A review of water quality studies relevant to northern Australia

A technical report from the CSIRO Victoria and Southern Gulf Water Resource Assessments for the National Water Grid

Katie Motson, Amrit Mishra, Nathan Waltham

Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville, Australia

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Aspects of the Assessments have been undertaken in conjunction with the Northern Territory and Queensland governments.

The Assessments were guided by three committees:

i. The Governance Committee: CRC for Northern Australia/James Cook University; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Agriculture and Fisheries; Queensland Department of Regional Development, Manufacturing and Water

ii. The joint Roper and Victoria River catchments Steering Committee: Amateur Fishermen's Association of the NT; Austrade; Centrefarm; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Cattlemen's Association; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; NT Farmers; NT Seafood Council; Office of Northern Australia; Parks Australia; Regional Development Australia; Roper Gulf Regional Council Shire; Watertrust

iii. The Southern Gulf catchments Steering Committee: Amateur Fishermen's Association of the NT; Austral Fisheries; Burketown Shire; Carpentaria Land Council Aboriginal Corporation; Health and Wellbeing Queensland; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Prawn Fisheries; Queensland Department of Agriculture and Fisheries; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Regional Development, Manufacturing and Water; Southern Gulf NRM

Responsibility for the Assessments' content lies with CSIRO. The Assessments' committees did not have an opportunity to review the Assessments' results or outputs prior to their release.

Acknowledgement of Country

CSIRO acknowledges the Traditional Owners of the lands, seas and waters of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture and pay our respects to their Elders past and present.

Photo

High sediment load, Alexander Falls, Southern Gulf. Source: CSIRO

Director’s foreword

Sustainable development and regional economic prosperity are priorities for the Australian, Queensland and Northern Territory (NT) governments. However, more comprehensive information on land and water resources across northern Australia is required to complement local information held by Indigenous Peoples and other landholders.

Knowledge of the scale, nature, location and distribution of likely environmental, social, cultural and economic opportunities and the risks of any proposed developments is critical to sustainable development. Especially where resource use is contested, this knowledge informs the consultation and planning that underpin the resource security required to unlock investment, while at the same time protecting the environment and cultural values.

In 2021, the Australian Government commissioned CSIRO to complete the Victoria River Water Resource Assessment and the Southern Gulf Water Resource Assessment. In response, CSIRO accessed expertise and collaborations from across Australia to generate data and provide insight to support consideration of the use of land and water resources in the Victoria and Southern Gulf catchments. The Assessments focus mainly on the potential for agricultural development, and the opportunities and constraints that development could experience. They also consider climate change impacts and a range of future development pathways without being prescriptive of what they might be. The detailed information provided on land and water resources, their potential uses and the consequences of those uses are carefully designed to be relevant to a wide range of regional-scale planning considerations by Indigenous Peoples, landholders, citizens, investors, local government, and the Australian, Queensland and NT governments. By fostering shared understanding of the opportunities and the risks among this wide array of stakeholders and decision makers, better informed conversations about future options will be possible.

Importantly, the Assessments do not recommend one development over another, nor assume any particular development pathway, nor even assume that water resource development will occur. They provide a range of possibilities and the information required to interpret them (including risks that may attend any opportunities), consistent with regional values and aspirations.

All data and reports produced by the Assessments will be publicly available.

Chris Chilcott

Project Director

The Victoria and Southern Gulf Water Resource Assessment Team

Project Director	Chris Chilcott
Project Leaders	Cuan Petheram, Ian Watson
Project Support	Caroline Bruce, Seonaid Philip
Communications	Emily Brown, Chanel Koeleman, Jo Ashley, Nathan Dyer

Activities

Agriculture and socio-economics	Tony Webster, Caroline Bruce, Kaylene Camuti[1], Matt Curnock, Jenny Hayward, Simon Irvin, Shokhrukh Jalilov, Diane Jarvis[1], Adam Liedloff, Stephen McFallan, Yvette Oliver, Di Prestwidge[2], Tiemen Rhebergen, Robert Speed[3], Chris Stokes, Thomas Vanderbyl[3], John Virtue[4]
Climate	David McJannet, Lynn Seo
Ecology	Danial Stratford, Rik Buckworth, Pascal Castellazzi, Bayley Costin, Roy Aijun Deng, Ruan Gannon, Steve Gao, Sophie Gilbey, Rob Kenyon, Shelly Lachish, Simon Linke, Heather McGinness, Linda Merrin, Katie Motson[5], Rocio Ponce Reyes, Nathan Waltham[5]
Groundwater hydrology	Andrew R. Taylor, Karen Barry, Russell Crosbie, Margaux Dupuy, Geoff Hodgson, Anthony Knapton[6], Shane Mule, Stacey Priestley, Jodie Pritchard, Matthias Raiber, Steven Tickell[7], Axel Suckow
Indigenous water values, rights, interests and development goals	Marcus Barber/Kirsty Wissing, Pethie Lyons, Peta Braedon, Kristina Fisher, Petina Pert
Land suitability	Ian Watson, Jenet Austin, Bart Edmeades[7], Linda Gregory, Ben Harms[10], Jason Hill[7], Jeremy Manders[10], Gordon McLachlan, Seonaid Philip, Ross Searle, Uta Stockmann, Evan Thomas[10], Mark Thomas, Francis Wait[7], Peter L. Wilson, Peter R. Wilson, Peter Zund
Surface water hydrology	Justin Hughes, Matt Gibbs, Fazlul Karim, Julien Lerat, Steve Marvanek, Cherry Mateo, Catherine Ticehurst, Biao Wang
Surface water storage	Cuan Petheram, Giulio Altamura[8], Fred Baynes[9], Jamie Campbell[11], Lachlan Cherry[11], Kev Devlin[4], Nick Hombsch[8], Peter Hyde[8], Lee Rogers, Ang Yang

Note: Assessment team as at September, 2024. All contributors are affiliated with CSIRO unless indicated otherwise. Activity Leaders are underlined. For the Indigenous water values, rights, interests and development goals activity (Victoria catchment), Marcus Barber was Activity Leader for the project duration except August 2022 – July 2023 when Kirsty Wissing (a CSIRO employee at the time) undertook this role.

[1]James Cook University; [2]DBP Consulting; [3]Badu Advisory Pty Ltd; [4]Independent contractor; [5]Centre for Tropical Water and Aquatic Ecosystem Research. James Cook University; [6]CloudGMS; [7]NT Department of Environment, Parks and Water Security; [8]Rider Levett Bucknall; [9]Baynes Geologic; [10]QG Department of Environment, Science and Innovation; [11]Entura

Shortened forms

SHORT FORM	FULL FORM
AADTVTA	ANZECC and ARMCANZ Default Trigger Value for Tropical Australia
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
AWRIS	Australian Water Resources Information System
DO	dissolved oxygen
DOC	dissolved organic carbon
EC	electrical conductivity
NA	not available
NS	not specified
NT	Northern Territory
TDS	total dissolved solids
WA	Western Australia
N	nitrogen
P	phosphorus
NAWR	Northern Australia Water Resources

Units

UNIT	DESCRIPTION
ha	hectare
L	litre
m	metre
mg	milligram
mm	millimetre
ms	millisiemens
NTU	nephelometric turbidity unit

Preface

Sustainable development and regional economic prosperity are priorities for the Australian, NT and Queensland governments. In the Queensland Water Strategy, for example, the Queensland Government (2023) looks to enable regional economic prosperity through a vision which states 'Sustainable and secure water resources are central to Queensland's economic transformation and the legacy we pass on to future generations.' Acknowledging the need for continued research, the NT Government (2023) announced a Territory Water Plan priority action to accelerate the existing water science program 'to support best practice water resource management and sustainable development.'

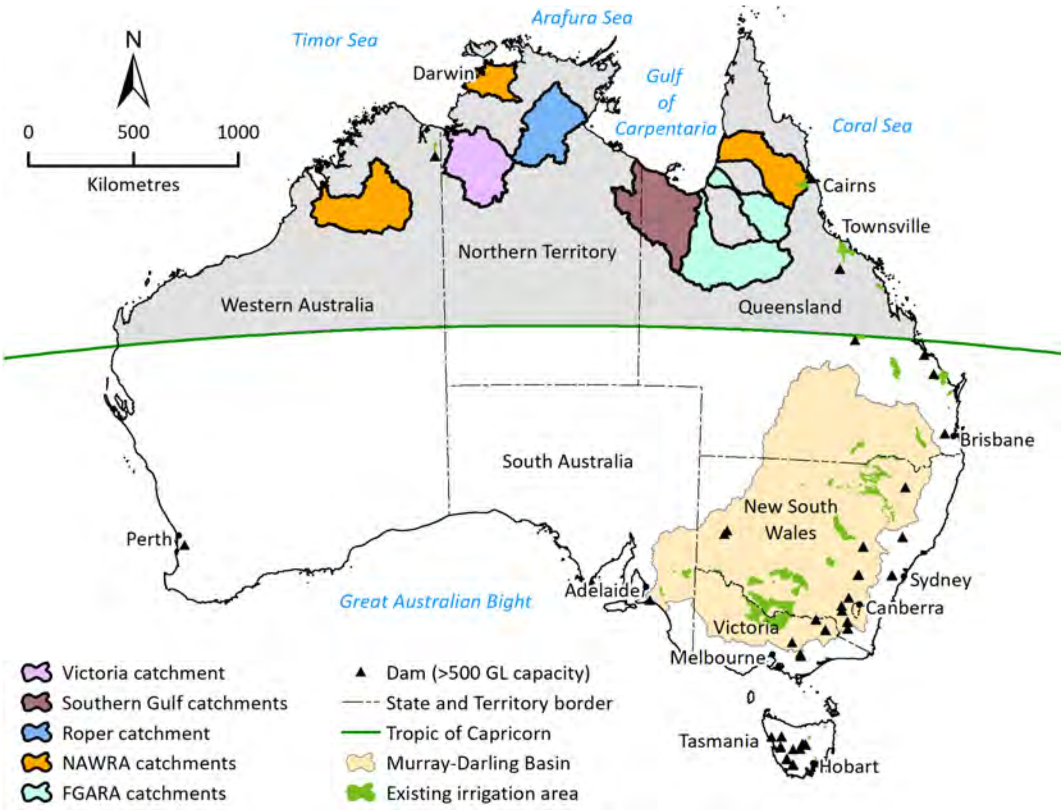
Governments are actively seeking to diversify regional economies, considering a range of factors, including Australia's energy transformation. The Queensland Government's economic diversification strategy for north west Queensland (Department of State Development, Manufacturing, Infrastructure and Planning, 2019) includes mining and mineral processing; beef cattle production, cropping and commercial fishing; tourism with an outback focus; and small business, supply chains and emerging industry sectors. In its 2024–25 Budget, the Australian Government announced large investment in renewable hydrogen, low-carbon liquid fuels, critical minerals processing and clean energy processing (Budget Strategy and Outlook, 2024). This includes investing in regions that have 'traditionally powered Australia' – as the North West Minerals Province, situated mostly within the Southern Gulf catchments, has done.

For very remote areas like the Victoria and Southern Gulf catchments, the land (Preface Figure 1-1), water and other environmental resources or assets will be key in determining how sustainable regional development might occur. Primary questions in any consideration of sustainable regional development relate to the nature and the scale of opportunities, and their risks.

How people perceive those risks is critical, especially in the context of areas such as the Victoria and Southern Gulf catchments, where approximately 75% and 27% of the population (respectively) is Indigenous (compared to 3.2% for Australia as a whole) and where many Indigenous Peoples still live on the same lands they have inhabited for tens of thousands of years. About 31% of the Victoria catchment and 12% of the Southern Gulf catchments are owned by Indigenous Peoples as inalienable freehold.

Access to reliable information about resources enables informed discussion and good decision making. Such information includes the amount and type of a resource or asset, where it is found (including in relation to complementary resources), what commercial uses it might have, how the resource changes within a year and across years, the underlying socio-economic context and the possible impacts of development.

Most of northern Australia's land and water resources have not been mapped in sufficient detail to provide the level of information required for reliable resource allocation, to mitigate investment or environmental risks, or to build policy settings that can support good judgments. The Victoria and Southern Gulf Water Resource Assessments aim to partly address this gap by providing data to better inform decisions on private investment and government expenditure, to account for intersections between existing and potential resource users, and to ensure that net development benefits are maximised.



Preface Figure 1-1 Map of Australia showing Assessment areas (Victoria and Southern Gulf catchments) and other recent CSIRO Assessments
FGARA = Flinders and Gilbert Agricultural Resource Assessment; NAWRA = Northern Australia Water Resource Assessment.

The Assessments differ somewhat from many resource assessments in that they consider a wide range of resources or assets, rather than being single mapping exercises of, say, soils. They provide a lot of contextual information about the socio-economic profile of the catchments, and the economic possibilities and environmental impacts of development. Further, they consider many of the different resource and asset types in an integrated way, rather than separately.

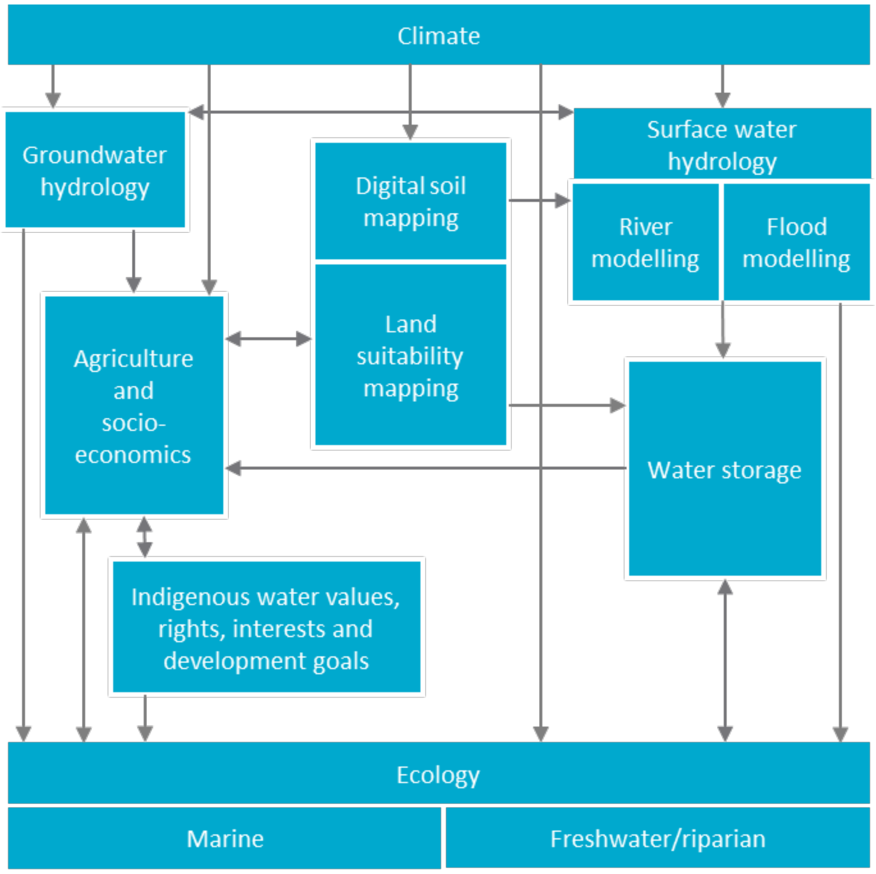
The Assessments have agricultural developments as their primary focus, but they also consider opportunities for and intersections between other types of water-dependent development. For example, the Assessments explore the nature, scale, location and impacts of developments relating to industrial, urban and aquaculture development, in relevant locations. The outcome of no change in land use or water resource development is also valid.

The Assessments were designed to inform consideration of development, not to enable any particular development to occur. As such, the Assessments inform – but do not seek to replace – existing planning, regulatory or approval processes. Importantly, the Assessments do not assume a given policy or regulatory environment. Policy and regulations can change, so this flexibility enables the results to be applied to the widest range of uses for the longest possible time frame.

It was not the intention of – and nor was it possible for – the Assessments to generate new information on all topics related to water and irrigation development in northern Australia. Topics not directly examined in the Assessments are discussed with reference to and in the context of the existing literature.

CSIRO has strong organisational commitments to Indigenous reconciliation and to conducting ethical research with the free, prior and informed consent of human participants. The Assessments allocated significant time to consulting with Indigenous representative organisations and Traditional Owner groups from the catchments to aid their understanding and potential engagement with their requirements. The Assessments did not conduct significant fieldwork without the consent of Traditional Owners.

Functionally, the Assessments adopted an activities-based approach (reflected in the content and structure of the outputs and products), comprising activity groups, each contributing its part to create a cohesive picture of regional development opportunities, costs and benefits, but also risks. Preface Figure 1-2 illustrates the high-level links between the activities and the general flow of information in the Assessments.



Preface Figure 1-2 Schematic of the high-level linkages between the eight activity groups and the general flow of information in the Assessments

Assessment reporting structure

Development opportunities and their impacts are frequently highly interdependent and, consequently, so is the research undertaken through these Assessments. While each report may be read as a stand-alone document, the suite of reports for each Assessment most reliably informs discussion and decisions concerning regional development when read as a whole.

The Assessments have produced a series of cascading reports and information products:

- Technical reports present scientific work with sufficient detail for technical and scientific experts to reproduce the work. Each of the activities (Preface Figure 1-2) has one or more corresponding technical reports.
- Catchment reports, one for each of the Victoria and Southern Gulf catchments, synthesise key material from the technical reports, providing well-informed (but not necessarily scientifically trained) users with the information required to inform decisions about the opportunities, costs and benefits associated with irrigated agriculture and other development options.
- Summary reports, one for each of the Victoria and Southern Gulf catchments, provide a shorter summary and narrative for a general public audience in plain English.
- Summary fact sheets, one for each of the Victoria and Southern Gulf catchments, provide key findings for a general public audience in the shortest possible format.

The Assessments have also developed online information products to enable users to better access information that is not readily available in print format. All of these reports, information tools and data products are available online at https://www.csiro.au/victoriariver and https://www.csiro.au/southerngulf. The webpages give users access to a communications suite including fact sheets, multimedia content, FAQs, reports and links to related sites, particularly about other research in northern Australia.

Executive summary

This report reviews international and national water quality studies, focusing on the environmental impacts and irrigation factors that influence water quality in tropical wet-dry regions and, in particular, northern Australia.

Key findings

Environmental impacts

Irrigation development can lead to significant environmental changes, including altered flow regimes and water quality degradation. Studies worldwide and from northern Australia highlight the risks posed by increased nutrient loading, pesticide application and salinity changes because of irrigated agriculture. Elevated levels of nitrogen, phosphorus and other contaminants may lead to eutrophication, affecting aquatic ecosystems and posing health risks.

Groundwater and surface water concerns

Irrigation practices in tropical wet-dry climates, such as those found in northern Australia, show a complex and context-specific relationship with water quality. Groundwater extraction for irrigation can lead to aquifer depletion, increased salinity, and potential contamination through nutrient leaching. Surface water quality can also deteriorate due to sedimentation, chemical runoff and altered hydrological cycles. The high variability in seasonal rainfall (wet and dry seasons) further complicates water quality management, particularly in tropical regions where high-flow events can transport substantial nutrient and pesticide loads into water bodies.

Specific trends for northern Australia

In northern Australia, the predominant irrigation method is surface irrigation, which has been shown to significantly affect water quality. Studies from regions like the Burdekin Haughton Water Supply Scheme and Ord River Irrigation Area highlight the elevated concentrations of nutrients and pesticides in irrigation runoff. While dilution effects during high-flow events (e.g. in the wet season) may help reduce contaminant concentrations, the ecological risks remain significant.

Long-term monitoring

A major limitation in advancing sustainable irrigation practices in northern Australia is the lack of comprehensive, long-term water quality data. This lack hinders efforts to understand baseline water quality conditions and how irrigation and agricultural expansion have affected these systems over time. Furthermore, while there have been some studies on the impacts of irrigation on cotton farming, the effects on other crops remain under-researched. Additionally, digital databases containing valuable historical water quality data are fragmented and incomplete, limiting accessibility.

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1 Introduction

1.1 Agricultural expansion and water resource development in northern Australia

Globally, water resource development has a known impact on downstream surface water and groundwater resources (Ayyandurai et al., 2022; McIntyre et al., 2011). The degree of this influence depends on a range of factors, such as the extent of agricultural development and the farming practices used, the soil profile and underlying geology, the local climate and time of year, changes in flow (e.g. from dam construction or groundwater extraction) and local land management practices (e.g. to prevent runoff from entering surface water and groundwater networks).

Northern Australia is a focus for agricultural expansion and water resource development (Australian Government, 2015). Therefore, to understand the environmental responses and socio-economic consequences of water resource development, and to ensure that northern Australia's water resources are developed sustainably, investigations into water resource availability and reliability, environmental impacts, implications for local Indigenous cultures and heritage, and social and economic prospects are necessary (Morán-Ordóñez et al., 2016). These investigations are of particular importance in northern Australia due to its rich cultural heritage and diversity of terrestrial and aquatic species (Arthington et al., 2015; Finlayson et al., 2006; Hansen et al., 2022; Williams et al., 2003), including economically important coastal fisheries (Staples and Vance, 1985) and species of international conservation significance, such as migratory birds and sharks and rays (Dawkins, 2022). Habitat and water quality protection are therefore critical to the long-term conservation of northern Australia's unique flora and fauna, including species of recreational, commercial and Indigenous cultural value.

1.2 Agriculture and water quality

Irrigated agriculture is vital to global food security: it covers only 20% of cultivated land but accounts for 40% of global food production (Food and Agriculture Organization, 2020). However, while agricultural expansion and water resource development may provide food security and other social and economic prospects, agricultural activities, such as irrigated agriculture, can have significant negative environmental impacts on both surface water and groundwater quality (see Table 1-1). This is mainly due to the inefficient application of fertilisers and pesticides, and the high volumes of irrigation water required. Crops worldwide use less than 50% of the fertiliser nitrogen applied (Bijay and Craswell, 2021), and irrigated agriculture is responsible for approximately 60% of fresh water withdrawals globally (Food and Agriculture Organization, 2021). These inefficient practices mean that excess nutrients and pesticides are available for leaching and/or transport via runoff from irrigation and rainfall events into local surface water and groundwater bodies. Nitrogen, phosphorus and potassium are the three primary nutrients used in agricultural fertilisers. In sufficient quantities, both nitrogen and phosphorus can stimulate high phytoplankton and algal growth, potentially leading to eutrophication and hypoxia or anoxia of receiving water bodies and threatening aquatic life (Carpenter et al., 1998).

Pesticides, used to increase agricultural productivity, can harm downstream aquatic ecosystems, flora and fauna. In mechanisms similar to nutrient transport, pesticides can enter surface water and groundwater bodies via infiltration, leaching and runoff from irrigation and rainfall events. These chemicals can be toxic to non-target species such as aquatic life and humans, affecting the nervous and immune systems, photosynthesis and growth (Cantin et al., 2007; Kaur et al., 2019; Naccarato et al., 2023). Pesticides can be carcinogenic (Mohanty and Jena, 2019), and they can cause multiple sub-lethal effects that can disrupt the ecological balance of aquatic systems and degrade aquatic communities (Giglio and Vommaro, 2022; Miller et al., 2020; Wang et al., 2022).

Other water quality variables that can have a significant effect on the health of aquatic species, communities and ecosystems include salinity, pH and suspended sediments. Increased salinity, indicated by electrical conductivity and total dissolved solids, can interfere with osmoregulatory processes, harming species not adapted to saline conditions (Hart et al., 2003). Variations in a water body's pH can negatively affect an organism's biochemical processes, leading to altered behaviour, function, growth and even reduced survival (United States Environmental Protection Agency, 2024). In aquatic ecosystems, elevated loads of suspended sediment can smother habitats and benthic invertebrates, affect the feeding and respiratory systems of aquatic species, and reduce light penetration, affecting photosynthetic activity (Chapman et al., 2017).

Table 1-1 Water quality variables reviewed and their impacts on the environment, aquatic ecology and human health

WATER QUALITY VARIABLE		THREATS TO AQUATIC ECOLOGY AND HUMAN HEALTH	REFERENCE
Nutrients	Nitrogen	Forms of nitrogen in freshwater systems include: nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3) and ammonium (NH_4^+) In excessive quantities, contributes to eutrophication and algal blooms, which can deplete oxygen and create hypoxic or anoxic conditions harmful to aquatic life Health threat to humans, particularly infants, and mammals	Carpenter et al. (1998)
	Phosphorus	High concentrations may lead to eutrophication and algal blooms, which can deplete oxygen and create hypoxic or anoxic conditions harmful to aquatic life	Mainstone and Parr (2002)
	Dissolved organic carbon (DOC)	A proxy for dissolved organic matter, affecting water clarity, temperature, biogeochemical processes, food webs and ecosystem productivity. DOC may exacerbate eutrophication and hypoxia in aquatic ecosystems and cause problems in drinking water treatment processes	Palviainen et al. (2022)
Pesticides (groups)	Arylurea	Includes pesticides such as diuron and tebuthiuron. May inhibit photosynthesis in plants and aquatic species. These pesticides are less soluble in water and better absorbed by the soil	Cantin et al. (2007), Fojut et al. (2012)
	Carbamates	Broad-spectrum pesticides that affect nerve impulse transmission – highly toxic to vertebrate species. Suspected carcinogens and mutagens. Relatively low persistence, not easily adsorbed to soil particles	Kaur et al. (2019), Rad et al. (2022)
	Chloroacetanilides	Affects cell division, disrupting aquatic plant growth, also toxic to aquatic insects. Persistent. Low binding affinity to soil particles but highly water soluble; therefore, it has a high capacity to leach to	ANZG (2020), Mohanty and Jena (2019)

WATER QUALITY VARIABLE		THREATS TO AQUATIC ECOLOGY AND HUMAN HEALTH	REFERENCE
		groundwater and end up in surface water. Carcinogens with moderate to high chronic toxicity	
	Dinitroanilines	Broad-spectrum herbicides with low water solubility; considered non-mobile in soil. Affect seed germination and root growth in plants. Variable, species-specific toxicity ranging from slightly to highly acute. Hazardous to animals and humans in sub-lethal concentrations. Known bioaccumulation in and acute toxicity to aquatic organisms	Giglio and Vommaro (2022)
	Neonicotinoids	Highly toxic to invertebrates, particularly aquatic insects. Sub-lethal toxicity in fish. High solubility. High chronic risk to global freshwater ecosystems. Suspected to be carcinogenic	Wang et al. (2022)
	Organochlorines	Persistent organic pollutants that can bioaccumulate in fatty tissues. These pesticides are toxic to humans, other animals and highly toxic to most aquatic life	Department of Climate Change, Energy, the Environment and Water (2021)
	Organophosphates	Broad-spectrum pesticides that control a wide range of pests via multiple functions. Organophosphate insecticides are toxic to both vertebrates and invertebrates, disrupting nerve impulse transmission	Kaur et al. (2019)
	Phenylpyrazole	These pesticides disrupt nerve impulse transmission. Toxic to aquatic organisms and birds. Phenylpyrazole pesticides, such as fipronil, found to degrade stream communities. Moderate water solubility and hydrophobicity. Slightly mobile in soils and moderate persistence	Gao et al. (2020), Miller et al. (2020)
	Triazine	Inhibits photosynthesis in plants, potentially leading to reduced plant growth and blocks food intake of insect pests. Short to moderate persistence depending on soil pH. Adverse and sub-lethal effects on terrestrial and aquatic non-target organisms, affecting growth and the nervous and immune systems	Naccarato et al. (2023)
Salinity		Can affect aquatic species' osmoregulatory processes, harming aquatic life not adapted to saline water. Significant increases in salinity may compromise the integrity of freshwater ecosystems	Hart et al. (2003)
Other	Total suspended solids	Can smother habitats, reduce light penetration through increasing turbidity, and affect the feeding and respiratory systems of aquatic organisms	Chapman et al. (2017)
	pH	Variations can negatively affect aquatic life stages – affecting their biochemical processes. Preferred pH range of 6.4–8.4 for aquatic species	United States Environmental Protection Agency (2024)

1.3 Natural processing of water contaminants

While elevated contaminants and water quality parameters can harm the environment and human health, there are several processes by which aquatic ecosystems can partially process contaminants and regulate water quality. Denitrification, for example, is the process of anaerobic microbial respiration which, in the presence of carbon, reduces nitrogen to nitrous oxide and dinitrogen gas (Martens, 2005). Therefore, denitrification is a naturally occurring process that can remove nitrogen from a water body, reducing nitrogen concentrations. Pesticides can also be naturally removed from water via chemical oxidation, microbial degradation or UV photolysis, although some chemically stable pesticides are highly persistent, and their microbial degradation is slow (Hassaan and El Nemr, 2020). Phosphorus, however, does not have a microbial reduction process such as denitrification. Instead, if not temporarily taken up by plants, phosphorus can be adsorbed to the surface of inorganic and organic particles and stored in the soil, or deposited in the sediments of water bodies such as wetlands (Finlayson, 2022). However, this phosphorus can be remobilised into solution and re-adsorbed, resulting in 'legacy' phosphorus that can affect water quality for many years (Records et al., 2016).

1.4 Concentrations versus loads

When monitoring and reporting on water quality variables, it is important to understand the ecological significance of reporting concentrations versus loads. Measuring concentrations of contaminants and water quality characteristics indicates the relative health of a water body at a particular time. Therefore, it is important to monitor concentrations of water quality variables over time to understand a water body's baseline water quality and any broader trends. Concentrations are a useful means of measurement as they have biological significance. For example, the nitrogen species ammonia becomes acutely toxic (96-hour LC_{50}) to the freshwater amphipod *Eulimnogammarus toletanus* at concentrations of 0.65 mg/L but is acutely toxic to salmon fry (*Oncorhynchus gorbuscha)* at only 0.08 mg/L (Camargo and Alonso, 2006). Understanding contaminant loads – that is, the total amount of contaminants entering a system over time – allows natural resource managers to understand the mass and/or volume of contaminants entering a system and the cumulative effect of contaminant inputs. Therefore, monitoring both contaminant loads and concentrations is key to developing comprehensive water quality management strategies.

1.5 Report aims

This report seeks to understand baseline water quality trends in northern Australian catchments and the relative risks of agricultural water resource development, specifically irrigation practices and environmental factors, on surface water and groundwater quality. The key aims of this chapter are to:

- review international studies to provide a context of the environmental factors and characteristics of irrigation schemes that have been found to influence surface water and groundwater quality, particularly in wet-dry tropical catchments
- collate available baseline water quality data for rivers across northern Australia
- collate existing water quality data and synthesise existing studies in the vicinity of irrigation areas across northern Australia
- synthesise results of existing water quality modelling studies in northern Australia and models used
- synthesise findings of studies in northern Australia that have related changes in water quality to changes in environmental conditions
- outline some of the knowledge gaps.

2 International irrigation development review

Understanding the intricate interplay between irrigation scheme characteristics, the environment, and surface water and groundwater quality is essential to sustainable water development and resource management. This review seeks to elucidate the diverse factors and characteristics inherent to irrigation practices and their environment that significantly affect both surface water and groundwater quality. By analysing and synthesising the global literature, particularly findings from wet-dry tropical climates, this study aims to uncover patterns and insights that may inform the sustainable development and management of water resources in northern Australia.

2.1 Methods

The method adopted for this review is an evidence synthesis, a form of 'rapid review' that identifies, compiles and combines relevant knowledge from multiple sources. This method involves constraining the search effort, while still applying methods to minimise author bias in the searches and evidence synthesis.

2.1.1 Published literature search and eligibility

Searches were performed using the literature search database, Scopus, and grey literature from the Northern Australia Water Resources (NAWR) digital library (https://nawrdl.github.io/ - /).

Search terms

A list of the search terms used to inform the online Scopus database search is provided in Table 2-1.

Table 2-1 Search terms for elements of the primary question (and secondary questions if relevant)

QUESTION ELEMENT	SEARCH TERMS
Subject/population	irrigation OR irrigat* AND 'water quality' OR nutrient* OR contamina* OR pollut* OR nitrogen OR nitr* OR phosph* OR pesticid* OR fungicid* OR insecticid* OR salinit* OR conductance OR conductivity OR turbidity OR sediment* OR 'dissolved oxygen' OR DO OR algae OR pH AND 'surface water' OR groundwater AND agriculture OR farm*
Exposure or intervention	Wet/dry tropics
Comparator (if relevant) /	-
Outcome	Removal, retention, denitrification, anammox, 'nitrate reduction', sedimentation, mitigation, deposition, efficacy, efficiency, effective*

Search strings

The search string used to conduct the online searches is presented in Table 2-2. The search string detailed in Table 2-2 features fewer subject-specific search terms than those collated in Table 2-1. This was done to reduce the number of search outputs (maximum search outputs were 5,847,516 studies) and maintain relevance to the topic. Several subject areas were also excluded from the searches to increase the relevance of the outputs obtained.

Table 2-2 Search string used for electronic searches

SEARCH FIELDS	SEARCH STRING	FILTERS	OUTPUTS
Article title, abstract, keywords	irrigation OR irrigat* AND 'surface water*' OR river* OR stream* OR lake* OR creek* OR groundwater AND 'water quality' AND agriculture OR farm* AND NOT sewage AND NOT microplastic* AND NOT bacteria AND NOT virus AND NOT 'drinking water' AND NOT potable	Date ≥1990 Article, book chapter, editorial, literature review, book, data paper, report Language = English Excluded subject areas: engineering, social sciences, medicine, energy, arts and humanities, decision sciences, neuroscience	1353 (1355 minus 2 duplicates)

Inclusion and exclusion criteria

Several inclusion and exclusion criteria were established to guide the initial and secondary screening processes and to minimise author biases in study selection. Inclusion and exclusion criteria are presented in Table 2-3.

Table 2-3 Inclusion and exclusion criteria applied to the search returns

QUESTION ELEMENT	INCLUSION	EXCLUSION
Subject/population	Studies focused on ground and surface water quality	Not water quality related, not ground and surface water quality
	Nitrogen and phosphorus in all forms Total suspended solids, sediments, fine sediments Pesticides, including insecticides, herbicides, fungicides	Related to water quality measures other than nutrients, fine sediments, pesticides (e.g. exclude genotoxins, plastics, Nitrous oxide emissions, bacteria, parasites and viruses etc.)
	Studies focused on ground and surface water quality because of environmental or irrigation factors	Potable water studies, or human impacts other than irrigation
	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	Urban-related studies and sources of contamination, e.g. mariculture, aquaculture, allotments, municipal waste, treated waste water and sewage
	Irrigation in pastoral and arable farmland	Agroforestry
Exposure or intervention	-	-
Comparator (if relevant)	-	-
Outcome	-	-
Language	Studies written in English	Studies not written in English
Study type	Studies published 1990–2024	Studies conducted before 1990 (unless essential)

QUESTION ELEMENT	INCLUSION	EXCLUSION
	Peer-reviewed and 'in press' studies and reports. (Reports on Australian systems have no date restriction)	Journal articles currently undergoing peer review
	Publicly available studies	Studies not publicly available
	Article, book chapter, editorial, literature review, book, data paper, report	Conference paper, conference review, note, editorial, erratum, letter, retracted, short survey
	Empirical	Non-empirical
	Experimental, observational, and/or modelling studies – so long as the model is appropriately built, i.e. trained with real-world data Pilot studies	Modelling studies not trained on real-world data Theoretical studies and methods papers

Screening process and data extraction

The initial screening involved reviewing each study's title and abstract to determine its eligibility for inclusion in the body of evidence, according to the inclusion and exclusion criteria (Table 2-3). This process reduced the 1353 studies from the Scopus search, NAWR digital library and author libraries to 481 (Figure 2-1).

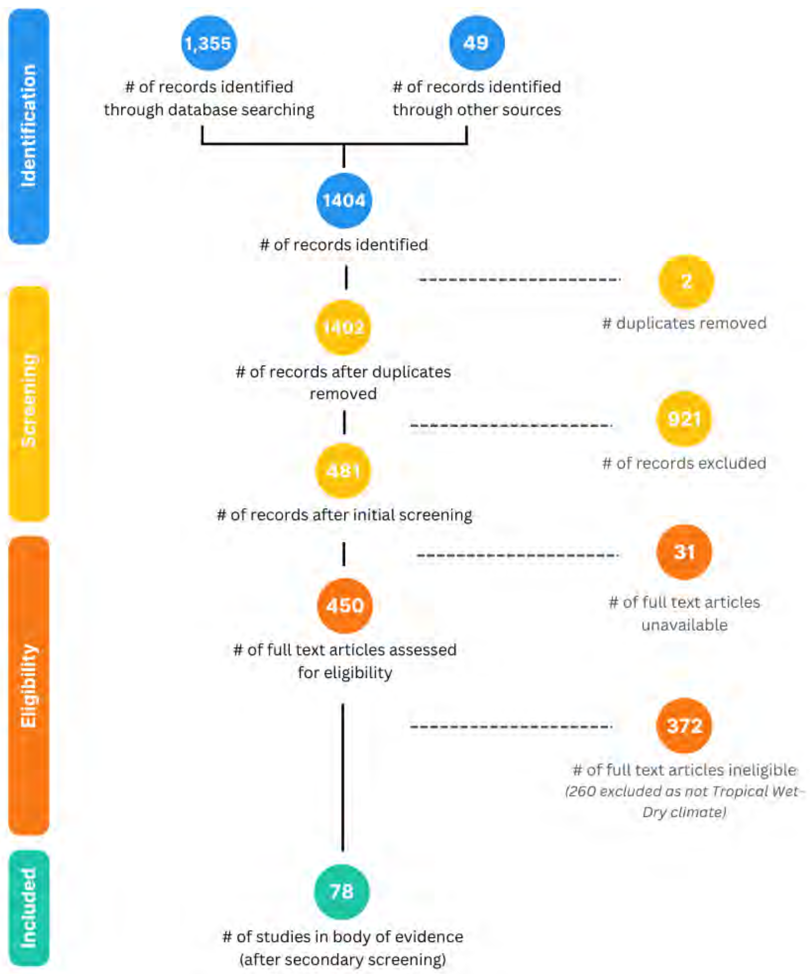

Figure 2-1 Flow chart of the literature identification, screening, eligibility and inclusion process and outcomes

The second screening reviewed each document fully to determine its eligibility according to the inclusion and exclusion criteria. Secondary screening and data extraction, in which characteristics of the study and its results were entered into a data sheet, were conducted simultaneously for efficiency. In total, 78 studies formed the body of evidence for this review (see Figure 2-1 and Appendix A).

2.2 Results and discussion

2.2.1 Characteristics of the body of evidence

Study climate conditions

For the global component of the literature review, the studies featured within the body of evidence covered multiple climates and latitudes but not the polar regions (Table 2-4). The body of evidence features a large proportion of tropical wet-dry climates (*n* = 38 studies), due to the tropical wet-dry focus of this review. Temperate (*n* = 12), Mediterranean (*n* = 11) and subtropical climates (*n* = 9) also feature prominently within the body of evidence.

Table 2-4 Number of studies featured within the body of evidence according to climate

CLIMATE	NUMBER OF STUDIES
Combination	1
Desert	5
Mediterranean	11
Subtropical	9
Temperate	12
Tropical wet	1
Tropical wet-dry	38
Total	78

Study locations

Of the 78 studies, 12 studies were from India, 9 studies were from the USA and 28 studies were from Australia, of which 26 studies were from northern Australia (Table 2-5).

Table 2-5 Number of studies featured within the body of evidence according to location (country)

COUNTRY	NUMBER OF STUDIES
Algeria	1
Australia	28
Northern Australia	*(26)*
China	1
Greece	1
India	12
Ireland	1
Japan	1

COUNTRY	NUMBER OF STUDIES
Mexico	2
Morocco	1
Portugal	1
Saudi Arabia	2
South Africa	2
South Korea	1
Spain	7
Tunisia	2
Turkey	3
USA	9
Uzbekistan	2
Vietnam	1
Total	78

Study types

Most studies within the body of evidence were observational (*n* = 56; 72%), with water quality measurements made in the field; 12% were experimental (*n* = 9) and the remaining 16% were modelling studies (*n* = 6) and reviews (*n* = 3) (Table 2-6).

Table 2-6 Number of studies featured within the body of evidence according to study type and location

LOCATION	STUDY TYPE				TOTAL
	EXPERIMENTAL	MODELLING	OBSERVATIONAL	REVIEW	
Global	9	11	56	2	78
Wet-dry tropics	5	5	27	1	38
Northern Australia	5	4	16	1	26

Study duration

The mean observation period (i.e., the timeframe over which data was collected) was approximately 3 years. Studies ranged from 9 days to 65 years in length (Table 2-7).

Table 2-7 Minimum, mean and maximum observation period (in years) from the body of evidence, according to study type.

STUDY TYPE	MEAN OBSERVATION PERIOD (YEARS)	MINIMUM OBSERVATION PERIOD (YEARS)	OBSERVATION PERIOD (YEARS)
Experimental	1	<1	4
Observational	2	<1	50
Observational and modelling	4	<1	65
Review	3	1	13
Overall mean observation period	**3**		

Study seasonality

Of the 38 studies conducted within tropical wet-dry climates, 33 stipulated the seasonality of the research. Most (64%) reported water quality results during both the wet and dry seasons, while 15% reported water quality results from a single dry season and 21% from a single wet season (Table 2-8).

Water quality in surface water and groundwater bodies

Only 11 of the 78 studies characterised water quality in both surface waters and ground waters. Most studies within the body of evidence focused on either groundwater (*n* = 37 studies) or surface water quality (*n* = 28) alone. Within the body of evidence, studies conducted within the wet-dry tropics focused mainly on either groundwater quality (*n* = 17) or surface water quality (*n* = 15) with fewer studies (*n* = 6) reporting water quality data in both (Table 2-8).

Table 2-8 Number of studies within the body of evidence reporting surface water and/or groundwater quality, according to climate

CLIMATE	BOTH	GROUNDWATER ONLY	SURFACE WATER ONLY
Desert	2	3	
Mediterranean	1	5	4
Subtropical		5	3
Temperate	2	4	6
Tropical wet		2	
Tropical wet-dry	6	17	15

In northern Australia, the majority of surface water and groundwater studies within the body of evidence are from the Ord River Irrigation Area (Figure 2-2).

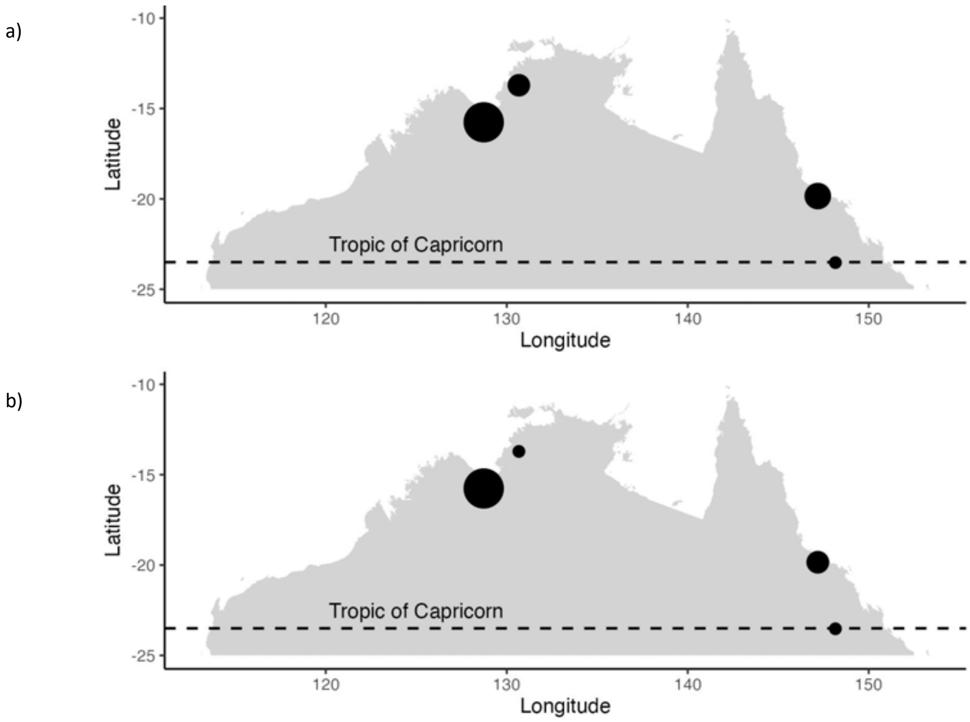

Figure 2-2 Number of studies reporting a) surface water and b) groundwater quality in northern Australia

Environmental and irrigation factors influencing surface and groundwater quality

Of the 78 studies within the body of evidence, 67 reported either an effect of the environment, irrigation or both upon surface water and/or groundwater quality. Irrigation factors were the most reported (by 40% of studies) followed by environmental factors (36%) and a combination of the two (24%) (Table 2-9).

Table 2-9 Number of studies featured within the body of evidence according to the factors found to affect surface water and groundwater quality

FACTOR AFFECTING WATER QUALITY	NUMBER OF STUDIES
Environment and irrigation	16
Environment	24
Irrigation	27
Total	67

2.3 Environmental factors influencing water quality

2.3.1 Climate, geography and water use

From the body of evidence, it is apparent that, in temperate countries, the use of groundwater or surface water resources or both for agriculture is region-specific (see Appendix B). In subtropical studies the trend differed, with groundwater used for agriculture in all regions featured within the body of evidence except for agricultural areas close to river basins where surface water was used (Appendix B).

Interestingly, no records within the body of evidence discussed the environmental factors affecting water quality within subtropical regions. Within the body of evidence, groundwater was the dominant source of irrigation water in the sub-tropics. The most reported water quality parameters in temperate regions were nutrients and electrical conductivity (EC), whereas in subtropical regions EC was the dominant water quality parameter reported (Appendix B).

Findings and trends from the wet-dry tropics and northern Australia

In northern Australia west of the Great Dividing Range, few studies have assessed the impact of environmental conditions and irrigation practices on water quality. To expand the evidence base, several studies from the Burdekin River catchment in Queensland have been incorporated into this synthesis.

The three jurisdictions of Australia's wet-dry tropics form part of this literature review: Queensland, the Northern Territory (NT) and Western Australia (WA). The major river basins featured are the Burdekin and Fitzroy in Queensland, the Daly River in the NT and the Keep and Ord rivers in WA.

2.3.2 Seasonal hydrology, rainfall and first-flush events

Rainfall, hydrology and first-flush events are well documented as pivotal environmental factors shaping surface water and groundwater quality across climates. Rainfall can both dilute and concentrate pollutants depending on the volume and intensity of the events. Studies show that above-average rainfall dilutes salt concentrations, decreasing electrical conductivity in groundwater systems (Koç, 2008). In surface water bodies, similar dilution effects were observed for nutrients like total phosphorus during increased streamflow events (Skhiri and Dechmi, 2012). However, high-intensity rainfall and high-flow events can also mobilise contaminants, leading to spikes in nutrient concentrations, especially when irrigation and agricultural fertilisation interact with rainfall patterns (Albus and Knighton, 1998; Shinozuka et al., 2016). These dynamics underscore the importance of understanding local hydrological events and incorporating vegetation management to mitigate the impact of contaminant mobilisation.

Findings and trends from the global literature

Table 2-10 outlines the mean percentage changes in water quality parameters from the wet to dry season in two distinct climate zones (subtropical and tropical wet-dry), highlighting the influence of seasonal hydrology, rainfall and first-flush events on surface water and groundwater quality. The table also presents the number of observations for each measurement. Note that many measurements have only one corresponding observation from the body of evidence.

In the subtropical climate of Bamako City, South Africa, hydrological factors predominantly led to a decrease in surface water concentrations of chloride (-12.5%), sodium (-52.3%), EC (-27.6%) and total dissolved solids (-29.8%) from the wet season to the dry season (Sangaré et al., 2023). Nitrate concentrations, on the other hand, increased by 36.1%, while phosphate exhibited a drastic decline of 99.9% (Sangaré et al., 2023). These fluctuations in nutrient concentrations reflect the complex interaction between water flow and nutrient retention in different seasonal conditions.

A key management practice identified to reduce the high contaminant loads of high-flow and rainfall events is the establishment and management of vegetation cover. In California, USA, pesticide concentrations were three times lower in runoff from experimental treatment plots planted with resident vegetation (grasses) than runoff from bare soil treatments (Joyce et al., 2004). Therefore, it is essential to understand and manage the dynamics of high-flow events to safeguard water quality in both surface water bodies and groundwater systems. Minimising the impact of contaminant mobilisation during such periods requires best management practices.

Findings and trends from the wet-dry tropics and northern Australia

In studies from tropical wet-dry climates (Table 2-10), hydrological factors, such as monsoonal rains and wet season flushing were found to reduce the electrical conductivity of surface water and groundwater bodies. This resulted in the reported mean electrical conductivity of groundwater and surface water bodies being 2.8% and 176% higher, respectively, in the dry season relative to the wet season (Ayyandurai et al., 2022; Bennett and George, 2011, 2014; Palanisamy et al., 2023; Sangaré et al., 2023; Townsend, 2019). Despite the increase in mean EC in both surface and groundwater systems from the wet season to the dry season, hydrological factors were attributed to a 33.4% and 9.4% decrease in the mean concentration of total dissolved solids from the wet season to the dry season in groundwater and surface systems, respectively

(Bennett and George, 2011, 2014; Palanisamy et al., 2023; Sangaré et al., 2023). Mean concentrations of total suspended solids also declined in surface water systems by 91.1% from the wet season to the dry season due to hydrological factors (Townsend, 2019).

From the body of evidence, nutrient concentrations have been found to decrease during the low flows of the dry season, with hydrological factors attributed to reductions in the mean concentrations of ammonium (76.5%; Townsend and Douglas, 2017), nitrate (95.5%; Sangaré et al., 2023; Townsend and Douglas, 2017), total nitrogen (89.3%; Bennett and George, 2011) and total phosphorus (81.6%; Bennett and George, 2011) in surface water bodies from the wet season to the dry season. In the dry season, this is attributed to low flows and higher residence times facilitating denitrification. In the wet season, high concentrations of nitrogen and phosphorus species have been attributed to nutrients being flushed from the soil and transported to nearby surface water bodies.

Table 2-10 Mean change in groundwater and surface water quality parameters from the wet season to the dry season attributed to hydrological factors. Values are from studies conducted within the wet-dry tropics.

WATER BODY	WATER QUALITY PARAMETER	MEAN % CHANGE FROM THE WET SEASON TO THE DRY SEASON (NUMBER OF OBSERVATIONS)
Groundwater	Bicarbonate (HCO_3^-)	31.2 (1)
	Electrical conductivity	2.8 (3)
	Total dissolved solids	-33.4 (1)
Surface water	Ammonium (NH_4^+)	-76.5 (1)
	Electrical conductivity	176.6 (6)
	Nitrate (NO_3^-)	-95.5 (1)
	Total dissolved solids	-9.4 (4)
	Total nitrogen	-89.3 (2)
	Total phosphorus	-81.6 (2)
	Total suspended solids	-91.1 (1)

Findings and trends from the wet-dry tropics and northern Australia

The wet-dry tropics of northern Australia exhibit distinct seasonal patterns in water quality due to extreme shifts between the wet and dry seasons. Several studies from northern Australia have highlighted the strong link between hydrology and water quality outcomes. In the Daly River in the NT, for example, nutrient concentrations in surface waters show considerable seasonal variation. Nitrate and ammonium concentrations in the Daly River peak during the wet season and gradually decrease during the wet-dry transition and into the dry season. This variability is driven by wet-season high flows, which transport nutrients from surrounding agricultural lands into receiving surface water bodies (Townsend and Douglas, 2017). In contrast, the dry season is characterised by groundwater-fed discharge, which typically results in increased salinity, as indicated by EC values.

The lower Keep River in WA further illustrates these seasonal dynamics. During the wet season, baseline levels of total nitrogen and total phosphorus are 1.3 to 13 times higher than the default trigger values for tropical Australia (Total nitrogen: 0.3 mg/L; Total phosphorus: 0.01 mg/L; Bennett and George, 2014). These trigger values, established by the Australian and New Zealand

Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand, are concentrations that, if exceeded, indicate a potential environmental problem, ‘triggering’ a management response. Similarly, turbidity and TSS levels during the wet season have been reported to exceed default trigger values (Turbidity: 2-15 NTU; TSS: 2-15 mg/L) as much as 22-fold (Bennett and George, 2014). These heightened levels of nutrients and sediments during high-discharge periods in the wet season can lead to adverse ecological impacts, such as algal blooms, which pose risks to water quality and ecosystem health.

In contrast, during the dry season, reduced water volumes lead to increased EC in both the Daly and Keep rivers, with some pools in the Keep River having EC values up to 167 times higher than default trigger values (2-25 mS/m; Bennett and George, 2014). Moreover, there is an inverse relationship between discharge and conductivity during events in the Daly River, where higher flows dilute EC values (Townsend, 2019).

These trends demonstrate that in the tropical wet-dry climate of northern Australia, water quality is highly responsive to seasonal hydrology: wet-season flows facilitate nutrient and sediment transport, and dry-season conditions lead to higher salinity and reduced water quality due to concentrated ions and dissolved solids. Understanding these patterns is essential for effective management of water resources, especially in the context of agricultural expansion and irrigation development in the region.

2.3.3 Climate change

Findings and trends from the global literature

A significant challenge to managing water quality is the impact of climate change on the global hydrological system. Increases in surface temperature are affecting rates of evaporation and transpiration and altering the frequency and intensity of rainfall events and storms (Zaitchik et al., 2023). From the body of evidence, few studies have focused on assessing the impacts of climate change on water quality (Table 2-11). In temperate regions, only two studies (one in Portugal and one in Uzbekistan) have addressed this issue, both based on modelling climate change impacts. Interestingly, few observational datasets were included from the climate change impact modelling in Portugal and none of more than 4 months. However, the modelling study from Uzbekistan included long-term datasets over the past 65 years (Table 2-11). Noting the large uncertainty associated with such modelling studies, the outcomes of the climate change modelling on water quality from Portugal suggest that local increases in temperature would be associated with increased potential evaporation evapotranspiration, resulting in increased salt concentration in the soil and water resources and directly affecting crop productivity (do Nascimento et al., 2024). Contrastingly, the climate modelling results from Uzbekistan suggest that the changing climate and associated rainfall would lead to a decrease in land-based runoff to river ecosystems, reducing the nutrient load in surface waters used for agricultural purposes (Jarsjö et al., 2017).

Table 2-11 Climate change factors affecting water quality globally

CLIMATE	COUNTRY	TYPE OF STUDY	STUDY DURATION (YEARS)	WATER SOURCE (SURFACE OR GROUNDWATER OR BOTH)	MECHANISM AFFECTING WATER QUALITY	CLIMATE CHANGE IMPACTS	REFERENCE
Temperate	Portugal	Observation and modelling	0.4	Groundwater	Irrigation	Increased evapotranspiration	do Nascimento et al. (2024)
Temperate	Uzbekistan	Observation and modelling	65	Surface water	Environment	Decreased runoff and discharge	Jarsjö et al. (2017)
Tropical	Vietnam	Observation and modelling	30	Surface water	Environment	Reduced flow and nutrient discharge	Whitehead et al. (2019)

Findings and trends from the wet-dry tropics and northern Australia

In the tropical regions, there is a single study from Vietnam that has used data from the past 30 years to model climate change impacts on water quality (Table 2-11). The outcomes suggest that, with a reduction in rainfall due to climate change, there would be a reduction in water flow, leading to low levels of nutrients in the surface waters used for agriculture in Vietnam (Whitehead et al., 2019).

In northern Australia, projections suggest significant shifts in temperature, rainfall patterns, storm activity and sea level as a result of climate change. Expected temperature increases ranging from 1.3 C (under the IPCC's intermediate climate change scenario, or Representative Concentration Pathway: RCP4.5) to 5.1°C (under the 'worst case' climate change scenario: RCP8.5) by 2090 will exacerbate heatwaves and affect evaporation and transpiration rates (Brown, 2018). These changes are likely to alter seasonal weather patterns and influence the local hydrological cycle, potentially altering the frequency and intensity of rainfall and storms.

In terms of precipitation, projections indicate increased intensity and variability, and extreme El Niño and La Niña events are anticipated to become more frequent (Brown, 2018). Such changes in rainfall patterns can lead to variable runoff and river discharge, influencing the EC, total dissolved solids and nutrient loads in surface water and groundwater bodies.

Additionally, sea levels are expected to rise between 0.27 m (under RCP4.5) and 0.87 m (under RCP8.5) above the 1986 to 2005 level by 2090 (Brown, 2018; CSIRO and Bureau of Meteorology, n.d.). Such rises in sea level are expected to increase the frequency and severity of coastal inundation, threatening low-lying areas and coastal habitats (Figure 2-3).

Within the body of evidence, there were no studies investigating the effects of climate change on surface water or groundwater quality in northern Australia.

Figure 2-3 Inundation in northern Australia under future sea-level rise (2030 to 2040)
Orange circles highlight potential changes to the coastline. Saltwater intrusion and erosion could see these areas extend further inland (CSIRO Oceans and Atmosphere, n.d.).

2.3.4 Landscape factors

Findings and trends from the global literature

The global literature reveals that environmental factors, particularly soil type and irrigation mechanisms, significantly affect water quality, irrespective of seasonal rainfall, hydrology or geology (Appendix C). In temperate regions, regardless of whether groundwater or surface water is used for agriculture, the application of fertilisers and the resulting runoff typically increase nutrient levels (e.g. total phosphorus or nitrogen) and salinity in receiving water bodies (Appendix C). However, in subtropical and tropical climates, there is a noticeable lack of detailed research on how different soil types and irrigation methods affect water quality. Limited available data suggest that the use of fertilisers and anthropogenic chemicals, coupled with runoff from seasonal rainfall, plays a more frequent role in degrading water quality than other factors. While rainfall and hydrology are major contributors, additional environmental factors – such as land use patterns and the slope of agricultural lands – also significantly influence water quality, though more research is needed to understand their global relationships.

Beyond irrigation and rainfall, landscape features like soil type, hydrogeochemistry and geomorphology also exert a substantial influence on surface water and groundwater quality. Hydrogeochemical processes, such as weathering and mineral dissolution, can affect surface water pH and ion concentrations, particularly bicarbonate levels (Zikalala et al., 2021). In groundwater systems, the permeability of geological formations plays a critical role; highly permeable formations can facilitate the transport of nitrates, leading to water quality degradation in irrigation zones (Chaudhuri et al., 2012). Factors like slope steepness and altitudinal gradients also influence water quality, with steeper slopes increasing runoff volumes and sediment losses (Ashraf et al., 1999). Additionally, soil type is a key determinant of groundwater quality. Compared to finer-textured soils, coarser, sandy soils promote greater infiltration due to their high macroporosity, which in turn leads to higher nutrient concentrations in groundwater (Aziane et al., 2020).

Findings and trends from the wet-dry tropics and northern Australia

In tropical wet-dry climates, such as in the Rangit River basin in India, the dissolution of carbonate and silicate minerals has been found to influence surface water quality by introducing ions such as calcium, magnesium, sodium, potassium, and chloride (Gupta et al., 2016). Similarly, in the Godavari district, the weathering of silicate minerals and marine clays contributes to fluctuations in groundwater conductivity and ion concentrations (Gurunadha Rao et al., 2013). These hydrogeochemical processes, particularly the dissolution of calcite and dolomite during monsoon seasons, are critical in determining groundwater quality, influencing calcium concentrations and, by extension, the sodium adsorption ratio. High sodium adsorption ratio values, driven by an imbalance of calcium and magnesium relative to sodium, can lead to soil salinisation and sodicity, further complicating water and soil management (Palanisamy et al., 2023).

In northern Australia, water quality is heavily influenced by the interaction between soil types, seasonal rainfall and associated runoff. Queensland's sandy and clayey agricultural soils are especially vulnerable, with runoff leading to increased levels of nutrients and electrical conductivity, which subsequently raises groundwater salinity and decreases overall water quality (Appendix E). Similar effects are observed in WA, where seasonal environmental factors play a dominant role in influencing water quality (Appendix E). Despite these known influences, there is a marked lack of scientific research focusing on the specific environmental factors affecting water quality in northern Australia. This gap underscores the need for more comprehensive studies to assess how soil types and seasonal hydrological events drive nutrient and contaminant transport in the region. Overall, while global studies offer insights into the hydrogeochemical processes influencing water quality, northern Australia requires targeted research to better understand the unique environmental and soil-driven factors affecting its water resources.

2.4 Irrigation factors influencing water quality

2.4.1 Irrigation method

Apart from natural rainfed irrigation, the two main irrigation techniques used globally are pressurised irrigation systems and gravity-flow distribution systems. Each method has distinct applications and trade-offs, depending upon the pedological, geomorphological and hydrological context and the crop to be cultivated. To summarise, pressurised irrigation systems can irrigate large areas with a high degree of precision, offering water-efficiency rates between 80% and 95% (Brouwer et al., 1988). Micro irrigation, or trickle irrigation delivers water directly to plant roots, minimising water losses from evaporation and runoff(Brouwer et al., 1988). Spray irrigation systems mimic natural rainfall by spraying water over crops; however, these systems are prone to water loss through wind drift and evaporation (Sarwar et al., 2021). Surface irrigation systems, including basin, border, and furrow irrigation methods use gravity to distribute water across fields and are often less efficient (Brouwer et al., 1988). Lastly, surge irrigation seeks to improve the efficiency of surface irrigation methods by intermittently supplying water to furrows, reducing runoff and the volume of water used (Kifle et al., 2008).

Findings and trends from the global literature

Of the 78 international and northern Australian studies reviewed, 34 specify the irrigation method used in the study location. Surface irrigation methods (n = 30), in particular furrow irrigation (n = 20), are the most commonly reported irrigation method. There are no discernible trends among climate zones and the irrigation methods employed (Table 2-12).

Table 2-12 Irrigation methods and the number of studies reporting these methods in each climate zone

IRRIGATION CATEGORY (NUMBER OF STUDIES)	IRRIGATION METHOD	CLIMATE ZONE (NUMBER OF STUDIES)
Micro irrigation (1)	Micro irrigation	Tropical wet-dry (1)
Micro and surface irrigation (2)	Micro and surface irrigation (generic)	Mediterranean (1)
	Micro and furrow irrigation	Tropical wet-dry (1)
Micro, spray and surface irrigation (1)	Micro, spray and surface irrigation	Temperate (1)
Centre pivot (1)	Centre pivot	Temperate (1)
Surface irrigation (30)	Border and furrow irrigation	Mediterranean (1)
	Surface irrigation (generic)	Desert (1)
		Mediterranean (4)
		Temperate (1)
		Tropical wet-dry (1)
	Surface irrigation and recirculation	Mediterranean (1)
	Furrow irrigation	Subtropical (1)
		Temperate (3)
		Tropical wet-dry (16)
	Irrigation canal network	Mediterranean (1)
Spray irrigation (3)	Spray irrigation	Subtropical (2)
		Temperate (1)
Total no. of studies		34

There was no distinct trend associating micro, centre-pivot and spray irrigation systems with surface or groundwater quality due to the low number of studies (n = 8) investigating surface water and groundwater quality in regions using these systems, aside from the application of fertilisers and pesticides (Albus and Knighton, 1998; Aziane et al., 2020; Grundy, 2012; Huebsch et al., 2013; Joyce et al., 2004; Skhiri and Dechmi, 2012; Van Antwerpen et al., 2012; Zikalala et al., 2021).

The global literature highlights several key trends in the relationship between irrigation practices and water quality, particularly the effects of surface irrigation systems across different climate zones (Table 2-13). In Mediterranean climates, before-and-after studies showed no change in chloride levels, but nitrate levels decreased by 33.3% between low- and high-flow conditions. Electrical conductivity also decreased by 20% (Causapé et al., 2006).

Table 2-13 Reported changes in water quality parameters, grouped by climate
Results are separated into before-and-after studies and studies reporting water quality in low-flow versus high-flow conditions.

		MEAN % CHANGE (NUMBER OF OBSERVATIONS)	
CLIMATE	WATER QUALITY VARIABLES	BEFORE-AND-AFTER STUDIES	LOW- AND HIGH-FLOW STUDIES
Mediterranean	Chloride (Cl-)	0 (1)	NA
	Nitrate (NO3−)	NA	−33.3 (1)
	Electrical conductivity	NA	−20 (1)
Tropical wet-dry	Ametryn	NA	−83.3 (1)
	Atrazine	−32.6 (1)	−66.7 (1)
	Diuron	NA	−56.5 (1)
	Fipronil	112.5 (1)	NA
	Pendimethalin	−41.7 (1)	NA
	Pirimicarb	−11 (1)	NA
	Quintozene	200 (1)	NA
	Total nitrogen	−36.9 (1)	NA
	Total phosphorus	8.6 (1)	NA

†NA = data not available.

Findings and trends from the wet-dry tropics and northern Australia

Very few, if any, of the reviewed studies investigated the impacts of irrigation methods on surface water and groundwater quality. This presents a significant gap in the literature and our understanding. In the lower Burdekin, the herbicides ametryn and atrazine showed decreases of 83.3% and 66.7%, respectively, between low- and high-flow events (Davis et al., 2013). Conversely, in the Ord River Irrigation Area, pesticides like fipronil and quintozene exhibited sharp increases with fipronil rising by 112.5% and quintozene by 200% (Moulden et al., 2006). This illustrates how irrigation practices, coupled with climate conditions, can either reduce or exacerbate water quality variables, posing challenges for water management in agricultural settings. The data also reveal that while some nutrients and pesticides are diluted by hydrological processes, others persist or even increase in concentration depending on specific climate and flow conditions.

2.4.2 Irrigation area

The USA has the largest irrigation area within the body of evidence. USA irrigation systems range from 4 ha to 181,300 ha, indicating its heavy reliance on irrigation for agriculture. Australia and Spain also display wide ranges in irrigation area; for example, Australian studies report irrigation areas ranging from 9 to 100,000 ha, reflecting the diversity of agricultural practices in the country.

Findings and trends from the wet-dry tropics and northern Australia

In northern Australia, conclusions regarding water quality changes associated with different irrigation areas are limited, due to the low number of studies. Paddocks from seven farms, distributed across the Burdekin delta, were sampled during high and low flow events over the course of 5 years. Overall, the results showed substantial declines in pesticide levels from low-flow (typically during the dry season) to high-flow events (typically occurring during the wet season), with ametryn decreasing by 83%, atrazine by 67%, and diuron by 56% (Davis et al., 2013).

2.4.3 Aquifer salinisation

The widespread use of irrigation practices significantly influences surface water and groundwater quality in agricultural regions worldwide. In groundwater systems in particular, irrigation activity can lead to the secondary salinisation of aquifers via seawater intrusion The over-extraction of groundwater for anthropogenic uses, such as irrigation, can lower the watertable. In coastal aquifers, this can lead to seawater encroachment and saline intrusion, increasing groundwater EC and total dissolved solids (Ayyandurai et al., 2022; Khezzani and Bouchemal, 2018; Sarkar et al., 2021; Taşan et al., 2022).

A second mechanism by which irrigation activity can lead to aquifer salinisation, is through the leaching of irrigation water into groundwater systems. Leaching of irrigation water can l increase the height of the watertable, bringing salts into the plant root zone. When water from the soil is taken up by plants or evaporated, these salts can accumulate in the soil (Kulmatov et al., 2018). In wet-dry tropical climates, implementing irrigation schemes can increase evapotranspiration due to increased crop transpiration during irrigation periods (do Nascimento et al., 2024). This increase in evapotranspiration has been found to increase groundwater concentrations of total dissolved solids and EC (Ali et al., 2008). Moreover, any salts accumulated in the soil can be leached back into the groundwater during rainfall events or irrigation periods (Ortiz and Jin, 2021).

2.4.4 Irrigation water quality

The quality of the irrigation water source also plays a crucial role in influencing surface water conductivity (Causapé et al., 2004). For example, in the Great Menderes Basin, Turkey, a negative feedback was established in which irrigation waters were draining into the Great Menderes River, the irrigation supply source. Due to high groundwater salinity levels and a statistically significant relationship between groundwater and drainage salinity, significant quantities of salt were subsequently transported to the Great Menderes River from irrigation schemes in the region and accumulated in the soil profile, negatively affecting riverine ecology and causing the extinction of two aquatic species (Koç, 2008). This cumulative effect underscores the complex interplay between irrigation practices, groundwater extraction, hydrology and the consequential changes in surface water and groundwater EC.

2.4.5 Fertiliser and pesticide application

Findings and trends from the global literature

Fertiliser applications on irrigated land can result in elevated levels of nutrients such as total phosphorus and total nitrogen in drainage waters, increasing surface water concentrations during the irrigation season (Barbieri et al., 2021; Mosley and Fleming, 2010). Different cropping systems under irrigation can also affect groundwater nutrient concentrations. For example, nitrate concentrations in mulch-till continuous sweet corn systems are 50% lower than in ridge-till cropping systems, which highlights the importance of best management agricultural practices in groundwater quality management (Albus and Knighton, 1998).

Among the observations that found an impact of irrigation practices on surface and/or groundwater quality, approximately 35% documented co-occurring environmental impacts and approximately 65% documented water quality impacts of irrigation practices alone. The most commonly reported irrigation mechanism affecting water quality was fertiliser application (15 observations; Table 2-14), followed by fertiliser application and the leaching of nutrients into groundwater bodies (6 observations).

Table 2-14 Irrigation mechanisms found to affect surface water and groundwater quality and the proportion of studies within the body of evidence that documented them

IRRIGATION MECHANISMS REPORTED TO AFFECT WATER QUALITY	NUMBER OF OBSERVATIONS
Altered hydrology	1
Discharge	1
Drainage systems	1
Fertiliser application	15
Fertiliser application and leaching	6
Groundwater extraction	1
Groundwater extraction, saline intrusion	4
Groundwater source	1
Irrigation drainage water	1
Irrigation return flows	2
Irrigation return flows, fertiliser application and leaching	1
Irrigation water quality	3
Irrigation water quality, fertiliser application, leaching	1
Leaching/infiltration	2
Leakage from supply and drainage channels	1
Mobilisation	2
Pesticide use	3
Pesticide use, pesticide type	1
Pesticide use, surface runoff, pesticide application method	1
Runoff	2

Findings and trends from the wet-dry tropics and northern Australia

In the wet-dry tropics, fertiliser application was reported to affect nutrient concentrations (potassium, total phosphorus, phosphate, total nitrogen, nitrate and ammonia), as well as sodium concentrations, electrical conductivity and total dissolved solids. However, while fertiliser application may have added nutrients to the system, these trends are masked by numerous additional and contextual factors influencing water quality in these areas and their water bodies.

The results presented in Table 2-15 highlight significant variations in the impact of fertiliser application on water quality in the wet-dry tropics and northern Australia. Globally, changes in nitrate concentrations show substantial variation, particularly in regions like India, where nitrate levels fluctuate drastically between pre- and post-monsoon periods. For example, nitrate levels in India showed both significant increases (up to 891.7% according to Gurunadha Rao et al. (2013))

and decreases (−24.7% and −47% according to Ayyandurai et al. (2022) and Palanisamy et al. (2023), respectively) from pre- to post-monsoon. In Mexico, nitrate concentrations increased by 106.3% from pre- to post-monsoon (Sedeño-Díaz et al., 2022). These global trends suggest that seasonal hydrological patterns, land use practices and fertiliser management significantly influence nutrient leaching and water quality, particularly in regions with heavy rainfall or distinct wet and dry seasons.

In contrast, northern Australia shows relatively less variability, trending towards reduced nutrient concentrations following the irrigation season or over time. Total nitrogen, for instance, saw reductions of 36.9% during the transition from irrigation to pre-wet season (Smith et al., 2007), and up to 90.9% in alluvial soils between 2009 and 2010 (Grundy, 2012). Phosphorus however, exhibited a slight increase of 8.6% during the transition from irrigation to pre-wet season (Smith et al., 2007).

Table 2-15 The impact of fertiliser application upon surface water and groundwater quality in the wet-dry tropics and northern Australia

Abbreviations as follows: not available (NA).

WATER QUALITY CATEGORY	WATER QUALITY VARIABLE	COUNTRY (REGION)	MEAN % CHANGE (MEASURE)	REFERENCE
Nutrients	Nitrate (NO_3^-)	India	−24.7 (Pre- to post-monsoon)	Ayyandurai et al. (2022)
		India	NA	Balamurugan et al. (2020)
		India	891.7 (Pre- to post-monsoon)	Gurunadha Rao et al. (2013)
		India	−47.0 (Pre- to post-monsoon)	Palanisamy et al. (2023)
		Mexico	106.3 (Pre- to post-monsoon)	Sedeño-Díaz et al. (2024)
		Korea	NA	Yoon et al. (2006)
	Ammonia-N (NH_3-N)	Korea	NA	Yoon et al. (2006)
	Total nitrogen	Korea	NA	Yoon et al. (2006)
		Australia (northern)	−36.9 (Irrigation season to pre-wet season)	Smith et al. (2007)
		Australia (northern)	−85.5 (clay soils, 2009 to 2010)	Grundy et al. (2012)
		Australia (northern)	−90.9 (alluvial soils, 2009 to 2010)	Grundy et al. (2012)
		Australia (northern)	NA	Oliver et al. (2006)
	Total phosphorus	Australia (northern)	8.6 (Irrigation to pre-wet season)	Smith et al. (2007)
		Korea	NA	Yoon et al. (2006)
	Phosphate (PO_4^{3-})	India	−40.5 (Pre- to post-monsoon)	Ayyandurai et al. (2022)

WATER QUALITY CATEGORY	WATER QUALITY VARIABLE	COUNTRY (REGION)	MEAN % CHANGE (MEASURE)	REFERENCE
	Potassium (K^+)	India	1.8 (Pre- to post-monsoon)	Ayyandurai et al. (2022)
		India	−10.2 (Pre- to post-monsoon)	Palanisamy et al. (2023)
Major ions	Sodium (Na^+)	India	11.8 (Pre- to post-monsoon)	Palanisamy et al. (2023)

2.4.6 Conclusion

The development of irrigation resources in northern Australia comes with significant environmental and hydrological challenges. The findings from this report highlight the impacts of environmental and irrigation factors on water quality, particularly in regions where seasonal rainfall, soil characteristics and agricultural runoff converge to influence both surface water and groundwater systems. The limited research in northern Australia underscores the need for a more comprehensive understanding of how irrigation practices affect water resources across varying soil types and under future climate change. Current data reveal that nutrient runoff, pesticide contamination and salinity are key concerns that, if not properly managed, could degrade local ecosystems and reduce water quality for agricultural and community use.

Sustainable water resource development involves prioritising long-term water quality monitoring and the implementation of best management practices, such as optimising fertiliser use and increasing the efficiency of pesticide application. Moreover, improving our understanding of the potential climate change impacts on water quality will increase our ability to manage water resources sustainably in a changing climate. Such efforts will require open data sharing and access, as a collaborative, informed and adaptive approach is essential to balancing the region’s agricultural growth with the protection of its valuable and vulnerable water resources.

3 Water quality data in northern Australia

3.1 Background

Water resource development in northern Australia requires careful management as it can lead to a range of environmental impacts, including changes to flow regimes (both surface water and groundwater), land use, river channel connectivity and natural waterway conditions, including water quality. The rivers, floodplains, coastal and nearshore regions of northern Australia support a diverse range of species that hold recreational, commercial and cultural values. To understand the potential risks to the natural river catchment environment that is associated with water resource development, this review examines international and national studies to summarise the environmental factors and characteristics of irrigation schemes that have been found to influence groundwater and surface water quality.

3.2 Baseline water quality data

The data availability from various government databases is presented in Appendix F. In addition to a few databases, there are several technical reports that investigated water quality in northern Australia, but their data are not accessible or publicly available. Moreover, the region lacks comprehensive water quality databases, particularly for surface water bodies. Such databases are necessary for assessing long-term trends and understanding the historical influences on current water quality variables. These are particularly important because, in many river systems, antecedent hydrological conditions influence water quality variables today. Therefore, past data, access to older reports and long-term monitoring studies are vital in understanding observations made today (Zikalala et al., 2021). However, much of this older knowledge is stored in reports that have not yet been digitised and so are unavailable for inclusion in large-scale reviews.

The simplest form of surface water and groundwater quality monitoring in northern Australia includes long-term datasets of water temperature and rainfall, with other physicochemical and abiotic water quality parameters recently added to the suite of variables frequently monitored (see Appendix F). The interactive map from the Bureau of Meteorology's Australian Water Data Service (http://www.bom.gov.au/waterdata/) provides detailed information on multiple sites across Australia that have long-term data loggers and river gauges, providing data on water volumes in storage, river and groundwater levels and water quality, as well as local water uses and restrictions. This website provides an online platform for the public to analyse and visualise regional water quality. Furthermore, the Australian Water Resources Information System (AWRIS) has set priorities for the next 5 years (2023 to 2028) to build: (i) a new national water data hub, (ii) a single platform for public water information, and (iii) a hydrological model integration and enhancement. AWRIS will also provide sustainable decision support, water information and data leadership, and water and hydro-climate science leadership.

The only sediment core-based long-term (100 years) monitoring of water quality available for northern Australia is in WA. Long-term monitoring data on drinking water quality has been collected in the NT but the data are not publicly available. For northern Queensland, long-term datasets (>4 million water quality records) that cover chemical, physical and biological properties of water and sediment are available for various rivers and aquifers from 1968 onwards. An interactive map on pesticide concentrations in water and sediment samples and Pesticide Risk Metric (https://prmdashboard.des.qld.gov.au/) across Queensland is also available from the Department of Environment, Science, and Innovation (https://apps.des.qld.gov.au/water-data-portal/map). Most states and territories in Australia have a water quality monitoring system in place, but there is a significant lack of up-to-date data available in a common platform for public usage. GIS files with the locations of monitoring sites are readily available for most states and territories in Australia, as are reports and peer-reviewed publications, but the associated water quality data are not.

In summary, only limited surface water and groundwater quality data for northern Australia are available to the public. These datasets have significant gaps in spatial and temporal coverage and in the water quality parameters monitored, and they are typically not maintained. Looking forward, AWRIS's priorities to centralise and improve national water data capabilities may begin to resolve the lack of collated and publicly available water quality data for northern Australia.

3.3 Existing water quality modelling studies in northern Australia

Water quality modelling is a key component of water resource development and management, but few water quality modelling studies have been conducted in northern Australia. The studies include is a mix of geochemical, soil salinity, water quality and integrated parameter models (Appendix G). However, these modelling studies are based on datasets with less than 5 years of data and, except the recent water quality model of Lillicrap et al. (2015), were developed almost 2 decades ago.

Lillicrap et al. (2015) is part of a report series that assesses the surface water chemistry of the 8000 ha Weaber Plain (Goomig Farmlands) in northern WA (Lillicrap et al., 2015; Lillicrap et al., 2011). The reports were commissioned in 2008 as part of the Ord River Irrigation Expansion project connecting the Weaber Plain to the Ord River Irrigation Area by constructing an irrigation supply channel. Initial groundwater-level simulations of the project revealed that introducing irrigation would lead the groundwater levels of the Weaber Plain to rise, potentially affecting soil salinity and surface water quality (Kellogg Brown and Root Pty Ltd, 2010, 2011). To eliminate this risk, groundwater management plans were developed to pump groundwater from beneath the Weaber Plain into the main irrigation supply channel. As part of the Ord River Irrigation Expansion project approvals process, several groundwater pumping scenarios were modelled to understand the impact of groundwater pumping on the water quality of the main irrigation supply (Lillicrap et al., 2015; Lillicrap et al., 2011). The AquaChem™ hydrochemical model was used to simulate groundwater and supply channel mixing and predict salinity levels resulting from the different pumping scenarios. These scenarios included 'expected' and 'worst case' conditions, varying in the volume of groundwater pumped and the flow rates within the supply channel. Results indicated that, under both scenarios, total dissolved solids in the groundwater under Weaber Plain, initially at 1162 mg/L, could be reduced to levels suitable for irrigation (178 to 192 mg/L) upon mixing with supply channel water.

Despite the significance of these findings, accessing technical reports, particularly those written before 1990, remains challenging. Due to their age and never having being digitised, a substantial number of historical technical reports are either inaccessible or lost, complicating efforts to understand baseline water quality dynamics across northern Australia. Efforts to enhance the accessibility and preservation of these critical reports are crucial. Current repositories like the Northern Australia Water Resources Digital Library, CSIRO's Research Publications Repository and others contain subsets of available reports but lack integration and comprehensive coverage. Establishing a unified, centrally managed repository is required to streamline access, optimise resource allocation, and ensure these valuable studies are readily available to researchers, policymakers and the public. Collaboration among stakeholders and organisations managing these repositories is essential to achieve this goal effectively, addressing challenges related to funding, staffing, maintenance and digital storage capacity.

While existing water quality modelling studies provide valuable insights into the impacts of agricultural development on northern Australia's water resources, the fragmented nature of available data highlights the need for systematic digitisation and consolidation efforts. Establishing a unified repository would not only enhance accessibility but also facilitate informed decision making and sustainable management of water resources in this ecologically significant region.

4 Knowledge gaps

Water resource management in irrigated agriculture faces numerous challenges and knowledge gaps at both international and national levels. This report highlights several key areas where further research is needed to improve our understanding of the influences of environmental factors and agriculture on water quality, particularly in tropical wet-dry regions. The following gaps highlight the complexities in managing water resources in northern Australia effectively.

Herbicide runoff and pesticide concentrations

There are significant uncertainties regarding the dynamics of herbicide runoff and temporal variations in soil pesticide concentrations. Understanding how these chemicals move through the environment, particularly after irrigation or rainfall, is critical for protecting water quality.

Soil amelioration and groundwater quality

The long-term impacts of repeated applications of soil amelioration agents, such as gypsum, on deep drainage and groundwater quality are not well understood. Research is needed to determine how these practices may affect both surface water and groundwater systems over time.

Lack of long-term monitoring data

One of the most critical gaps is the absence of robust and long-term water quality monitoring data, particularly because of the importance of antecedent hydrology, agriculture and fertiliser use in influencing current and future water quality conditions. Accurate simulation of water quality across a river basin, for example, is particularly challenging due to the lack of consistent datasets. This hampers the ability to predict trends and make informed decisions about water resource management.

Fertiliser efficiency

There is a pressing need to enhance fertiliser use efficiency through best management practices and use of slow-release fertilisers. Current practices in some areas has resulted in nutrient runoff, which can degrade water quality. Predicting future fertiliser use trends globally adds another layer of complexity to this issue.

Climate change and hydrological uncertainty

Climate change compounds existing challenges in water resource management by altering global patterns of evaporation, evapotranspiration and precipitation. These changes introduce new uncertainties and reduce the predictability of the hydrological cycle, affecting groundwater recharge and complicating efforts to achieve sustainable water management. There is also a lack of understanding about how climate change will inevitably affect water quality.

Knowledge gaps in northern Australia

In northern Australia, water quality research is limited, particularly in regard to how irrigation practices affect water quality beyond cotton farming operations. Most studies focus on cotton, leaving gaps in the assessment of other agricultural systems. Additionally, the region lacks comprehensive water quality databases, especially for surface water bodies. Such databases are crucial for assessing long-term trends and understanding how historical conditions influence present-day water quality variables.

Past hydrological conditions also play a critical role in shaping current water quality. Many older reports and long-term monitoring studies are either inaccessible or have been lost, as government technical reports have often been destroyed or lost when staff have retired or left their positions. This loss of information hinders comprehensive reviews of water quality trends. Establishing a centralised repository for water quality data and literature is essential for improving collaboration, data access, and informed decision making in northern Australia.

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Appendices

Appendix A

Author(s), publication year and title for reports and journal articles included within the body of evidence

AUTHOR(S)	YEAR	TITLE
Albus WL and Knighton RE	1998	Water quality in a sand plain after conversion from dryland to irrigation: tillage and cropping systems compared
Ali and Salama	2003	Groundwater quality in the Ord irrigation area, its suitability for irrigation and prediction of salinity and sodicity hazards
Ali et al.	n.d.	Evaluating impacts of drainage discharge from engineering salinity schemes on water and soil chemistry of downstream river systems of the wheat belt of Western Australia
Ali et al.	2002	Geochemical interactions between groundwater and soil, groundwater recycling and evaporation in the ORIA
Alqarawy A	2023	Characterization of groundwater in Quaternary aquifer of the Yanbu Al-Nakhl Basin, Al-Madinah Al-Munawarah Province using pumping tests and hydrochemical techniques
Ashraf MS, Izadi B, King BA and Neibling H	1999	Field evaluation of furrow irrigation performance, sediment loss, and bromide transport in a highly erosive silt loam soil
Ayyandurai R, Venkateswaran S and Karunanidhi D	2022	Hydrogeochemical assessment of groundwater quality and suitability for irrigation in the coastal part of Cuddalore district, Tamil Nadu, India
Aziane N, Larif M, Khaddari A, Ebn touhami M, Zouahri A, Nassali H and Elyoubi MS	2020	State of nitric pollution of the Mnasra aquifer, coastal zone of the Gharb plain (Morocco)
Balamurugan P, Kumar PS, Shankar K, Nagavinothini R and Vijayasurya K	2020	Non-carcinogenic risk assessment of groundwater in southern part of Salem district in Tamilnadu, India
Barbieri MV, Peris A, Postigo C, Moya-Garcés A, Monllor-Alcaraz LS, Rambla-Alegre M, Eljarrat E and López de Alda M	2021	Evaluation of the occurrence and fate of pesticides in a typical Mediterranean delta ecosystem (Ebro River Delta) and risk assessment for aquatic organisms
Bennett D and George RJ	2014	Goomig Farmlands development: baseline water quality in the lower Keep River
Bennett et al.	2016	Cockatoo Sands in the Victoria Highway and Carlton Hill areas, East Kimberley: hydrogeology, aquifer properties and groundwater chemistry
Bennett DL and George RJ	2011	Surface water characteristics of the Weaber Plain and lower Keep River catchments: data review and preliminary results
Bern CR and Stogner RW	2017	The Niobrara Formation as a challenge to water quality in the Arkansas River, Colorado, USA
Bouarfa S, Marlet S, Douaoui A, Hartani T, Mekki I, Ghazouani W, Aissa IB, Vincent B, Hassani F and Kuper M	2009	Salinity patterns in irrigation systems, a threat to be demystified, a constraint to be managed: Field evidence from Algeria and Tunisia

AUTHOR(S)	YEAR	TITLE
Causapé J, Quílez D and Aragüés R	2006	Groundwater quality in CR-V irrigation district (Bardenas I, Spain): Alternative scenarios to reduce off-site salt and nitrate contamination
Causapé J, Quílez D and Aragüés R	2004	Salt and nitrate concentrations in the surface waters of the CR-V irrigation district (Bardenas I, Spain): diagnosis and prescriptions for reducing off-site contamination
Causapé J, Quílez D and Aragüés R	2006	Irrigation efficiency and quality of irrigation return flows in the Ebro River Basin: An overview
Chaudhuri S, Ale S, DeLaune P and Rajan N	2012	Spatio-temporal variability of groundwater nitrate concentration in Texas: 1960 to 2010
Davis AM, Thorburn PJ, Lewis SE, Bainbridge ZT, Attard SJ, Milla R and Brodie JE	2013	Environmental impacts of irrigated sugarcane production: Herbicide run-off dynamics from farms and associated drainage systems
De Miguel A, Martínez-Hernández V, Leal M, González-Naranjo V, De Bustamante I, Lillo J, Martín I, Salas JJ and Palacios-Díaz MP	2013	Short-term effects of reclaimed water irrigation: *Jatropha curcas* L. cultivation
do Nascimento TVM, de Oliveira RP and Condesso de Melo MT	2024	Impacts of large-scale irrigation and climate change on groundwater quality and the hydrological cycle: a case study of the Alqueva irrigation scheme and the Gabros de Beja aquifer system
El Alfy M, Lashin A, Abdalla F and Al-Bassam A	2017	Assessing the hydrogeochemical processes affecting groundwater pollution in arid areas using an integration of geochemical equilibrium and multivariate statistical techniques
Elango L, Kumar SS and Rajmohan N	2003	Hydrochemical studies of ground water in Chengalpet region
Farhat B, Chrigui R, Rebai N and Sebei A	2023	Analysis of hydrochemical characteristics and assessment of organic pollutants (PAH and PCB) in El Fahs plain aquifer, northeast of Tunisia
Gautam A and Rai SC	2023	Hydrogeochemical characterization and quality assessment of groundwater resources in the Upper-Doab region of Uttar Pradesh, India
Gikas GD	2014	Water quality of drainage canals and assessment of nutrient loads using QUAL2Kw
González-Acevedo ZI, Padilla-Reyes DA and Ramos-Leal JA	2016	Quality assessment of irrigation water related to soil salinization in Tierra Nueva, San Luis Potosí, Mexico
Grundy P and Hickman M	2012	Feasibility of cotton production in the Burdekin
Gupta S, Nayek S and Chakraborty D	2016	Hydrochemical evaluation of Rangit River, Sikkim, India: using Water Quality Index and multivariate statistics
Gurunadha Rao VVS, Tamma Rao G, Surinaidu L, Mahesh J, Mallikharjuna Rao ST and Mangaraja Rao B	2013	Assessment of geochemical processes occurring in groundwaters in the coastal alluvial aquifer
Harter T, Davis H, Mathews MC and Meyer RD	2002	Shallow groundwater quality on dairy farms with irrigated forage crops
Huebsch M, Horan B, Blum P, Richards KG, Grant J and Fenton O	2013	Impact of agronomic practices of an intensive dairy farm on nitrogen concentrations in a karst aquifer in Ireland

AUTHOR(S)	YEAR	TITLE
Jarsjö J, Törnqvist R and Su Y	2017	Climate-driven change of nitrogen retention–attenuation near irrigated fields: multi-model projections for Central Asia
Joyce BA, Wallender WW, Angermann T, Wilson BW, Werner I, Oliver MN, Zalom FG and Henderson JD	2004	Using infiltration enhancement and soil water management to reduce diazinon in runoff
Khezzani B and Bouchemal S	2018	Variations in groundwater levels and quality due to agricultural over-exploitation in an arid environment: the phreatic aquifer of the Souf oasis (Algerian Sahara)
Koç C	2008	Environmental effects of salinity load in Great Menderes Basin irrigation schemes
Kulmatov R, Groll M, Rasulov A, Soliev I and Romic M	2018	Status quo and present challenges of the sustainable use and management of water and land resources in Central Asian irrigation zones – the example of the Navoi region (Uzbekistan)
Lillicrap A, Raper P, George RJ and Bennett DL	2011	Groundwater chemistry of the Weaber Plain: preliminary results
Lillicrap A, George RJ, Ryder A and Bennett DL	2015	Groundwater chemistry of the Weaber Plain (Goomig Farmlands): baseline results 2010–13
Liu X, Zhang G, Xu YJ, Zhang J, Wu Y and Ju H	2021	Determining water allocation scheme to attain nutrient management objective for a large lake receiving irrigation discharge
Mosley LM and Fleming N	2010	Pollutant loads returned to the lower Murray River from flood-irrigated agriculture
Moulden, J H, Yeates, S J, Strickland, G R, Plunkett, G M	2006	Developing an environmentally responsible irrigation system for cotton in the Ord River Irrigation Area
Oliver and Kookana	2006	On-farm management practices to minimise off-site movement of pesticides from furrow irrigation
Oliver and Kookana	2006	Minimising off-site movement of contaminants in furrow irrigation using polyacrylamide (PAM). I. Pesticides
Oliver and Kookana	2006	Minimising off-site movement of contaminants in furrow irrigation using polyacrylamide (PAM). II. Phosphorus, nitrogen, carbon, and sediment
Ortiz AC and Jin L	2021	Chemical and hydrological controls on salt accumulation in irrigated soils of southwestern US
Palanisamy M, Krishnan T, Rahaman A, Jothiramalingam K, Thiyagarajan I and P SK	2023	Geochemical characterisation and geostatistical evaluation of groundwater suitability: a case study in Perambalur District, Tamil Nadu, India
Panaskar DB, Wagh VM, Muley AA, Mukate SV, Pawar RS and Aamalawar ML	2016	Evaluating groundwater suitability for the domestic, irrigation, and industrial purposes in Nanded Tehsil, Maharashtra, India, using GIS and statistics
Parslow et al.	2003	The response of the lower Ord River and estuary to management of catchment flows and sediment and nutrient loads. Ord-Bonaparte Program Project 3.4/4.1/4.2b
Paul et al.	2011	Weaber Plain aquifer test results
Petheram C, Bristow KL and Nelson PN	2008	Understanding and managing groundwater and salinity in a tropical conjunctive water use irrigation district

AUTHOR(S)	YEAR	TITLE
Pollock et al.	2003	Water levels and water quality trends in the ORIA for the period Sept 01-Mar 03
Pradhan S, Chandrasekharan H, Sehgal VK, Chakraborty D, Jain N, Kamble K and Kamra SK	2010	Effects of monsoon on groundwater quality for irrigation in Gohana Block of Haryana
Raper et al.	2015	Preliminary soil and groundwater assessment of the Mantinea Development area, East Kimberley, Western Australia
Salama et al.	2002	Hydrochemical and isotopic characteristics of the surface and groundwater of the hydrological zones of the Ord Stage 1 Irrigation Area
Sangaré LO, Sun H, Ba S, Konté MS, Samaké M and Zheng T	2023	A multivariate approach to assessing the water quality of the Bamako reach of the Niger River in Mali as irrigation water
Sarkar B, Islam A and Majumder A	2021	Seawater intrusion into groundwater and its impact on irrigation and agriculture: evidence from the coastal region of West Bengal, India
S Sedeño-Díaz JE, López-López E, Rodríguez-Romero AJ, Leos KF, Martínez MT and Sánchez OEE	2022	Using different multivariate approaches to assess water quality of qanats in arid zones of Southern Central Mexico
Shinozuka K, Chiwa M, Nakamura K, Nagao S and Kume A	2016	Stream water nitrogen eutrophication during non-irrigated periods in a paddy-dominated agricultural basin in a snowfall area in Japan
Singh PK, Verma P and Tiwari AK	2018	Hydrogeochemical investigation and qualitative assessment of groundwater resources in Bokaro district, Jharkhand, India
Skhiri A and Dechmi F	2012	Impact of sprinkler irrigation management on the Del Reguero river (Spain) II: Phosphorus mass balance
Smith A, Pollock D, Palmer D and Price A	2007	Ord River Irrigation Area (ORIA) groundwater drainage and discharge evaluation: survey of groundwater quality 2006
Smith et al.	2006	Ord River Irrigation Area (ORIA) groundwater drainage and discharge evaluation: piezometer installation report
Somay MA and Gemici U	2012	Groundwater quality degradation in the Büyük Menderes River coastal wetland
State of Queensland (Department of Natural Resources)	1998	Emerald Irrigation Area: drainage management study – project report
Swarna Latha P and Nageswara Rao K	2012	An integrated approach to assess the quality of groundwater in a coastal aquifer of Andhra Pradesh, India
Taşan M, Demir Y and Taşan S	2022	Groundwater quality assessment using principal component analysis and hierarchical cluster analysis in Alaçam, Turkey
Thayalakumaran T, Lenahan MJ and Bristow KL	2015	Dissolved organic carbon in groundwater overlain by irrigated sugarcane
Townsend SA	2019	Discharge-driven seasonal pattern of ionic solutes, suspended sediment and water clarity for a tropical savanna river in northern Australia

AUTHOR(S)	YEAR	TITLE
Townsend SA and Douglas MM	2017	Discharge-driven flood and seasonal patterns of phytoplankton biomass and composition of an Australian tropical savannah river
Valiente N, Carrey R, Otero N, Soler A, Sanz D, Muñoz-Martín A, Jirsa F, Wanek W and Gómez-Alday JJ	2018	A multi-isotopic approach to investigate the influence of land use on nitrate removal in a highly saline lake-aquifer system
van der Laan M, van Antwerpen R and Bristow KL	2012	River water quality in the northern sugarcane-producing regions of South Africa and implications for irrigation: a scoping study
Whitehead PG, Jin L, Bussi G, Voepel HE, Darby SE, Vasilopoulos G, Manley R, Rodda H, Hutton C, Hackney C, Tri VPD and Hung NN	2019	Water quality modelling of the Mekong River basin: climate change and socioeconomics drive flow and nutrient flux changes to the Mekong Delta
Wilkins DW	1998	Summary of the Southwest Alluvial Basins regional aquifer-system analysis in parts of Colorado, New Mexico, and Texas
Yeates	2016	Comparison of delayed release N fertiliser options for cotton on clay soils with urea; yield, N fertiliser uptake and N losses in runoff – Burdekin 2013–2015
Yoon K-S, Cho J-Y, Choi J-K and Son J-G	2006	Water management and N, P losses from paddy fields in southern Korea
Zikalala P, Kisekka I and Grismer M	2021	Hydrological processing of salinity and nitrate in the Salinas Valley agricultural watershed

Appendix B

Country-specific water quality variables in various global regions derived from the body of evidence

Abbreviations as follows: not available (NA), not specified (NS), electrical conductivity (EC), total dissolved solids (TDS). Nutrients include phosphate, total phosphorus, nitrate, ammonia and total nitrogen. Major ions include bicarbonate, sulfate, chloride, sodium, calcium and magnesium, minor ions include fluoride, and minerals include silica.

COUNTRY	LOCATION	SEASON (DRY OR WET OR BOTH)	WATER RESOURCE (GROUNDWATER, SURFACE WATER BOTH)	RAINFALL (MM)	IRRIGATION OR ENVIRONMENTAL EFFECTS ON WATER QUALITY	WATER QUALITY VARIABLES	REFERENCES
Temperate							
Portugal	Alentejo	Both	Groundwater	517	Irrigation	Major ions	do Nascimento et al. (2024)
USA	California	Both	Surface water	470	Irrigation	Nutrients	Zikalala et al. (2021)
	California	Both	Groundwater	290	Irrigation	Nutrients, EC	Harter et al. (2002)
	Colorado	NA	Surface water	320	Both	Minerals	Bern et al. (2017)
Turkey	Alaçam	NA	Groundwater	784	Irrigation	EC	Taşan et al. (2022)
	Great Menderes Basin	Irrigation season only	Both	656	Environment, Irrigation	EC	Koç (2008)
	Soke plain	NA	Groundwater	963	Both	EC	Somay and Gemici (2012)
Spain	Bardenas irrigation district	Both	Groundwater	419	Both	Nutrients, EC	Causapé J et al. (2006)
	Petrola Endorheic Basin	Not specified	Both	400	Irrigation	Nutrients	Valiente et al. (2018)
	Seville	Both	Groundwater	650	Both	Nutrients, EC	De Miguel et al. (2013)
Uzbekistan	Navoi region	Dry	Groundwater	90	Irrigation	Salinity	Kulmatov et al. (2018)
	Kziljar	Both	Surface water	100	Environment	Nutrients	Jarsjö et al. (2017)
China	Songnen plain	Not specified	Both	400	Irrigation	Nutrients	Liu et al. (2021)
Ireland	Cork	Both	Groundwater	1200	Irrigation	Nutrients	Huebsch et al. (2013)
Korea	Namwon-si	Both	Both	1313	Both	Nutrients	Yoon et al. (2006)

COUNTRY	LOCATION	SEASON (DRY OR WET OR BOTH)	WATER RESOURCE (GROUNDWATER, SURFACE WATER BOTH)	RAINFALL (MM)	IRRIGATION OR ENVIRONMENTAL EFFECTS ON WATER QUALITY	WATER QUALITY VARIABLES	REFERENCES
Subtropical							
Tunisia	Zaghouan region	Dry	Groundwater	296	Irrigation	Nutrients, EC, TDS, major ions	Farhat et al. (2024)
	Kebili Province	Both	Groundwater	100	Irrigation	EC	Bouarfa et al. (2009)
Algeria	Northern Algeria	NS	Groundwater	250	Irrigation	EC	Bouarfa et al. (2009)
South Africa	Crocodile river	Both	Surface water	880	Irrigation	EC	van der Laan et al. (2012)
	Lomati river	Both	Surface water	760	Irrigation	EC	van der Laan et al. (2012)
	Pongola river	Both	Surface water	610	Irrigation	EC	van der Laan et al. (2012)
Tropical							
India	New Delhi	Both	Groundwater	567	Irrigation	EC	Pradhan et al. (2010)
	Andhra Pradesh	Both	Groundwater	456	Both	EC	Gurunadha Rao et al. (2013)
	Sikkim	Wet	Surface water	1150	Environment	pH, EC, TDS, nutrients, major ions	Gupta et al. (2016)
	Tamil Nadu	Both	Groundwater	1446	Both	pH, EC, TDS, major and minor ions, nutrients	Ayyandurai et al. (2022)
	Tamil Nadu	Both	Groundwater	908	Both	pH, EC, major ions	Palanisamy et al. (2023)
	Tamil Nadu	Wet	Groundwater	1512	Environment	pH, EC, TDS, major ions, nutrients	Balamurugan et al. (2020)
	Jharkhand	Both	Groundwater	1363	Both	Nutrients	Singh et al. (2018)
	Uttar Pradesh	Wet	Groundwater	650	Environment	Minerals	Gautam and Rai (2023)
	Andhra Pradesh	Dry	Groundwater	1000	Environment	EC, major ions, nutrients	Swarna Latha and Rao (2012)
	Maharashtra	Wet	Groundwater	950	Environment	EC, TDS, major ions	Panaskar et al. (2016)
	Tamil Nadu	Wet	Groundwater	1210	Both	Nutrients, major ions, minerals	Elango et al. (2003)
Mexico	Tehuacan Valley	Both	Groundwater	450	Environment	EC, nutrients, major ions	Sedeño-Díaz et al. (2022)
	San Luis Potosí	Both	Surface water	444	Irrigation	TDS	González-Acevedo et al. (2016)

Appendix C

Environmental factors affecting water quality globally

Abbreviations as follows: not applicable (NA), nitrogen (N), phosphorus (P), sodium (Na), magnesium (Mg) and potassium (K).

COUNTRY	LOCATION	SOIL TYPES	WATER SOURCE (SURFACE OR GROUNDWATER OR BOTH)	ENVIRONMENTAL MECHANISM AFFECTING WATER QUALITY	IRRIGATION MECHANISM AFFECTING WATER QUALITY	EFFECTS ON WATER QUALITY	REFERENCES
TEMPERATE							
Spain	Bardenas Irrigation District no. V	Saso (soils associated with glacis), very stony, permeable	Groundwater	Low rainfall	Fertiliser applications	Less groundwater dilution and high nutrients	Causapé J et al. (2006)
Spain	Peralta de Alcofea	Alluvial soil	Surface water	Hydrology	Fertiliser application	Total P decreased with increasing streamflow	Skhiri et al. (2012)
Uzbekistan	Navoi region	sandy soils with low humus content	Both	NA	Irrigation and fertiliser application	Groundwater salinisation	Kulmatov et al. (2018)
Turkey	Great Menderes Basin	Sand, silt, clay	Both	Precipitation	Irrigation return flow	Increase in annual precipitation reducer groundwater salinity	Koç (2008)
USA	North Dakota	Alluvial	Groundwater	Hydrology	Fertiliser application	Total P decreased with increasing streamflow	Albus et al. (1998)
USA	Texas	Fine to coarse grain, gravel, sand, silt, clay and caliche	Groundwater	Geology	Fertiliser application	Permeable soil type leads to enhanced N in the groundwater	Chaudhuri et al. (2012)
USA	Idaho	Portneuf silt loam	Surface water	Slope	NA	High runoff volume and sediment loss and low infiltration	Ashraf et al. (1999)
USA	Texas	Saneli silty- clay loam, Harkey loam, and Tigua silty-clay	Both	NA	Leaching infiltration	Salt intrusion into groundwater	Ortiz et al. (2021)
SUBTROPICAL							
Tunisia	Zaghouan region	Clay	Groundwater	Hydrogeochemical processes	Fertiliser application	Weathering, and leaching increases anthropogenic contaminants	Farhat et al. (2024)
TROPICAL							
India	Tamil Nadu	Sand, Clay, alluvium	Groundwater	Weathering	NA	Weathering process increases the major ions such as Na, Mg and K in groundwater	Elango et al. (2003)

Appendix D

Water quality variables in tropical wet-dry regions of Australia derived from the body of evidence

Abbreviations as follows: not applicable (NA), not specified (NS), electrical conductivity (EC), total dissolved solids (TDS), dissolved organic carbon (DOC), nitrogen (N) and phosphorus (P).

COUNTRY	REGION	RIVER CATCHMENT	SEASON (DRY, WET, BOTH)	WATER RESOURCE (GROUNDWATER, SURFACE WATER, BOTH)	RAINFALL (MM)	IRRIGATION OR ENVIRONMENTAL EFFECTS ON **WATER QUALITY**	**WATER QUALITY** VARIABLES	REFERENCES
Australia	Queensland	Burdekin	Both	Surface water	1000	Both	Herbicides	Davis et al. (2013)
			Wet	Groundwater	960	Environment	DOC	Thayalakumaran et al. (2015)
			Both	Groundwater	1000	Irrigation	EC	Petheram et al. (2008)
			Wet	Surface	650	Both	Total N Insecticides Herbicides	Grundy and Hickman (2012)
		Fitzroy	Both	Surface water	640	Irrigagtion	EC Turbidity Total N Total P	State of Queensland (Department of Natural Resources) (1998)
	Northern Territory	Daly	Both	Surface water	1070	Environment	EC Turbidity	Townsend (2019)
			Both	Surface water	973	Environment	Nitrate Ammonium	Townsend and Douglas (2017)
	Western Australia	Keep	Both	Surface water	1142	Environment	EC DO Total N Total P	Bennett and George (2014)
			Both	Both	800	Environment	EC TDS pH Total N Total P	Bennett and George (2011)

COUNTRY	REGION	RIVER CATCHMENT	SEASON (DRY, WET, BOTH)	WATER RESOURCE (GROUNDWATER, SURFACE WATER, BOTH)	RAINFALL (MM)	IRRIGATION OR ENVIRONMENTAL EFFECTS ON **WATER QUALITY**	**WATER QUALITY** VARIABLES	REFERENCES
			Both	Both	800	Both	Herbicides Insecticides	Grundy and Hickman (2012)
		Ord	Dry	Groundwater	879	Irrigation	pH EC Herbicides	Smith et al. (2006)
			Both	Surface water	879	Environment	Turbidity Nitrate Total P	Parslow et al. (2003)
			Dry	Groundwater	879	NA	pH EC	Paul et al. (2011)
			NS	Groundwater	879	Both	TDS	Raper et al. (2015)
			Both	Surface water	879	Irrigation	pH	Ali and Salama (2003)
			Both	Both	879	Irrigation	pH EC TDS Major ions	Ali et al. (2002)
			Dry	Both	879	NA	EC	Salama et al. (2002)
		Ord and Keep	Both	Groundwater	802	NA	pH EC TDS Major ions Total N Total P Nitrate	Bennett et al. (2016)

Appendix E

Environmental factors affecting water quality in Australia

Abbreviations as follows: not applicable (NA), electrical conductivity (EC) and nitrogen (N).

COUNTRY	LOCATION	SOIL TYPES	WATER BODY SAMPLED (SURFACE OR GROUNDWATER OR BOTH)	MECHANISM AFFECTING WATER QUALITY	IRRIGATION MECHANISM AFFECTING WATER QUALITY	ENVIRONMENTAL EFFECTS ON WATER QUALITY	REFERENCES
Australia	Queensland	Sandy	Groundwater	Rainfall	Mobilisation of minerals	Rainfall infiltrating groundwater aquifers and increasing dissolved organic carbon and salt content	Petheram et al. (2008)
	Queensland	Baratta clay	Surface water	Rainfall	Runoff	Rainfall increases N concentration in runoff water	Yeates (2016)
	Queensland	Heavy clay	Surface water	Rainfall	Fertiliser application	Increase in concentration of fertiliser residues	Grundy and Hickman (2012)
	Western Australia	Aquitaine and Cununurra	Groundwater	Soil type	NA	Increased groundwater salinities due to the soil type	Lillicrap et al. (2011)
	Western Australia	Clay	Groundwater	Rainfall/geology	Runoff/rising watertable	Runoff increases EC and rising water to the sediment surface increases soil salinity	Raper et al. (2015)
	Western Australia	Cununurra clay, sandy loam, cockatoo sand	Groundwater	Hydrogeochemical process	Evaporation	Exceptional levels of major ions in the water due to increased evaporation and interaction with mineral exchanges	Ali et al. (2002)

Appendix F

Baseline water quality databases available for northern Australia

Abbreviations are as follows: not applicable (NA), not specified (NS).

DATA	CATCHMENT	STATE / TERRITORY	YEAR START	YEAR END	LINK	NOTES
1. Natural Resources Division HYDSYS Water Quality Database, Bureau of Meteorology	Daly catchment	NSW QLD	2012	2021	https://data.gov.au/data/dataset/f7edc5e5-93ee-4527-bed5-a118b4017623	NA
2. DNRME 2017	Fitzroy catchment and others	QLD	NS	NS	https://water-monitoring.information.qld.gov.au/ Metadata: https://water-monitoring.information.qld.gov.au/wini/documents/telem/TP_GW.HTM	Data available as CSV file
3. Australian Water Resources Information System	Murray–Darling catchment	QLD NSW ACT VIC SA	NS	NS	http://www.bom.gov.au/water/about/wip/awris.shtml Catchment map details: https://mdbwip.bom.gov.au/murray-darling-basin/ - 4.6/-31.5/147	Metadata available online The presence/absence of river gauges, storage and groundwater bore. Information is available online
4. WAMSI 2 - KMRP Project 2.2.9: Historical Water Quality using sediment records	NS	WA	2013	2017	https://tinyurl.com/2kn58add	From CSIRO data portal Data publicly available
5. Territory Stories – repository of reports relating to the NT specifically: NT Power and Water Corporation	NA	NT	NA	NA	https://territorystories.nt.gov.au/?query=water quality database	Report repository
6. Australian Groundwater Explorer	Murray catchment	All	2012	2022	http://www.bom.gov.au/water/groundwater/explorer/index.shtml	Information on Murray catchment is provided, but 'Request for data' is required for other catchments under the National Aquifer Framework
7. Australian Water Data Service	NA	NA	NA	NA	https://portal.wsapi.cloud.bom.gov.au/arcgis/apps/sites/ - /australian-water-data-service	Repository of spatial water data, APIs and maps

DATA	CATCHMENT	STATE / TERRITORY	YEAR START	YEAR END	LINK	NOTES
8. Northern Territory bore locations, water quality and groundwater levels	NA	NT	1985	2019	Dataset: https://data.nt.gov.au/dataset/nt-bore-locations-water-quality-and-groundwater-levels Metadata: http://www.ntlis.nt.gov.au/metadata/export_data?type=html&metadata_id=2DBCB7711FC106B6E040CD9B0F274EFE - Citation	NT bore water quality data
9. Townsend, S. A. (2019). Discharge-driven seasonal pattern of ionic solutes, suspended sediment and water clarity for a tropical savanna river in northern Australia. Marine and Freshwater Research, 70(11), 1585–1602. https://doi.org/10.1071/MF19017	Daly catchment	NT	2007	2018	https://www.publish.csiro.au/mf/Fulltext/MF19017	Information available in the article: 11-year water quality dataset Only 5.5 years of data collection over the 11-year period Discrete data: 2.9 years, time series data: 0.4 years
10. Paul, RJ, Raper, GP, George, RJ, Wright, NJ, Lillicrap, AM and Gardiner, PS 2019, 'Groundwater investigations to support irrigated agriculture at La Grange, Western Australia: 2013–18 results', Resource management technical report 398, Department of Primary Industries and Regional Development, Perth	NS	WA	1987	2013	https://library.dpird.wa.gov.au/rmtr/400/	Information is mostly available as publications and reports Microbial water quality: https://www.health.wa.gov.au/Articles/A_E/Bacterial-water-quality
11. Department of Environment Science and Innovation - Long term Historical Trend Water Quality Monitoring Data	Fitzroy River, Lake Eyre catchment, Great Artesian catchment, Murray–Darling catchment	QLD	1968	Ongoing	https://wetlandinfo.des.qld.gov.au/wetlands/assessment/monitoring/current-and-future-monitoring/historical-trend-water-quality-monitoring-data.html	Kml boundary file is available online freely to download Metadata: Needs a request to water.data@qld.gov.au
12. Pesticide Reporting Portal, Department of Environment Science and Innovation, Queensland	NA	QLD	NS	Ongoing	https://storymaps.arcgis.com/stories/c0f0c6d7d88a4fd3a5541fe59f41ff75	Metadata: https://apps.des.qld.gov.au/water-data-portal/

DATA	CATCHMENT	STATE / TERRITORY	YEAR START	YEAR END	LINK	NOTES
13. Australian Government (Data Portal)	NA	NA	NA	NA	https://data.gov.au/data/dataset/?q=water+quality&sort=extras_harvest_portal+asc,+score+desc,+metadata_modified+desc&_organization_limit=0	Metadata: Different formatting (e.g. PDF, XLS, ZIP, TXT)
14. Butler, B. 2008. Report 5: Water quality. In GP Lukacs and C.M. Finlayson (eds) 2008. A Compendium of Ecological Information on Australia's Northern Tropical Rivers. Sub-project 1 of Australia's Tropical Rivers – an integrated data assessment and analysis (DET18). A report to Land and Water Australia. National Centre for Tropical Wetland Research, Townsville, Queensland	Northern Tropical Rivers	QLD NT WA	NS	NS	https://www.dcceew.gov.au/sites/default/files/documents/triap-sp1-water-quality.pdf	NA
15. Salama R, Bekele E, Pollock D, Bates L, Byrne J, Hick W, Watson G and Bartle G (2002) Hydrological response units of the Ord Stage 1 Irrigation Area and the dynamic filling of the aquifers of the Ivanhoe and Packsaddle Plains	Ord River	WA	NS	NS	Data unavailable	NA
16. Salama R, Bekele E, Bates L, Pollock D and Gailitis V (2002) Hydrochemical and isotopic characteristics of the surface and groundwater of the hydrological zones of the Ord Stage I Irrigation Area. CSIRO Land and Water Technical Report No 8/02	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2002/tr8-02.pdf	Data unavailable
17. Ali R, Salama RB, Pollock DW and Bates L (2002) Geochemical interactions between groundwater and soil, groundwater cycling and evaporation in the ORIA. CSIRO Land and Water Technical Report 21/02	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2002/tr21-02.pdf	Data unavailable
18. Barr AD and Salama RB (2002) Preliminary surface water – groundwater interaction modelling: water balances. CSIRO Land and Water Technical Report No 22/02	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2002/tr22-02.pdf	Data unavailable
19. Ali R and Salama RB (2003) Groundwater quality in the Ord Irrigation Area, its suitability for irrigation and prediction of salinity and sodicity hazards. CSIRO Land and Water Technical Report 07/03	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2003/tr7-03.pdf	Data unavailable
20. Salama RB and Pollock DW (2003) Preliminary appraisal of salinity development in the Packsaddle	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2003/tr17-03.pdf	Data unavailable

DATA	CATCHMENT	STATE / TERRITORY	YEAR START	YEAR END	LINK	NOTES
Creek Area. CSIRO Land and Water Technical Report No. 17/03						
21. Pollock DW and Salama RB (2003) Construction of a monitoring system to study the effectiveness of dewatering boreholes to manage rising groundwater levels in the Ivanhoe Plain, Ord River. CSIRO Land and Water Technical Report 36/03	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2003/tr36-03.pdf	Data unavailable
22. Barr AD, Pollock DW and Salama RB (2003) Surface water - groundwater interaction modelling: leakage from the Ord Irrigation Area channel network. CSIRO Land and Water Technical Report 37/03	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2003/tr37-03.pdf	Data unavailable
23. Smith AJ, Salama RB and Pollock DW (2003) Groundwater flow modelling of Ivanhoe and Packsaddle Plains: interim report of model development and calibration. CSIRO Land and Water Technical Report 38/03	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2003/tr38-03.pdf	Data unavailable
24. Viney NR (2003) Modelling surface water in the Ord River Irrigation Area (ORIA). CSIRO Land and Water Technical Report 39/03	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2003/tr39-03.pdf	Data unavailable
25. Pollock DW, Salama RB and Viney NR (2003) Water levels and water quality trends in the Ord River Irrigation Area (ORIA) for the period September 2001 – March 2003. CSIRO Land and Water Technical Report 40/03	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2003/tr40-03.pdf	Data unavailable
26. Charlesworth PB (2003) Reducing tailwater sediment and chemical loads. Report to Land and Water Australia by CSIRO Land and Water	Ord River	WA	NS	NS	Weblink: not published online	Data unavailable
27. Parslow J, Marvelashvili N, Palmer D, Revill A, Robson B, Sakov P, Volkman J, Watson R and Webster I (2003) Ord-Bonaparte Program Project 3.4/4.1/4.2B: The response of the lower Ord River and estuary to management of catchment flows and sediment and nutrient loads: final report. Report to Land and Water Australia by CSIRO Marine Research	Ord River	WA	NS	NS	Weblink: not published online	Data unavailable

DATA	CATCHMENT	STATE / TERRITORY	YEAR START	YEAR END	LINK	NOTES
28. Smith AJ, Pollock DW, Salama RB and Palmer D (2005) Ivanhoe Plain aquifer pumping trial July 2003 – April 2005: Stage 1 Ord River Irrigation Area, Kununurra, Western Australia. CSIRO Land and Water Technical Report 24/05	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/technical2005/tr24-05.pdf	Data unavailable
29. Smith AJ, Pollock DW and Palmer D (2006) Groundwater management options to control rising groundwater level and salinity in the Ord Stage 1 Irrigation Area, Western Australia. CSIRO Land and Water Science Report 70/06	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/science/2006/sr70-06.pdf	Data unavailable
30. Ali R and Slaven T (2006) Irrigation scheduling for water and salinity management in the Ord Irrigation Area. CSIRO Land and Water Science	Ord River	WA	NS	NS	NA	NA
31. Smith AJ, Hick W, Galbraith R and Palmer D (2006) Ord River Irrigation Area (ORIA) groundwater drainage and discharge evaluation: piezometers installation report. CSIRO Land and Water Science Report 72/06	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/science/2006/sr72-06.pdf	Data unavailable
32. Smith AJ, Pollock D, Palmer D and Price A (2007) Ord River Irrigation Area (ORIA) groundwater drainage and discharge evaluation: survey of groundwater quality 2006. CSIRO Land and Water Science Report 44/07	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/science/2007/sr44-07.pdf	Data unavailable
33. Smith AJ (2008) Rainfall and irrigation controls on groundwater rise and salinity risk beneath the Ord River Irrigation Area, northern Australia. Hydrogeology Journal, 16(6), 1159–1175	Ord River	WA	NS	NS	PDF available upon request: https://link.springer.com/article/10.1007/s10040-008-0301-6	Data unavailable
34. Smith A. Pollock D. and Palmer D. (2009) Ord River Irrigation Area annual groundwater elevation and water-table depth 1995 to 2008. CSIRO: Water for a Healthy Country National Research Flagship	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/waterforahealthycountry/2009/wfhc-Ord-River-water-table-mapping.pdf	Data unavailable
35. Smith AJ and Price A (2009) Review and assessment of soil salinity in the Ord River Irrigation Area. CSIRO: Water for a Healthy Country National Research Flagship	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/waterforahealthycountry/2009/wfhc-ORIA-salinity-assessment.pdf	Data unavailable
36. Smith AJ, Palmer D and Carwardine B (2009) Evaluation of a trial groundwater drain on Ivanhoe Plain	Ord River	WA	NS	NS	Link error: http://www.clw.csiro.au/publications/wa	Data unavailable

DATA	CATCHMENT	STATE / TERRITORY	YEAR START	YEAR END	LINK	NOTES
in the Ord River Irrigation Area. CSIRO: Water for a Healthy Country National Research Flagship					terforahealthycountry/2009/wfhc-groundwater-drain-ivanhoe-plain.pdf	
37. Smith AJ, Pollock DW and Palmer D (2010) Groundwater interaction with surface drains in the Ord River Irrigation Area, northern Australia: investigation by multiple methods. *Hydrogeology Journal*, 18(5), 1235–1252	Ord River	WA	NS	NS	PDF available upon request to author: https://link.springer.com/article/10.1007/s10040-010-0596-y	Data unavailable
38. Carter J, Smith AJ, Ali M, Silberstein R, Doody T, Byrne J, Smart N, Robinson C, Palmer C, Slaven T, Smith P and Palmer, D (2010) Interaction between trees and groundwater in the Ord River Irrigation Area. CSIRO: Water for a Healthy Country National Research Flagship	Ord River	WA	NS	NS	NA	NA

Appendix G

Global and Australian water quality modelling studies

CLIMATE	LOCATION	MODEL	STUDY MODEL DURATION (YEARS)	REFERENCES
Mediterranean	Spain	BAS potential crop evapotranspiration model	1 year	Causapé et al. (2006)
Mediterranean	Portugal	SWAT+ hydrological model	19 years	do Nascimento et al. (2024)
Mediterranean	Greece	QUAL2Kw water flow and quality model	2 years	Gikas (2014)
Temperate	Uzbekistan	Global change models, hydrological modelling	65 years	Jarsjö et al. (2017)
Temperate	China	Delft3D hydrodynamic-water quality model	2 years	Liu et al. (2021)
Tropical wet-dry	Vietnam	INCA water flow and quality model	30 years	Whitehead et al. (2019)
Temperate	USA	Weighted Regressions on Time, Discharge, and Season	27 years	Zikalala et al. (2021)
Northern Australia				
Tropical wet-dry	(Northern) Australia	PHREEQC geochemical model	0.3 years	Ali et al. (2002)
Tropical wet-dry	(Northern) Australia	LEACHC soil salinity model	1.9 years	Ali and Salama (2003)
Tropical wet-dry	(Northern) Australia	Water quality model	4 years	Lillicrap et al. (2015)
Tropical wet-dry	(Northern) Australia	Integrated hydrodynamic, sediment and biogeochemical models	1.25 years	Parslow et al. (2003)

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Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
csiro.au

For further information

Environment
Dr Chris Chilcott
+61 8 8944 8422
chris.chilcott@csiro.au

Environment
Dr Cuan Petheram
+61 467 816 558
cuan.petheram@csiro.au

Agriculture and Food
Dr Ian Watson
+61 7 4753 8606
Ian.watson@csiro.au