; Shahid et al., 2018; Wang et al., 2022b;

Yamasaki et al., 2022), and only three of these provided removal efficiencies for nutrients and pesticides (Pavlidis et al., 2022a; 2022b; Rigotti et al., 2021). From those treatment/constructed wetland studies that provided annual loading and removal rates of TN (n = 40), there was an average removal efficiency of 46%. For TP the average removal efficiency of treatment/constructed wetlands was 49% (n = 38) and for TSS, treatment/constructed wetlands had an average removal efficiency of 57% (n = 10). For pesticides, the average removal efficiency of treatment/constructed wetlands was 69.2%, and this is substantially lower than in natural wetlands (98.5% average pesticide removal efficiency), but is the highest average removal efficiency reported for treatment wetlands across all pollutants (range 38.04–64.6%). From the body of evidence, treatment/constructed wetlands were reported to remove $NH_4^+$ the most efficiently (~64%, n = 11) and $PO_4$ the least 38% (n = 5).

For treatment/constructed wetlands, removal efficiencies for all contaminants were found to be influenced by hydrology (nutrients: n = 22, pesticides: n = 4, sediments: n = 4) and vegetation (nutrients: n = 56, pesticides: n = 8, sediments: n = 6; Figure 4).

### Bioreactors

Relevant to the water quality improvement efficiency of nutrients, pesticides, and sediments, two studies were found each in the United States, China, and Australia (n = 6, Table 12). Data were provided for the efficiency of bioreactors in removing TN, $NO_3^-$, $NH_4^+$, TP and the pesticide Ametryn with maximum removal efficiencies of 80%, 98%, 68%, 55% and 66.2% respectively (David et al., 2015; Du et al., 2016; Hunt et al., 2008; Navaratna et al., 2012).

*Table 12. Types of bioreactors featured within the body of evidence and the number of bioreactor studies conducted according to country.*

| Bioreactor | Australia | China | United States |
|---|---|---|---|
| Aerated and non-aerated biofilm reactors | | 1 | |
| Column bioreactor | | | 1 |
| Eco-soil reactor | | 1 | |
| Membrane bioreactor | 1 | | |
| Tile woodchip bioreactors | 1 | | 1 |
| **Total** | **2** | **2** | **2** |

### Wetland type comparison

From the review of the literature here, Table 11 shows that nutrient removal rates are generally higher in natural wetlands and lowest in treatment wetlands. Pesticide removal is also relatively high in these systems. However, there are no studies on the pesticide/herbicide removal efficacy of wetlands in the GBR catchment area, only studies that measure concentrations in wetlands. Sediment can accumulate in restored wetlands and is most efficiently removed in treatment wetlands. These conclusions are also supported by other literature such as Forbes et al. (2012) which showed that nutrient removal rates are higher in natural wetlands and lowest in treatment wetlands. Wang et al. (2019) suggest that this is due to hydraulic loading variables and the size and configuration of treatment wetlands such as vegetated drains.

### Additional factors affecting water quality removal efficacy

*Secondary Question 4.7.1 – What are the key factors that affect the efficacy of natural/near-natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality and how can these be addressed at scale to maximise water quality improvement?*

Behind the values of contaminant removal efficiency, there are numerous factors to consider, such as season (e.g., Chen et al., 2015; Kröger et al., 2008; Lu et al., 2017), rainfall intensity (e.g., Chescheir et al., 1991; Etheridge et al., 2017), hydroperiod (e.g., David et al., 2015; Shukla et al., 2011), and land use (e.g., Liu & Tong, 2011; Satkowski et al., 2018) (see Figure 4). Ryder and Fares (2008) found variable water quality efficiencies among three natural/constructed wetlands in a Hawaiian watershed (TSS – 74 to 85%; TP -81 to -256%; TN -47 to 22%, $NH_4^+$ -53 to 23% and $NO_3^-$ -4 to 6%) – a result suggesting that, dependent on these contextual factors, wetlands can both export and/or process and retain nutrients. The variability in the aforementioned values was related to the engineering design being insufficient for the size of the contributing agricultural area. Wetlands can therefore be both highly efficient in their water quality improvement, e.g., removing up to 100% of pesticides and 95% of sediment loads in vegetated drains (Philips et al., 2021), but also inefficient, e.g., exporting TP (-11%), TN (-8.4%) and TSS (-4%) in restored wetlands (Jordan et al., 2003).

Understanding the factors that affect water improvement quality efficiency in wetlands is therefore crucial and provides important insight into the design requirements, maintenance, and expected improvements possible from a wetland site, and the broader values that might be enhanced or lost. Overwhelmingly, the major factors that affect water quality from this review were the vegetation community (extent of local species and maintenance; reported in 36% of studies – e.g., Bhomia & Reddy, 2018; Min et al., 2015; Zhao et al., 2012) and hydrology (control and residence time which can be modelled for local conditions; reported in 20% of studies – e.g., Kim et al., 2004; Knox et al., 2008; Sim et al., 2008; Wilcock et al., 2012; see Table 13). Both factors combined, if understood, controlled, and managed appropriately, would greatly assist the efficacy of wetlands for the objective of water quality improvement. Specifically, the high variation observed in removal efficiencies across all wetland types and contaminants is due to factors such as variations in wetland size, age and drainage area (e.g., Bason et al., 2017; Campaneli et al., 2021; Jia et al., 2019; Khare et al., 2019; Tanner et al., 2013), and whether sampling was conducted across all seasons, or singularly within the wet or dry season (e.g., O'Geen, 2006), as well as whether hydrology (e.g., retention time, rainfall, groundwater influence) was measured alongside water quality (Appelboom et al., 2008; Cai et al., 2017).

For pesticides, several studies sampled only during the wet season and many others do not provide this contextual information. This is problematic, as wetland hydrology and therefore water quality improvement efficiency varies between wet and dry seasons. Sampling in a single season therefore biases our understanding of a wetland's capacity for longer-term water quality improvement (e.g., Tanner et al., 2005; Zhao et al., 2019). Hydrology may be particularly important in the removal of soluble pesticides, such as neonicotinoids that break down in ultraviolet (UV) light, and so their removal efficiency may increase with longer residence time. For example, due to a high intensity rainfall event that reduced the residence time of experimental wetlands in Missouri, the removal efficiencies of three different herbicides (atrazine, metolachlor and glyphosate) were reduced. Low removal efficiencies in the experimental wetlands were also attributed to high pesticide loads and soil erosion (Lerch et al., 2017). As such, geology, soil composition and physicochemical condition are also key to the pesticide removal efficiencies of wetlands, with soils capable of sorbing nutrients and pesticides, but also capable of leaching nutrients and pesticides once saturated (e.g., Axt & Walbridge, 1999; Cao et al., 2018; Kao et al., 2002). This is especially important for organochlorine, organophosphate and synthetic pyrethroid pesticides that have low solubility in water and tend to bind with particulate matter and become deposited in sediments. Due to the low numbers of studies investigating wetland pesticide removal within GBR catchments, greater research effort is required in the region. Specifically, future research focus should be directed towards those pesticides known to have negative implications for coral reefs and other coastal habitats.

*Table 13. Summary of variables examined in the 206 studies that were identified as an influence on water quality improvement efficiency in wetlands. This is most relevant to the secondary question 4.7.1 of the Evidence Review.*

| Variables influencing water quality improvement efficiency | Count of studies from the body of evidence |
|---|---|
| Vegetation | 80 |
| Hydrology | 46 |
| Other | 22 |
| Landscape context | 13 |
| Environmental factors | 10 |
| Climate | 8 |

| Variables influencing water quality improvement efficiency | Count of studies from the body of evidence |
|---|---|
| Management | 8 |
| Nutrients | 8 |
| Sediments/Soil | 6 |
| Anthropogenic disturbance | 1 |
| Hydrology & vegetation | 1 |
| Sediments/Soil & Vegetation | 1 |
| Vegetation & Environment factors | 1 |
| **Grand Total** | **206** |

For nutrients, water flow rate and hydraulic residence time were paramount in determining wetland removal efficiency, with TN removed more effectively in static water relative to flowing, and $NH_4^+$ removal highest in high-flowing waters (e.g., Kröger et al., 2012; Mu et al., 2020; Yi et al., 2010). High variability in removal efficiencies of nutrients was also often due to variations in inflow and loading rates, inflow volumes and thus hydraulic residence time (Zhang et al., 2017), with longer studies that sample both wet and dry seasons, measuring both water quality and hydrological variables able to capture this variation (Jordan et al., 2003; Kaplan et al., 2011; Laterra et al., 2018; Moustafa, 1999; Niu et al., 2016). Vegetation presence/absence was also largely responsible for variability in nutrient removal efficiency (Lu et al., 2010; Menon & Holland, 2013), with one study finding efficiencies ranging from 59–65% in unvegetated plots and 86–88% in vegetated plots (Jacklin et al., 2020). The same study also found that alien and indigenous plant assemblages performed similarly in their water quality improvement efficiency. While species composition can result in variable removal efficiencies, the magnitude of variability relative to factors such as inflow volume/rate, hydraulic residence time, and vegetation presence/absence is an important consideration (Jacklin et al., 2020; Lu et al., 2014; Wang et al., 2019). The same applies to sediment removal efficiencies, with high and sustained removal efficiencies occurring due to small variations in wetland area, volume and residence time (Kaplan et al., 2011), and highly variable removal efficiencies the result of altered inflow and hydraulic residence time (Jordan et al., 2003; Kato et al., 2007; Niu et al., 2016). Vegetated treatment systems and buffer strips are effective at increasing sediment removal efficiencies (Arora et al., 2010), with efficiencies further increased in treatment/constructed wetlands through the addition of retention basins and sediment traps (Alemu et al., 2017; Phillips et al., 2021; Zhao et al., 2016). Plant community density and root density are also important variables in determining a wetland's water quality improvement efficiency, although this is not a linear relationship (Ibekwe et al., 2007; Lv & Wu, 2021; Shahid et al., 2018).

When measuring the water quality improvement efficiency of wetlands, it is important to take antecedent conditions into account, particularly following storm activity (Gall et al., 2018). For example, seasonal and long-term variations in soil moisture deficit and evapotranspiration can significantly impact wetland hydrology, leading to large variations in sediment removal efficiency among similarly sized storm events (Gall et al., 2018). In addition to the aforementioned factors, a number of variables have been described as important, but to a far lesser degree when compared to vegetation and hydrology, for example, landscape context (e.g., land use upstream of wetlands – 5% of studies), environmental factors including climate change (9%), sediment delivery and storage/accumulation (2%). Surprisingly, management actions such as maintenance were rarely mentioned as a contributing factor to reduced efficacy (7%), which is interesting given vegetation maintenance was considered as highly important. A range of other factors were highlighted (16%) including rubbish/trash accumulation, which provides important insight into the need to consider local nuanced conditions for each project site. A potentially important factor that was not identified from the tropical/subtropical literature examined here, is the need to consider the number and spatial pattern of wetlands within a watershed. This aspect has been found to impact wetland efficiency in temperate regions (e.g., Hansen et al., 2018). The landscape context of a wetland is important information that is not always reported within such studies.

There was only one study published that evaluated the role bioreactors have in processing nutrients in agricultural catchments within the GBR (Manca et al., 2021). Here, the authors found that bioreactors installed on a sugarcane farm in the wet tropics of north Queensland were effective at removing $NO_3^-$, with beds extracting a higher rate when compared to wall designs (Manca et al., 2021). Since completing the literature searches and data extractions for this Evidence Review, a second study has been published evaluating the role of bioreactors in processing nutrients in agricultural catchments within the GBR and but has not been included within the formal body of evidence (due to timing of publication). In this second study, the authors also installed denitrifying woodchip bioreactors on a sugarcane farm in the wet tropics of north Queensland and found that they reduced the concentration of nitrate-N in intercepted waters (average 41% reduction; Cheesman et al., 2023). Though removal rates were limited by nitrate-N availability, for example, a load reduction over the 2018/19 season was just 0.11 kg N $ha^{-1}$ $yr^{-1}$. The limited performance was considered to be due to the dynamic nature of nitrogen loads in this system as a high proportion of the annual nitrogen load occurs during the 'first flush' (the first rainfall event of the wet season) and therefore bypasses the system (refer to the nutrient transport and delivery characteristics for the GBR catchments in Question 4.5, Burford et al., this SCS for further information). The results highlight the fact that performance is a function of the hydraulic context of the catchment and the design of the structure (Cheesman et al., 2023). The efficacy revealed in Cheesman et al. (2023)is not included in Table 11 (only Manca et al., 2021), as the study was published outside the date range for inclusion in this review, but is included here as it is a valuable addition to the GBR literature.

Controlling water passage through wetlands and their engineering design can result in improved water quality efficacy, meaning wetlands that are larger could provide greater treatment opportunities (Birgand et al., 2016; Littlejohn et al., 2014; O'Geen et al., 2007). Evidence from the literature supports that appropriately sized wetlands (or using natural settings in an appropriate design), with sufficient residence time, could improve water quality outcomes (She et al., 2018). Similarly, Ji and Jin (2016), using modelling approaches, concluded that increasing water depth in wetlands increases retention time which improved water quality processing prospects.

The second major theme emerging after hydrology is the vegetation community.

- Some studies have combined both flow and vegetation communities in experiments to optimise the flow rate necessary for specific vegetation species (the premise is that longer residence time and more vegetation results in a higher processing rate of nutrients) and thus maximise water quality improvements (Wang et al., 2019). For example, Zhang et al. (2021b) found that TN removal efficacy in wetlands increased from 17.95% in unvegetated wetlands to 29.8% in vegetated wetlands; Tyler et al. (2012a) found that TN efficacy increased from 26.9% in unvegetated wetlands to 50% in vegetated wetlands; Sasikala et al. (2009) found that TN improved from 44% to 58.2% removal with vegetation, but this increased further to 67.4% with fluctuating water levels.
- The cover of vegetation in wetlands is also important, with excessive growth presenting a negative challenge for water quality objectives, with excessive aquatic weeds contributing to poor water quality conditions for aquatic species such as fish (Veitch et al., 2007).
- In grass swales adjacent to riparian areas, studies revealed that larger and intact swales were more effective in slowing flow sufficiently for improved water quality (particularly for nutrient species and some pesticides; Welsh et al., 2019; Yorlano et al., 2022). For example, Alemu et al. (2017) showed that increasing buffer strip widths along riparian areas from 3 to 10 m improved TP removal efficiency from 47% to 99%, TSS from 76% to 94% and nitrate from 50% to 85%.
- She et al. (2018) also present data suggesting that ditches with vegetation in the landscape are not effective for water nutrient processing unless they are appropriately large enough for the size of the contributing catchment.
- A number of studies investigated local macrophyte species and their ability to process nutrients, with some species found to be more efficient than others (Ibekwe et al., 2007; Rigotti et al., 2021).
- Mature tree species are also capable of removing nutrients from within the edge areas of wetlands, given that wetlands can expand and contract depending on local hydrology and rainfall (Adame et al., 2019a).
- Vegetation cover is important in reducing nutrient runoff from agricultural hillsides (Zhang et al., (2020b).

Wetlands are also places where pesticides and herbicides can be detected (refer also Question 5.1, Negri et al., this SCS for further detail), and many studies have examined pesticide and herbicide levels as part of routine monitoring, or to detect which of these chemicals are present (Vymazal & Březinová, 2015). In the review, the scope was confined to evaluation between the inlet and outlet as a way to decipher efficacy. This resulted in the inclusion of only a small number of studies, and for each, they showed a general improvement: chlorpyrifos (between 23 and 91.5%; Moore et al., 2002; Werner et al., 2010), permethrin (50%; Moore et al., 2002); atrazine (89%; Locke et al., 2011), fluometuron (81%; Locke et al., 2011), bifenthrin (96.91%; Bennett et al., 2005), and Lambda-cyhalothrin (98.76%; Bennett et al., 2005).

### Limitations in monitoring and evaluation

The time over which monitoring or research experimentation occurs can be particularly important in environmental science studies, owing to the vagaries of seasonal, climate and interannual changes in conditions. For wetlands, another important context-dependent factor is that they are dynamic over spatial scales (e.g., depth, edge/centre) which also requires consideration when designing an efficacy evaluation program. In the review here, the duration of water quality studies was variable, and there was no obvious logic to the timescale imposed (but is likely that funding is the causal factor resulting in the study duration and even the starting point of the evaluation). Studies ranged from a single sampling event (Liu et al., 2013), through to several years (Ham et al., 2010; McJannet et al., 2012b), or up to 38 years in some cases (Sánchez-Carrillo et al., 2021). A breakdown of the average number of years of monitoring and evaluation were: bioreactors (n = 5, 0.12 yrs); natural wetlands (n = 19, 6.6 yrs); near-natural (n = 37, 5.6 yrs); restored wetlands (n = 18, 2.1 yrs); treatment wetlands (n = 121, 2.1 yrs); and combined wetland studies (n = 9, 0.89 yrs). Overall, the average study duration was 2.9 yrs (n = 217).

Seasonal variation is also an important consideration in monitoring and evaluation. Of the studies examined, 36% reported data collection in both wet and dry seasons, ~2% in the dry season only and 5% in the wet season only. The remaining 57% of studies did not provide sufficient data to clearly decipher the seasons sampled, which means the data are unable to be examined in the context of seasonal influences and that the interpretation of the conclusions presented in these studies is limited. Of the studies conducted over both the wet and dry seasons, 26% (n = 19) and 25% (n = 18) found that vegetation and hydrology respectively affected the water quality improvement efficiency of wetlands. Of those studies conducted in the dry season only, nutrients (n = 1), sediments (n = 1), and vegetation (n = 1) were found to affect water quality improvement efficiency and those conducted solely in the wet season found hydrology (n = 5) and vegetation (n = 3) to affect water quality improvement efficiency. This perhaps illustrates the importance of sampling representatively across both wet and dry seasons to effectively understand wetland water quality processes, function, and removal efficiencies long-term.

Another important aspect of the evaluation program is knowing how long the wetland had been established before the evaluation commenced. This information is important for evaluating treatment/constructed wetland efficiency, as the more mature the wetland is prior to monitoring, the higher the chance that it has accumulated carbon – which is necessary for bacterial processing of available nutrients (Martínez et al., 2018). Moreover, maturation over time is required for constructed/treatment wetlands to reach a more stable state of equilibrium (Mitsch & Gosselink, 1993). Only a single study outlined that water sampling commenced in a wetland that was less than 1 year since construction (Ham et al., 2010). Providing these details in future studies would be a useful contextual addition for managers.

Wetlands engineered in the studies examined ranged in size (and depth) which is generally a function of the topography and connectivity with downstream waterways. Most wetlands in this review were less than 1 $km^2$ in total size (Jordan et al., 2003), with an average size of approximately 2–3 $km^2$ (Adame et al., 2019a) and the largest being a tidal freshwater marsh in South Carolina that was 9 $km^2$ (Neubauer et al., 2019). Unfortunately, wetland size was only reported in 7% of the studies examined. Basic site information relating to the location and dimensions of study wetlands, their spatial pattern within a watershed, as well as the presence and number of other, connected wetlands, should be a standard set of details reported in publications. Of particular interest, but omitted largely by the subtropical/tropical body of evidence, is the relationship between these variables and the size and shape of wetlands, as well as the cumulative effect of multiple wetlands within a watershed.

Measuring or reporting information on the hydrology along with the water quality information occurred in 47% of studies, while 44% of studies focused only on water quality with no reference to hydrology, while 7% of studies only examined wetland hydrology and not water quality conditions.

### Findings relevant to future evaluation of efficacy

The sampling strategy, how samples are collected, and frequency of sampling, are also important considerations in field monitoring campaigns. From the evidence in this review, there are broad and varying ways that samples are collected, in the spatial and temporal ranges measured, and the field and laboratory equipment used. The range in different approaches does make a review of approaches difficult, and to give an overall impression of this variation, some examples are provided below:

- Water samples collected twice weekly from influent, midpoint, and effluent of wetland cells for laboratory analysis (Borges et al., 2009).
- Weekly water samples collected as surface grabs at the inflow and outflow of the target wetland (Ardón et al., 2010; Díaz et al., 2012).
- Positioning a water quality probe network through the wetland with pipes pumping samples to a central chamber unit for collection (Birgand et al., 2016).
- Water samples measured at the inlet and outlet to a wetland using auto-samplers and sensors programmed to collect samples to represent the hydrograph (McJannet et al., 2012a; 2012b).
- Using data loggers, pressure transducer combination weirs, and automatic water samplers to conduct inlet and outlet sampling (Kovacic et al., 2000).
- Determining sediment deposition rates using horizon markers positioned along the wetland system (Noe & Hupp, 2009).
- Groundwater sampling in wells adjacent to wetlands using grab samples from bores (Messer et al., 2012).
- Groundwater sampling using piezometers and high-frequency loggers to characterise water quality relative to wetland surface water quality collected monthly (Matteson et al., 2020).

There were also a number of manipulative and mesocosm experiments designed to characterise nutrient uptake and processing rates (Simonin et al., 2018) in wetland sediments and plants (emergent and floating) (Adame et al., 2021; Tyler et al., 2012a).

The water quality parameters measured in wetlands were variable and likely a response to the research question and experimental design used. Of the studies examined here, the most common nutrient forms were total nitrogen (54%) and total phosphorus (19.9%). The other common parameters were nitrate ($NO_3^-$; 10.7%), ammonium ($NH_4^+$; 7%), total suspended solids (6%) and dissolved inorganic nitrogen and phosphate ($PO_4^{3-}$; 1.8%). In addition to these, there were many other water quality variables measured including dissolved oxygen, pH, biological oxygen demand, chemical oxygen demand, a range of pesticides and other nutrient forms (e.g., dissolved organic nitrogen), various heavy metals, chlorophyll-*a*, salinity and temperature. Overlooked by the search methods used in this Evidence Review however, are urea-based pesticides and fertilisers, which are increasingly used in crop farming systems. Urea-based chemicals are of particular concern, as urea is an important nutrition source for harmful algal bloom species, and so these products may have greater, negative effects upon the health of coastal waters relative to traditional fertilisers and pesticides. Within the body of evidence, only one study addressed the efficacy of constructed wetlands in the treatment and removal of urea-based pesticides, finding low removal efficiencies of ~50%, relative to other pesticide groups (60–100% removed; Vymazal & Brezinova, 2015). Therefore, the efficiency of wetlands in removing urea-based agricultural products is an important research area, requiring policy and management consideration.

Twenty-one percent of studies had an experimental design where water sampling occurred at both the defined inlet and outlet to wetlands, with most of these in engineered treatment wetlands.

### 4.1.2 Recent findings 2016–2022 (since the 2017 SCS)

The 2017 SCS contained a section on wetland condition and produced a review consensus which was supported by the few available published data specifically within the GBR catchments. That review provided a summary account of the components and processes occurring in wetlands in Queensland and provided a risk review of emerging challenges and threats to wetland services. Since the 2017 SCS, nine additional works have been produced concerning the water quality improvement capacity and efficiency of wetlands in the Great Barrier Reef catchment (Adame et al., 2019a; 2019b; 2021; Buelow & Waltham, 2020; Kavehei et al., 2021; Manca et al., 2021; Wallace et al., 2022; Waltham et al., 2020a; 2020b). While these works have improved our understanding of the role and efficiency of Queensland wetlands in regulating water quality, relative to the value of the Great Barrier Reef and the level of investigation internationally, there remains more research investigation to complete. In particular, wetland efficacy in different settings requires more research (i.e., land use such as grazing or banana plots, climates such as wet and dry tropics, or geology with different soils), which is supported by this current Evidence Review.

Methods used to examine the processing of nutrients in wetlands of the GBR have included sediment and aquatic macrophyte nitrogen isotope enrichment experiments (Adame et al., 2019a; 2021; Kavehei et al., 2021), installing autosamplers to catch inflow and outflow events (McJannet et al., 2012b; McKergow et al., 2004; Wallace et al., 2022), grab and groundwater sampling (Kavehei et al., 2021; Mayo et al., 2018; McJannet et al., 2012b). Within the body of evidence, only two studies measured and modelled water and nutrient balances in GBR wetlands (McJannet et al., 2012a; Wallace et al., 2022), while Adame et al. (2019b) modelled water quality processing potential over a larger floodplain scale. Overall, the number of suitable comprehensive studies within the GBR is very small and more of this type of research is needed to quantify the efficacy of a range of wetland types in both the dry and wet tropics. In addition, there are no studies on the pesticide/herbicide removal efficacy of wetlands in the GBR.

### 4.1.3 Key conclusions

The key conclusions from this review are that there is a major constraint in our understanding of the specific role of wetlands in processing nutrients, sediments, and pesticide/herbicides within the GBR catchment area. This is particularly apparent when compared to the evidence and research reviewed here, which mainly includes overseas published studies. Investment into monitoring water quality conditions in nearshore and offshore waters is extensive, supported via a large, coordinated program (Marine Monitoring Program) with the data used in a range of reporting and management tools. The same investment is required to understand and monitor the performance of wetlands in providing water quality services, which would require an expansion of the scope and geographical coverage of the Paddock to Reef Wetland Condition Monitoring Program. However, it is acknowledged that following a values-based approach to wetland conservation, protection, and restoration, wetlands are also important for providing for a range of other services (e.g., biodiversity, cultural services etc.). While there has been a small increase in the number of focused research and evaluation projects into wetlands in the GBR, supported via national and government funding rounds (e.g., NESP), further research within the GBR catchment area is required. Specifically, increased research effort is needed to determine the efficacy of a range of wetlands in water quality improvement, and on how to scale up individual studies to achieve broader objectives. Investment into wetland-focused studies will also allow managers to examine and understand the level of uncertainty in their efficacy, and how to maximise efficacy (e.g., which wetland plant species are most suitable, what is the residence time necessary to maximise sediment and nutrient removal, and what is the role of groundwater in wetland water quality processing).

### 4.1.4 Significance of findings for policy, management, and practice

From this Evidence Review, the greatest proportion of published studies on wetlands for water quality treatment are from the United States and China. Studies in Australia and the GBR are far fewer in total, supporting the need for this review to draw on studies from abroad. There is not yet enough data to assess spatial and temporal trends in wetland efficacy in the GBR, whereas some published studies from overseas are supported by data collected over several decades. By comparison, water quality studies in GBR wetlands are relatively new and short-term.

Further evidence is required to increase confidence in the potential pollutant removal efficiencies of wetland treatment systems in agricultural landscapes in the Great Barrier Reef catchment area. This review has identified several major knowledge gaps for further research that could contribute to improved confidence in the knowledge base. These include:

- Improving our understanding of the spatial (wet and dry tropics) and temporal drivers of variability in water quality improvement efficiency reported in overseas studies, within the context of the GBR catchment area. This includes better/more frequent data collection/data resolution and modelling of the hydrology and water cycle in wetlands.
- Better characterisation of organic nutrients in wetlands.
- The characterisation of long-term changes in wetland sediment nutrient stores which will allow more robust estimates of the timescales over which management interventions are likely to be effective.
- Inclusion of hydrological modelling in all wetland projects, which includes representation of 'first flush' events which are known to often deliver the greatest proportion of pollutants to the GBR, to best understand the potential processing of nutrients, sediments and pesticides in wetlands.
- While treatment wetlands can provide water quality improvement prospects, there is a need to understand how the site-based water quality improvements translate to the overall catchment load.

There is also a need for ongoing monitoring of the efficacy of wetlands and their contribution to pollutant removal in the landscape (i.e., inflow versus outflow), which should align with the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) and the GBR Marine Monitoring Program for Inshore Water Quality (MMP WQ). Such a program would provide managers with a deeper understanding of the efficacy of wetlands in the GBR catchment area and would assist with designing experimental research and monitoring programs to fill the major gaps in knowledge.

#### 4.1.5. Uncertainties and/or limitation of the evidence

A summary of the key uncertainties and/or limitations in the evidence base is presented below:

- The number of studies relating to wetlands and water quality improvement efficacy is limited in the GBR, particularly when compared to other wetlands globally (e.g., the Everglades and Mississippi delta and catchment in the United States, and the Yellow River and floodplain, alongside regional and coastal areas of China).
- There is a wide range of approaches to monitoring water quality outcomes from wetland systems, including a range of sampling equipment (e.g., flow gauges, auto-samplers, loggers, grab samples and piezometers), sampling frequencies, study duration, time of year (i.e., wet or dry season), wetland size, and additional important information (e.g., vegetation cover or hydroperiod). The inclusion of all these details in publications, as supplementary, would assist with comparisons and provide greater context for managers to consider when planning projects.
- While the Paddock to Reef Wetland Condition monitoring that began in 2018 is a fruitful starting point (Australian & Queensland Government, 2022), it is not yet spatially and temporally incomparable to monitoring efforts overseas. This is different to nearshore and inshore water quality monitoring undertaken as part of the Marine Monitoring Program (MMP – see Question 4.1, Robson et al., this SCS). Such long-term datasets would allow researchers to establish baselines, provide insight into the importance of wetland age and maturation, provide a better understanding of the influence of long-term climatic change and understand when management intervention is required and likely to be most effective.
- The approach of collecting water quality samples at the defined inlet and outlet to wetlands, and building a water balance model for wetland sites, is not very common and is often carried out in a piecemeal way. Studies that do not include relevant methodological details or model the water balance over a reasonable period (several years) make interpretation of the water

quality improvement efficacy difficult. Further, consideration and evaluation of additional water sources in wetlands, particularly groundwater, are rarely considered or included, which further limits the interpretation of water quality data and the ability to assess the full water and nutrient balance.

- Designing a treatment wetland that is appropriate for the feeding catchment size is rarely considered or examined. Moreover, elements of wetland design such as vegetation, deep water zones, and maintenance requirements are generally overlooked.

## 4.2 Contextual variables influencing outcomes

A summary of the contextual variables that are influencing the question outcome or relationship is outlined in Table 14.

*Table 14. Summary of contextual variables for Question 4.7.*

| Contextual variables | Influence on question outcome or relationships |
|---|---|
| Temperature | In an experimental study investigating surface water temperature impacts on coastal wetland denitrification, $NO_3^-$ removal processes were negatively affected by colder temperatures (5–14 °C), but $NO_3^-$ removal was almost three times greater in the warmer temperature treatment (20 °C; Bowes et al., 2022). Removal of TN and $NO_3^-$ have also been found to show seasonal variation, with removal efficiencies increasing during warmer summer months in vegetated ecological ditches in China (Chen et al., 2015). The relationship between removal efficiencies of constructed wetlands in North Carolina, US and mass inflow was affected by temperature and nitrogen species, with $NO_3^-$ removal correlated to inflow in the warmer months and Ammonia removal correlated to inflow during the cooler months (Hunt et al., 1999). The influence of temperature on wetland water quality improvement efficiency may potentially be affected by changes in global temperatures as a result of climate change. |
| Storm events | Storm activity results in greater catchment load runoff that could be channelled through wetlands for treatment. As a result of runoff from storm events, pollutants such as atrazine also increase in concentration. Natural wetlands in North Carolina, US were found to remove >80% of nitrogen, 91% of total suspended sediments, 59% of total phosphorus, and 100% of the atrazine pollution that resulted from several storm events (Kao et al., 2001; 2022; Kao & Wu, 2001).<br><br>According to the IPCC Sixth Assessment Report (2023), storm activity, extreme weather events such as cyclones, and heavy precipitation events have likely increased in frequency and intensity as a result of global warming and will continue to increase in frequency and intensity under further warming. Whether the existing network of wetlands (e.g., their size and hydrology) is appropriate for this future climate variability is unknown. However, in modelling recent and projected future climate change scenarios (namely changes in temperature and rainfall patterns), Schmidt et al. (2019) found that agricultural best management practices (i.e., treatment wetlands, bioreactors, and vegetated buffer strips), exhibited reduced removal efficiencies of total nitrogen, total phosphorus, and sediments due to 'more intense runoff events, biological responses to changes in soil moisture and temperature, and exacerbated upland loading'. |
| Hydrology | Hydrology in wetlands is an important attribute to understand and examine in any water quality project. Without this understanding, the water quality data are difficult to impossible to comprehend. From the review here, many studies have included at least some hydrological data, but many do not. An example of a detailed hydrological and water quality study in the GBR catchment used auto-samplers on the inlet and |

| Contextual variables | Influence on question outcome or relationships |
|---|---|
| | outlet to the wetland, collecting water samples across the hydrograph (McJannet et al., 2012b). This approach is complex to set up but generates a complete understanding of water quality changes over multiple years, whereas grab samples (which are commonly used) will generally miss the first flow and peak flow stages, which are necessary in developing event mean concentrations.<br><br>Examining all water source inputs into wetlands is also critical. The least well-known is groundwater, which can be a persistent source of nutrients into or out of wetlands and is generally overlooked in many studies and models (Messer et al., 2012). There has been some effort to understand the contribution of groundwater to nutrient process modelling in wetlands, but this should become more standard practice in future projects (Kavehei et al., 2021; Wallace et al., 2022). |
| Vegetation | Vegetation in wetlands, including riparian edge zones, is important in processing nutrients and slowing flow to facilitate sediment deposition and denitrification. This has been shown in many studies (e.g., Aust et al., 2012; Cui et al., 2020; Tyler et al., 2012b). Mature trees in wetlands have been also shown to be important in processing nutrients in wetlands (Adame et al., 2019a). Vegetation communities in wetlands can be floating, emergent or submerged, and there has been some species-specific investigation into the nutrient removal capacity of local species in wetlands (Zhang et al., 2016). These results have generally shown that different species have different nutrient processing efficacies (Moore & Locke, 2020; Nifong & Taylor, 2021; Rodrigo et al., 2018). Developing nutrient and sediment processing potential for local aquatic vegetation species would assist with modelling the efficacy of wetlands in improving water quality outcomes. |
| Nutrients and sediments | In determining wetland water quality improvement efficiencies, it is important to understand and quantify pollutant loading, as this can significantly determine water quality outcomes (Zhao et al., 2020). For example, in mesocosm experiments subject to wet-dry cycles, mesocosms with higher P loading lead to higher P flux, compared to mesocosms with lower P loading rates (Moustafa et al., 2012). Nutrient concentrations within a wetland can also influence water quality improvement efficiency, with the ratio of carbon to nitrogen found to have a significant positive relationship to nitrogen removal efficiency (Nsenga Kumwimba et al., 2018; Zhang et al., 2022). |
| Invasive species | The current extent and potential future spread of invasive species is currently an expensive challenge for landholders and managers and will likely continue to be a challenge in the future. Currently, wetland systems are largely degraded with excessive aquatic weeds, and those that aren't have a regular program of maintenance (either physical removal of water weeds or spraying) in place. These weeds, under excessive conditions, can have impacts on water quality, including reduced dissolved oxygen and elevated temperature cycling (Waltham et al., 2020a) and can impact nutrient removal efficiencies (Liu et al., 2013; Veitch et al., 2007). |
| Maintenance | The maintenance of wetlands in terms of removing excessive weeds, sediment accumulation, rubbish, and invasive species is critical. Without a long-term plan of maintenance that includes future work costs, protection of wetland habitats will inevitably be compromised. For example, aquatic weed removal in a small creek on the Burdekin floodplain was not followed with a plan to continue weed removal, resulting in initially improved water quality conditions (e.g., dissolved oxygen concentrations) deteriorating again (Waltham et al., 2020b). The only example of a long-term maintenance plan has been developed via a riparian management agreement, where annual funding from landholders, water board, Regional Natural |

| Contextual variables | Influence on question outcome or relationships |
|---|---|
| | Resource Management group, and local Council allowed weed removal to continue for more than 20 years (Waltham et al., 2020a). In constructed wetlands, maintenance is necessary to ensure algal loads are controlled and that dissolved oxygen levels are maintained for local fish populations (O'Geen, 2006). For any wetland project, either the construction of treatment wetlands or the restoration of natural or near-natural settings, a long-term maintenance plan is critical. |

## 4.3 Evidence appraisal

### Relevance

The relevance of the overall body of evidence was Moderate (5/9). The relevance of the body of evidence to the question for the study approach and reporting of results, spatial and temporal relevance were each rated as Moderate, scoring 2.1, 1.7, and 1.6 out of 3 respectively. Of the 238 articles included in the review of Question 4.7, 26 were given a High score for overall relevance to the question, 134 were ranked as Moderate and 78 as Low. Thirteen percent (30 of 238) of studies included in the review had a High spatial relevance score, 40% (96 of 238) were rated as Moderate and 47% (112 of 238) had a Low spatial relevance score. As for temporal relevance, 36 studies (15%) were ranked with High temporal relevance, 71 studies as Moderate (30%) and 131 studies as Low (55%). In the context of this question, this means that while the content of many studies was relevant to answering Questions 4.7 and 4.7.1, they have moderate to limited spatial and temporal generalisability. Within the body of evidence, the reduced spatial and temporal generalisability is due to the high volume of short-term experimental studies included (see Table 15). While the inclusion of experimental studies limits the spatial and temporal generalisability, these studies provide valuable insight into the mechanisms driving water quality improvement efficiency in wetlands.

*Table 15. Summary of study types from the 238 studies used to address Questions 4.7 and 4.7.1 of the Evidence Review.*

| Study type | Count of studies from the body of evidence |
|---|---|
| Conceptual | 2 |
| Experimental | 66 |
| Experimental mesocosm | 42 |
| Modelling | 33 |
| Observational | 67 |
| Observational & Experimental mesocosm | 2 |
| Observational & Modelling | 2 |
| Observational, Experimental & Modelling | 1 |
| Review | 6 |
| Theoretical | 17 |
| **Total** | **238** |

### Consistency, Quantity, and Diversity

Due to the limited number of studies conducted within the GBR catchment area, the search was expanded to include studies conducted within tropical and subtropical climates in locations outside of the GBR. As a result, a high number of studies comprise the body of evidence (n = 238), of which 45% (108 of 238) are purely experimental (experimental studies and mesocosms) and 14% (n = 33) are model-based. The high number of modelled or laboratory studies may impose some limitations regarding the application of results to 'in-field' contexts but help to inform secondary question 4.7.1. Twenty-eight percent of studies (n = 67) within the body of evidence are based on field-collected data and are therefore of greater relevance to question 4.7. Despite the predominance of experimental and modelling studies within the body of evidence, the diversity of the body of evidence was rated as High and the consistency as Moderate, due to the number and variety of studies included and the level of agreement among them (see Table 13 and Table 15). Although the body of evidence used is both substantial and comprehensive, in excluding temperate studies a large portion of the published literature has not been reviewed. Therefore, in future, studies from temperate climates could be included to try to fill the knowledge gaps from the limited number of studies conducted within the GBR. While it is conceivable that many of the same challenges may have been also identified under a more comprehensive review featuring temperate studies (e.g., hydrology, vegetation, and maintenance), other learnings and considerations might have arisen that would be important to consider in this Evidence Review.

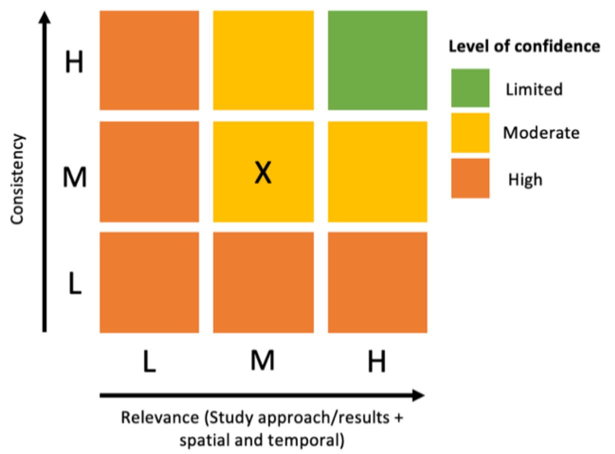
### Additional Quality Assurance (Reliability)

The overall internal validity of the body of evidence was high, with 88% of studies rated as 'High' and 12% rated as 'Low'. Authors have therefore placed less emphasis on the few studies rated as 'Low'. It is acknowledged that a single perfect paper does not exist and that there are many logistical, financial, and other restraints to experimental design and execution. Particularly for wetlands, the level of replication is often very low, as higher levels of replication are mostly unfeasible, impractical, and prohibitively costly. Therefore, pseudoreplication can be unavoidable and is often an accepted norm in studies of wetland water quality; this was an important consideration when rating studies for internal validity.

### Confidence

Twenty-eight percent of studies (n = 67) within the body of evidence are based on field-collected data and are therefore of greater relevance to question 4.7 (e.g., than theoretical and/or experimental studies), as field-based sampling and measurement is the most accurate way to determine water quality improvement efficiency (see Table 15). Despite the predominance of experimental and modelling studies within the body of evidence, the diversity was rated as High and the consistency as Moderate, due to the number and variety of studies included and the level of agreement among them (see Table 13 and Table 15). Due to the moderate relevance, consistency and diversity of the studies included, the overall confidence within the body of evidence is 'Moderate' (Table 16).

*Table 16. Summary of results for the evidence appraisal of the whole body of evidence in addressing the primary question. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency. The final row summarises the additional quality assurance step needed for questions using the SCS Evidence Review method.*

| Indicator | Rating | Overall measure of Confidence |
|---|---|---|
| **Relevance (overall)** | Moderate |  |
| -To the Question | Moderate | |
| -Spatial | Moderate | |
| -Temporal | Moderate | |
| **Consistency** | Moderate | |
| **Quantity** | High (238 studies) | |
| **Diversity** | High (45% experimental, 28% observational, 14% modelling, 7% theoretical, 3% mixed and 3% reviews) | |

| Indicator | Rating | Overall measure of Confidence |
|---|---|---|
| **Additional QA (Reliability)** | High | • Most studies (88%) rated High in the reliability assessment, with only 12% rating Low.<br>• The common causes of 'low' reliability were due to the high proportion of experimental and experimental mesocosm studies included within the body of evidence.<br>• Studies given a 'low' reliability rating were identified during the synthesis stage, with less emphasis being placed on those findings. |

## 4.4 Indigenous engagement/participation within the body of evidence

The inclusion of Indigenous groups in the design of wetland monitoring and restoration of these important ecosystems is becoming increasingly recognised in ensuring projects fulfil broad objectives and expectations. There were no studies, to the best of the authors' knowledge, that included at least some level of input from Indigenous groups.

## 4.5 Knowledge gaps

A summary of the proposed knowledge gaps is outlined in Table 17.

*Table 17. Summary of knowledge gaps for Question 4.7.*

| 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 |
|---|---|---|
| Wetland hydrological dynamics over multiple years. | What is the residence time of water in different wetland types and how does this vary in time? | This information would allow catchment wide wetland efficacy to be assessed and assist in the design of treatment wetlands and restoration of natural and near-natural wetlands. |
| Water quality conditions under different hydrograph periods. | What does the shape of the nutrient and sediment concentration graph look like for different land uses and rainfall event sizes? | These data would assist the design of treatment wetlands and restoration of natural and near-natural wetlands. |
| Dissolved oxygen cycling in wetlands. | What is the optimal range of dissolved oxygen concentrations necessary to maximise nutrient processing in wetlands? What are the wetland requirements to optimise these desirable dissolved oxygen concentrations? | Designing treatment wetlands and restoration of natural and near-natural wetlands. |
| Sediment particle size distribution in wetlands. | To what extent do wetlands capture and retain sediments from flow events? What is the distribution of sediment (and particulates) particle sizes stored in, and passing through wetlands? | Improved understanding of the sediment accumulation rates in wetlands. |

| 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 |
|---|---|---|
| Vegetation specific nutrient and sediment processing potential. | To what extent do native wetland aquatic species provide water quality improvement? What density and/or % cover of vegetation is most effective for water quality improvements? | Knowledge on the specific role each wetland plant species has in improving water quality. These data would be used in modelling efficacy and for cost-effective assessments. |
| Engineered treatment wetlands. | What is the optimal sized wetland to treat catchments, for each dominant land use in the wet tropics? What is the optimal sized wetland to treat catchments, for each dominant land use in the dry tropics? What role would bioreactors have in the landscape in providing water improvement in agricultural areas? | Model development for effective design and construction for land use and environmental conditions in GBR catchments. This model design could be used in catchment scale monitoring to back calculate how many wetlands are needed, among other land use strategies, to achieve water quality targets. Cost benefit analysis could be completed. |
| Groundwater contribution to water balance and nutrient processing in wetlands. | What is the degree of interaction between groundwater and surface waters in wetlands, and how does this interaction change over spatial-temporal scales in the GBR? What are the drivers of groundwater contribution to wetlands and how does this change with land use, land use change and in restoration of wetland ecosystems? | Groundwater contribution to wetlands is poorly understood, even overlooked, in studies in the GBR, but also more broadly. Modelling the contribution of groundwater to wetlands is complex and can vary over complex spatial-temporal scales. |
| Floating treatment wetlands (FTW). | How does the removal efficiency of floating treatment wetlands compare to *in situ* constructed/treatment wetlands? What is the potential for FTW use in the tropics? How is the water quality improvement efficiency of FTWs maximised? | There is evidence elsewhere that FTW can treat nutrients. Pilot studies are needed to determine their utility and application in the tropics. |
| Epibenthic algal mats. | Do epibenthic algal mats improve the water quality removal efficiency of natural/restored/ treatment/constructed wetlands? | Epibenthic algal mats are highly productive and may contribute to the water quality improvement efficiency of wetlands. |

## 5. Evidence Statement

The review of the evidence for **Question 4.7** was based on 238 studies, undertaken in tropical and subtropical locations and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (45% experimental, 28% observational, 14% modelling, 7% theory-based, 3% mixed and 3% reviews), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

**Summary findings relevant to policy or management action**

The focus of this review was the efficacy of natural and near-natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in water quality improvement (nutrients, sediments and pesticides) in agricultural landscapes. Global evidence has revealed that wetlands can process, retain and in some cases export nutrients (dissolved and particulate) and sediments from multiple land uses, with a wide-ranging capacity for pollutant retention. However, there are few peer reviewed studies that comprehensively measure or model their efficacy for water quality improvement in the Great Barrier Reef catchment area. Wetlands are highly dynamic ecosystems, and efficacy can be variable, affected by local conditions such as soils, topography, hydrology, climate, land use and vegetation communities. Critical factors for optimising the efficacy of water quality improvement include: the presence and maintenance of vegetation communities; hydrological characteristics including the wetland size relative to the contributing catchment area, flow rate, loss pathways and water residence time; and the type and input concentration of the targeted pollutant. The establishment of long-term and values-based whole-of-system management plans are also essential and must include adequately resourced and regular monitoring on the performance, health and function of the wetlands and associated flora and fauna, and long-term maintenance plans. Global evidence shows that natural and near-natural wetlands are typically more effective at nutrient and pesticide removal than constructed or restored wetlands, and that sediment is often retained in wetlands but can be remobilised in large flow events. Therefore, ensuring the long-term protection and health of existing natural and near-natural wetlands is critical. Further evidence of the efficacy of wetlands for pollutant management in agricultural landscapes is needed to increase confidence that wetlands could be used as a water quality improvement tool for managers and landholders in the Great Barrier Reef catchment area.

**Supporting points**

- Research on the efficacy of wetlands in terms of water quality improvements has largely occurred in the United States (49% of total studies examined) and China (18%), with very few studies in Australia (6%, n = 15), of which 13 were from the Great Barrier Reef catchment area. The parameters assessed also vary: 72% of studies measured nutrient concentrations, 8% pesticide concentrations and 2.5% sediments; the remainder examined various combinations of these pollutants.
- While local studies have measured denitrification rates in wetland soils and plant nutrient processing rates, it is not possible to derive long-term nitrogen removal from these data or assess wetland performance without knowledge of the wetland hydrology (mainly residence time). There are no studies that measure the pesticide/herbicide removal efficacy of wetlands in the Great Barrier Reef catchment area, only studies that measure *in situ* concentrations.
- The evidence demonstrates high variability in nutrient, sediment and pesticide removal efficiency between wetland types and locations within agricultural landscapes. This is illustrated by the range of efficiencies for parameters including total suspended sediments: -4–94%; total nitrogen: -4–97%; total phosphorus: 1.8–97.6% and pesticides: 14.3–100%. These differences are strongly driven by the vegetation community (extent and maintenance; reported in 36% of studies) and hydrology (control and residence time; reported in 20% of studies). The mean efficacy and variability between wetland types is also highlighted (note that those with less than 5 studies have low confidence):

  - For natural wetlands: total nitrogen reduced by 63.5% (5 studies, range 27–96.4%), total phosphorus reduced by 74.5% (3 studies, range 59–97.6%), total suspended sediment reduced by -45% (2 studies, range -1–91%) and pesticide reduced by 98.5% (2 studies, range 97–100%).
  - For near natural wetlands: total nitrogen reduced by 33.5% (6 studies, range 11.6–83%), total phosphorus reduced by 54.6% (6 studies, range 6–93%) and there were no results for total suspended sediments or pesticides.
  - For restored wetlands: total nitrogen reduced by 38% (1 study), total phosphorus reduced by 52.4% (2 studies, range 25.7–59%), total suspended sediments reduced by 34.9% (2 studies, range -4–73.8%) and there were no results for pesticides.
  - For treatment wetlands: total nitrogen reduced by 46.4% (40 studies, range -4–97%), total phosphorus reduced by 49.3% (38 studies, range 1.8–96.5%), total suspended sediments reduced by 57.1% (10 studies, range 1.1–94%) and pesticide reduced by 69.2% (16 studies, range 3.6–100%).
  - For bioreactor systems: total nitrogen reduced by 80% (1 study), there were no results for total phosphorus or total suspended sediments, and pesticide removal was 47% (2 studies, range 14.3–100%).
- There is no standard approach for monitoring and evaluating the efficacy of wetlands for water quality improvement in the Great Barrier Reef catchment area. Studies have had different research questions, experimental approaches, equipment use, water quality variables of interest, and the frequency and duration of monitoring. Site-based performance reporting should be presented relative to the catchment load, providing greater context when considering whole-of-catchment water quality improvement.
- Since the 2017 Scientific Consensus Statement there has been increased research effort to quantify the efficacy of wetlands as a tool for water quality improvement. This research, in conjunction with the development of the Queensland Government's values-based framework, provides a positive foundation for understanding the values and ecological function of wetlands, and increasing confidence in pollutant removal efficiencies.
- More research is needed to decipher which wetland types are likely to be most beneficial for water quality improvement in different settings (i.e., land uses, groundwater contribution, climates, and soils), configuration of multiple systems in the landscape, the spatial and temporal drivers of variability, quantification of delivery pathways (surface and groundwater), pesticide removal efficiencies (particularly those found to impact Great Barrier Reef ecosystems), improved characterisation of nutrient processing, long-term changes in wetland nutrient and sediment stores, and evidence of the timescales over which management interventions are likely to be effective.

# 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 4.7

## Theme 4: Dissolved nutrients – catchment to reef

**Primary question 4.7** 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)?

**Secondary question 4.7.1** What are the key factors that affect the efficacy of natural/near-natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality and how can these be addressed at scale to maximise water quality improvement?

## Author team

| Name | Organisation | Expertise | Role in addressing the Question | Sections/Topics involved |
| --- | --- | --- | --- | --- |
| 1. Nathan Waltham | Centre for Tropical Water and Aquatic Ecosystem Research | Aquatic ecology, Environmental management, Wetland restoration | Lead Author | All Sections |
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| 3. Bianca Molinari | $C_2O$ Consulting | Aquatic ecology, trophic ecology, environmental science | Contributor | Question setting, conceptual model, searches, and data extraction. |