National Groundwater Research Priorities

June 2024

Flinders University

NATIONAL CENTRE FOR
GROUNDWATER
RESEARCH AND TRAINING

ISBN: 978-1-923178-05-2

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Citation: For bibliographic purposes, this report may be cited as:
Cook PG, Richardson S, Baker P, Barron O, Carrara E, Douglas B, Evans R, Hamilton S, McKelvey, Moggridge B, Nelson R, Pandey S, Papworth S, Robinson D, Searle J, Thiele Z, Trott S, Vertessy R (2024) National Groundwater Research Priorities. National Centre for Groundwater Research and Training, Australia. DOI: https://doi.org/10.25957/ayqy-gw06

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Executive Summary

Groundwater is an important source of water on the driest inhabited continent on earth. This is evident through the connection, understanding and value it holds for Indigenous People surviving and thriving for over 65,000 years. Today, groundwater supplies between one fifth and one third of Australia's water consumption, and is central to our water, food and energy security and our natural environment.

This paper summarises priority research areas that require investment to allow Australia to build its capacity for sustainable future management of groundwater across Australia.

Groundwater accounts for more than 90% of all water used across almost 50% of Australia's land area and is the main water source over more than 80% of the country. In some parts of the country, groundwater is the only available water source, particularly during extended dry periods. It is used in agricultural and pastoral activities, for mining, manufacturing, and industry, and for urban or household supply. Almost one third of Australia's irrigation is dependent on groundwater and 38% of our metal ore mining development.

In 2013, the direct use value of extracted groundwater in Australia was estimated at $4.1 billion per annum. Accounting for flow on effects to other industries, the economic contribution of groundwater use to Gross Domestic Product across the Australian economy was estimated to be $6.8 billion per annum. The total value of production where ground water is a significant input was conservatively estimated at $34 billion per annum.

Groundwater's value to the economy, however, is greater than such average figures suggest as it is critical to water, food, and energy security. Groundwater provides value beyond that derived from its extractive use, as it supports our tourism and forestry industries.

The health of traditional lands, of which water is an intrinsic and sacred part, is intimately linked to the cultural and spiritual identity of Indigenous People and communities.

Groundwater also plays a critical role in sustaining ecosystems and maintains springs, streamflow in most of Australia's perennial streams, and waterholes in ephemeral and intermittent streams, during dry seasons and during droughts.

Significant advances in groundwater science, management and policy have been made over recent decades, but there are several contemporary and emerging challenges that will increase pressure on groundwater resources.

The Australian population is projected to grow to between 37.4 and 49.2 million by 2066. Yet even today, one quarter of Australia's 288 groundwater management areas are over-allocated. Australia is not ready to manage a doubling of groundwater demand within the next few decades without addressing key knowledge gaps.

To secure environmentally sustainable groundwater supplies we need pro-active investment in groundwater science and its adoption in future water management solutions.

Climate change is predicted to reduce groundwater recharge in many of Australia's productive agricultural regions threatening groundwater supplies. Maximising groundwater use while simultaneously minimising impacts on other users and on the environment requires robust knowledge and management that can rapidly adapt to a changing environment.

Groundwater is also a critical resource for energy production and mining. Improved science and management will be required to ensure Australia's food, water and energy security and protect the environment.

Eighteen research priorities have been identified (across eight themes) to prepare for a growing demand on groundwater due to the joint impacts of climate change, impending El Nino conditions, population growth, an increase in mining, and a shift in Australia's energy mix. They include the need to improve our knowledge of our groundwater systems, the need to develop better approaches for predicting the impacts of groundwater extraction, and the need to develop better management systems that can rapidly respond to changing water demands and groundwater conditions. The following eight management and research themes have been identified, and research priorities have been identified for each of these. The management imperatives and associated research priorities relate to

- Groundwater Management, Climate Change and Water Security
    - *Develop methods to identify stressed groundwater resources and tools to manage local impacts.*
    - *Understand the impacts of climate change on groundwater recharge, water demand, and cropping systems.*
    - *Develop better conjunctive surface water and groundwater management approaches.*

- Protecting Groundwater-Dependent Ecosystems
    - *Improve remote sensing techniques for identification of GDEs, and rapid field assessment tools to ground truth satellite data.*
    - *Develop a database of ecosystems historically impacted by groundwater decline and tools for predicting future impacts.*

- Incorporating Indigenous Cultural Knowledge and Values
  - *Create a framework to support explicit groundwater management/allocation to protect Indigenous cultural values.*
  - *A shift in the groundwater research community from a 'consultation' approach towards supporting co-designed/co-led research and Indigenous-led research that informs groundwater policy and management.*

- Characterising and Modelling Groundwater Systems
  - *Develop tools to better characterise geological controls on groundwater flow.*
  - *Quantify groundwater – surface water exchange at basin scales.*
  - *Quantify uncertainty in groundwater recharge estimates, including flood recharge from rivers, and recharge beneath irrigation areas.*
  - *Quantify the uncertainty of groundwater models that is due to uncertain conceptualisation and characterisation of groundwater systems.*

- Protecting Water Quality
  - *Review baseline water quality data and water quality status and trends across Australia. Assess the suitability of current water quality monitoring.*
  - *Better understand the link between groundwater extraction and water quality change and incorporate this knowledge into comprehensive and effective monitoring and management schemes.*
  - *Explore the potential productive use of saline groundwater, including the potential to substitute saline water for existing freshwater use in industry and mining.*

- Monitoring Systems and Data Sharing
  - *Develop automated tools and protocols to manage and make available increasing data volumes. Develop rules to encourage data sharing and a national database to capture data that is collected and stored by different organisations.*

- Groundwater for Mining and Energy
  - *Develop tools to better predict and manage impacts on groundwater from mining operations, including cumulative impacts where multiple mines, some closed and some operational, are within a single catchment.*
  - *Develop improved tools to understand the influence of subsidence on the groundwater resource and dependent users and ecosystems, and on aquifer properties.*

- Science Communication
    - *Develop methods and materials to support building community knowledge of groundwater systems, risks and uncertainty.*

As well as responding to these priorities, there is a pressing need to increase the number of trained hydrogeologists to deliver on these and other challenges, and to manage our growing reliance on groundwater. And we need to better communicate the value of groundwater, how it supports mining, industry, agriculture and ecosystems, and that it can only continue to do so if it is managed carefully and sustainably.

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1. INTRODUCTION

Groundwater is one of Australia's most important natural resources. It is central to our water, food and energy security, our culture and our natural environment.

In recent years, the total water consumption in Australia has been approximately 15,000 GL per annum. Depending on climate conditions, each year between one fifth and one third of this water is sourced from groundwater.[1] Groundwater is the main water source over more than 80% of the country, and accounts for more than 90% of all water used across almost half of Australia's land area.[2] In some parts of the country, groundwater is the only available water source. Of the groundwater used nationwide, approximately 60% is used for agricultural and pastoral activities. Approximately 10% is used in mining, 15% supports manufacturing and industry, and 15% is urban or household supply. Almost one third of Australia's irrigation industry is dependent on groundwater, and 38% of our metal ore mining industry. [3] Perth, the capital city of Western Australia, is also groundwater-dependent, accessing approximately 50% of its water supply from groundwater.[4]

Groundwater is a critical resource for many remote Indigenous communities.[5] Despite this, there is limited information on the cultural value of groundwater to Indigenous People, or the knowledge they hold about these water systems. There have been many localised studies, but limited information is available on this connection for larger scale aquifers or groundwater systems. There are culturally significant groundwater dependant sites, including springs, rock holes, hanging swamps, shallow and perched water tables, and cave systems.[6]

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[1] BOM, 2021. Water in Australia 2019-20. Bureau of Meteorology, Commonwealth of Australia, June 2021.

[2] Harrington and Cook, 2014. Groundwater in Australia, National Centre for Groundwater Research and Training, Australia.

[3] Deloitte, 2013. Economic Value of Groundwater in Australia. Report prepared for the National Centre for Groundwater Research and Training.

[4] BOM, 2021, op. cit.

[5] At the 2022 Australasian Groundwater Conference held in Perth, a collaboration between the Australian IAH President, the Conference President and an Indigenous hydrogeologist prepared a Declaration, which acknowledges, champions and supports respecting Indigenous knowledge in groundwater activities, deliberations, decisions and policies. This Declaration is the first of its kind within the international groundwater community. See BraBelDeclaration_IAH Australia

[6] Moggridge, 2020. Aboriginal People and Groundwater. *Proceedings of The Royal Society of Queensland*, 126, 11-27.

In 2013, the direct use economic value of extracted groundwater in Australia was estimated at $4.1 billion per annum.[7] Accounting for flow on effects to other industries, the economic contribution of groundwater use to Gross Domestic Product across the Australian economy was estimated to be $6.8 billion per annum. The contribution is greatest in manufacturing and industry (35% of value-add) and mining (24%) but also very significant in irrigated agriculture, as drinking water for livestock and for urban water supply. The total value of production where ground water is a significant input was conservatively estimated at $34 billion per annum. Groundwater also provides value beyond that derived from its extractive use, as it supports our tourism and forestry industries.

Groundwater's value to the economy, however, is greater than such average figures suggest as it is critical to water security. Annual rates of renewal (recharge) are typically small compared to the volumes of water within aquifers, and so the aquifer levels are much less susceptible to drought than dam levels or river flows. Groundwater is also critical for food security. Irrigated crops make up about 30% of the value of Australia's agricultural production[8], and crops that are irrigated with groundwater are less affected by droughts than those irrigated with surface water. Irrigation thus becomes more heavily dependent on groundwater in dry years, and as Australia moves into an El Nino cycle, our reliance on groundwater is certain to increase.

Water use is inextricably linked to energy production. All sources of energy require water in their production process, and energy is required to make water available for human use. Globally, 15% of water withdrawn is for energy production.[9] As Australia's energy mix changes and the reliance on renewable energy increases, the spatial patterns of energy's water needs are likely to change. Australia's plans to increase energy production from hydrogen will require increased access to water.

Groundwater plays a critical role in sustaining ecosystems. It maintains streamflow in most of Australia's perennial streams during dry seasons and particularly during droughts. Iconic ecosystems on our dry continent that are dependent on groundwater include mound springs of the Great Artesian Basin, permanent lakes and wetlands of the Swan Coastal Plain, WA, coastal lake stromatolites of WA, the permanent coastal lake, dune and beach ridge plain ecosystems of coastal NSW and coastal sand islands of NSW and Qld, and many of Australia's river red gum forests. Some animals also rely on access to groundwater in the subsurface. In Tasmania, burrowing crayfish dig down to the water table and rely on the proximity of groundwater for their habitat. Although groundwater-dependent ecosystems

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[7] Deloitte, 2013, op. cit.

[8] Water for Food. Australian Government, DCCEEW.

[9] United Nations. Water and Energy.

(GDEs) cover only a small area of the vegetated land surface, they contribute significantly to social, economic, biodiversity and spiritual values.[10]

Groundwater extraction creates a change in the water resource. This, in turn, creates an impact on users and ecosystems dependent on that resource. The question is not whether an impact will occur, but of the location, nature, magnitude and timing of the impact. Disputes between groundwater users have occurred in response to coal seam gas exploration and development and will become more common as demands on groundwater increase. Groundwater extraction can also cause changes in groundwater quality, as poorer quality water from other aquifer layers can move it to replace the water is extracted. Seawater intrusion occurs where seawater moves into productive aquifers to replace water that is withdrawn in coastal areas. Other human activities can also affect groundwater quality. Fertilisers and pesticides can leak from agricultural lands to contaminate aquifers, infiltration through the soil can transport industrial chemicals into subsurface water storages, and groundwater level decline can lead to groundwater acidification and development of acid sulphate soils. Development of dryland and irrigated agriculture can lead to salinisation of subsurface aquifers.

Climate change is another human-induced impact on groundwater systems. Climate change is predicted to reduce recharge rates of aquifers underlying many of Australia's productive agricultural regions threatening groundwater supplies. The Australian population is projected to grow to between 28.3 and 29.3 million by 2027, and to between 37.4 and 49.2 million by 2066[11]. The demand for groundwater is certain to increase faster than the rate of population growth, as surface water is becoming fully utilised. In 2016, there were 288 groundwater management areas in Australia, covering approximately 75% of the continent, and one quarter of these were over-allocated.[12] Australia is not ready to manage a doubling of groundwater demand within the next few decades.

Significant advances in groundwater science, management and policy have been made over recent decades, but there are contemporary and emerging challenges that will increase pressure on groundwater resources. The 2021 State of the Environment Report[13]

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[10] Murray et al., 2003. Groundwater-dependent ecosystems in Australia: It's more than just water for rivers. *Ecological Management and Restoration*, 4(2), 110-113.

[11] Australian Bureau of Statistics. Population Projections, Australia.

[12] Barnett et al., 2020. Groundwater in Australia: Occurrence and management issues. In Rinaudo et al. (ed.) *Sustainable Groundwater Management*, Global Issues in Water Policy 24, Springer, pp.109-127

[13] Cresswell et al., 2021. Australia state of the environment 2021: overview, independent report to the Australian Government Minister for the Environment, Commonwealth of Australia, Canberra. DOI: 10.26194/f1rh-7r05.

documents increased dependence on groundwater and an increase in widespread water restrictions. It also reports a persistence in lower-than-average groundwater levels in many parts of Australia, attributed primarily to the extreme climatic conditions and ongoing pressures from water resource development. We need to better protect our groundwater resource to ensure Australia's food, water and energy security and protect the environment. Maximising groundwater use while simultaneously minimising impacts on other users and on the environment requires robust knowledge and management that can rapidly adapt to a changing environment. The strategic objectives presented in the National Groundwater Strategic Framework[14] explicitly recognises a need for investment in increasing our understanding of groundwater systems and the diverse social, economic and environmental values they support. Bridging the science-policy gap is equally crucial. The 2020 review[15] of the National Water Initiative[16] acknowledges that knowledge generation has been integral to water reform achievements under the National Water Initiative and that governments have a role to play in funding water-related research. It also highlights that provision of robust science is not enough to develop effective evidence-based policy and decision makers need to know that information exists and those working in the water sector also need the capacity and capability to use best available science effectively.

Demands on groundwater are likely to increase in the future, and so the need to manage groundwater sustainably will become more and more acute. Yet at a time when groundwater is becoming increasingly important for Australia's future, there is a national shortage of hydrogeologists.[17]

There is a pressing need to increase the number of trained hydrogeologists working in government, industry and university sectors. There is also a need to focus research efforts on areas where they can add most value and best contribute to addressing our national challenges. The NCGRT, together with its partner agencies, thus began a process to develop and/or refine nationally relevant groundwater research priorities using feedback from a range of groundwater managers and practitioners from government, industry and consulting across Australia. It is expected that a renewed focus on research that is aligned with national priorities will lead to more effective connections between science, policy and management. This in turn will mean more effective consultation with communities that can

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[14] Council of Australian Governments (2016) Intergovernmental Agreement on the 2016–2026 National Groundwater Strategic Framework. Council of Australian Governments, Canberra.

[15] Productivity Commission 2021, National Water Reform 2020, Inquiry Report no. 96, Canberra.

[16] Council of Australian Governments (2004) The National Water Initiative. Council of Australian Governments, Canberra.

[17] Australian Government Skills Priority List June 2023.

influence policy and/or communities that are impacted by policy decisions. This report describes the outcomes of these discussions.

1.1 Scope of this Report

The focus of this report is on challenges related to groundwater availability and management, and the impact of groundwater use on other users, and on surface water resources and groundwater-dependent ecosystems. We include groundwater issues relevant to agriculture, industry, mining, urban and remote community supply and the environment. Both water quantity and water quality issues are important, although contamination of groundwater in urban environments and regional areas that are linked to manufacturing and defence industries are specifically excluded. We therefore do not discuss issues related to groundwater contamination by PFAS or other industrial chemicals.

The reports seeks to identify *research priorities*. There is a need for increased resources across many areas of groundwater investigation and management, including but not limited to increasing numbers of monitoring bores and training of staff. While important, these issues are not directly covered in this report.

This is the first time for more than 25 years that a national approach has been undertaken to identify and describe priority areas for groundwater research.[18]

1.2 Methodology

An online workshop was held on 7th June 2023 to discuss challenges related to groundwater availability and management, and the impact of groundwater use on other users, and on surface water resources and groundwater-dependent ecosystems. The workshop comprised presentations followed by a panel discussion. Presenters included representatives from the Commonwealth and State governments, water utilities, mining and energy companies, and the university sector. A full list of presenters and panellists is provided in the appendix to this report. The workshop was advertised on the NCGRT website and through direct email, and was attended by representatives from government, research and private sectors.

We asked workshop participants:

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[18] Barber et al., 1995. Groundwater Issues in Australia: Their significance and the Need for Research. Stage 1 Report: Identification of Priorities. Centre for Groundwater Studies Report No. 59, May 1995.

- What we currently don’t know **how** to do (or how to do **well**), rather than where resource limitations are preventing things being done,
- Where our current approaches have limitations,
- The new data, process understanding or tools that are needed to do things better,
- What are the most significant communication, governance or institutional challenges.

A summary of research priorities arising from the workshop discussion is presented in this report.

2. RESEARCH PRIORITIES

Research priorities raised in the workshop have been grouped into eight subject areas. These research priorities, together with others that were not raised in the initial workshop but that were raised in subsequent discussions, are listed below. A total of eighteen discrete research priorities were identified.

2.1 Groundwater Management, Climate Change and Water Security

2.1.1 Background

Groundwater management in Australia and globally largely relies on basin-scale volumetric limits on extraction. In some areas, when management plans were first developed, regional extraction limits were set equal to the total water being extracted at that time.[19] Since meters were often not in place, the total extraction was sometimes estimated from irrigated areas and nominal irrigation rates for different crop types. In some other areas, extraction limits for were set equal to an estimate of the volume of aquifer recharge. In most cases, the extraction limits were not set in a manner that would necessarily minimize impacts on other groundwater users or protect groundwater-dependent ecosystems. Modifying management rules to produce more sustainable outcomes for dependent industries and users and for the environment has been challenging. In some areas, the preferred solution has been to impose temporary restrictions on use where water levels or other resource condition limits are under pressure. However, this approach is also not without its challenges. As demand for groundwater increases, there is potential for groundwater resource conflict. There is a need for better approaches for managing groundwater to ensure the sustainability of the environment and to protect users who depend on the resource, particularly in the face of climate change, population growth and increasing water demand.

2.1.2 Groundwater Management Rules

While regional groundwater management usually relies on volumetric limits on extraction, this is often supplemented by local management rules that are designed to prevent competition between different users and minimise impacts on groundwater-dependent

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[19] Barnett and Williamson, 2020. New approaches for allocation reductions and groundwater salinity management in South Australia. In Rinaudo et al. (ed.) *Sustainable Groundwater Management*, Global Issues in Water Policy, 24. Springer, pp.355-363.

ecosystems. There has been insufficient research on how these rules should be designed and implemented to achieve desired cultural, environmental and water use objectives. There is a need for better methodologies for identifying when groundwater resources are under stress, and better approaches for deciding when this should lead to ameliorative action. These approaches need to consider where sentinel bores should be located relative to sensitive areas, likely delays between groundwater stress indicators being observed at sentinel bores and ameliorative action being taken, and time lags between reductions in groundwater extraction and resulting improvements in groundwater condition. The widespread availability of data loggers and telemetry systems raises the possibility of much more responsive groundwater management that involves a larger number of sentinel bores. With modern technologies changes in groundwater condition can be observed in real time and management systems adjusted accordingly. There is a huge potential to improve groundwater management by taking advantages of these technologies.

Research Priority 1-1. **Develop methods to identify stressed groundwater resources and tools to manage local impacts.**

2.1.3 Climate Change

Understanding the impacts of climate change on groundwater resources remains a priority. Several studies have examined the effect of climate change on groundwater recharge, including analysing the effects of climate change predictions from up to 16 global climate models[20]. While results from the models can differ, for the median future climate prediction, 79% of the continent is projected to experience a reduction in recharge, with 21% of the continent experiencing a recharge reduction of more than 20%. South-west Western Australia and the southern Murray-Darling Basin, areas where groundwater supports important agricultural production, are amongst the areas predicted to have lower groundwater recharge.[21] Most studies, however, have focussed on changes in diffuse recharge beneath agricultural and pastoral land, and more work is needed on impacts of focussed areas, such as recharge from ephemeral and perennial rivers (see also Section 2.4.3). There are also data gaps related to changes in the frequency and magnitude of

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[20] Crosbie et al., 2012. An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. *Climate Change*, 117, 41-53.

[21] Barron et al., 2011. Climate change impact on groundwater resources in Australia: summary report. CSIRO Water for a Healthy Country Flagship, Australia.

extreme events (prolonged droughts, floods or intense storms) on groundwater systems. There has also been little consideration of changes in water demand resulting from climate change and changes in cropping systems or crop types, or how changes in recharge will affect groundwater-dependent ecosystems or cultural water values.

***Research Priority 1-2.* Understand the impacts of climate change on groundwater recharge, water demand, and cropping systems.**

2.1.4 Conjunctive Groundwater - Surface Water Management

It is now widely understood that pumping groundwater can impact streamflow. This can be a problem for stream condition, where reduced flows inhibit ecosystem function or result in poor water quality. It is also a problem for downstream water users that are no longer able to extract permitted volumes. It has been estimated that flow of the Murray River has reduced by almost 200 GL/year due to groundwater pumping between 1993/94 and 1999/2000, and that this reduction in flow would increase to 700 GL/year by 2050.[22] The impact of groundwater pumping on surface water systems was one of the reasons for the adoption in 2012 of a cap on groundwater extraction in the Murray Darling Basin.[23]

While the problem of groundwater pumping impacting streamflow is well known, the solution is not. While conjunctive management of surface water and groundwater systems is widely espoused, and groundwater management usually considers potential impacts on surface water systems, there are few examples of truly conjunctive groundwater – surface water management in Australia. When managed carefully and with good knowledge of the groundwater system, groundwater can be a more drought resilient option then surface water. There is potential to improve the resilience of water supplies and perhaps to increase rates of water use through conjunctive management. Managed aquifer recharge (MAR) has been gaining global relevance and increasing traction in Australia as one part of the solution to water security.[24] However, it remains often overlooked or underutilised as a tool in conjunctive water management. In addition to improving water security, MAR can be used

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[22] SKM, 2003. Projections of Groundwater Extraction Rates and Implications for Future Demand and Competition for Surface Water. Murray-Darling Basin Commission, Publication 04/03.

[23] Walker et al., 2020. Potential cumulative impacts on river flow volume from increased groundwater extraction under the Murray-Darling Basin Plan. *Australasian Journal of Water Resources*, 24(2), 105-120, DOI: 10.1080/13241583.2020.1804042

[24] Dillon et al., 2020. Managed aquifer recharge for water resilience. *Water* 12.7 (2020): 1846.

to protect GDEs, improve source water quality, and as a hydraulic barrier to prevent saltwater intrusion. Despite its many benefits, there are also limitations and risks that need to be considered including operational issues and aquifer clogging, policy complexities, contamination risk, geochemical changes in aquifers and altered flow pattens.

Research is urgently needed in conjunctive groundwater – surface water management and integration of techniques such as MAR.

Research Priority 1-3. **Develop better conjunctive surface water and groundwater management approaches.**

2.2 Protecting Groundwater-Dependent Ecosystems

2.2.1 Background

Many ecosystems are dependent on groundwater, including most perennial rivers, lakes and wetlands, springs, and some estuarine and marine environments. Many of these ecosystems also have knowledge and cultural values attributed to them (see Section 2.3). Groundwater-dependent ecosystems (GDEs) require access to groundwater on a permanent or intermittent basis to meet their water requirements, and ecosystem services may be affected if groundwater availability is reduced. In Australia, impacts of declining groundwater levels have been documented on the native sclerophyllous vegetation of the Swan Coastal Plain, on threatened root mats in phreatic pools and cave streams in Western Australia, reductions in flow of iconic mound springs of the Great Artesian Basin, and the loss of 70% of the original wetland extent in the southeast of South Australia.[25,26]

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[25] Neville et al., 2010. Groundwater-dependent ecosystems and the dangers of groundwater overdraft: a review and an Australian perspective. *Pacific Conservation Biology*, 16, 187-208.

[26] Government of South Australia. Wetlands.

2.2.2 Identifying GDEs and Quantifying their Water Use

Many approaches have been undertaken to locally identify and map GDEs.[27,28] While intensive field techniques are valuable, they are mostly restricted to research studies and are considered too costly for widespread application. Over the last decade, advances in technology and requirements to detect and monitor GDEs across broader spatial scales has seen an emphasis placed on developing and applying remote sensing methods.[29] A continental-scale map, the GDE Atlas, has been developed using a combination of local and expert knowledge and satellite remote sensing.[30,31] This map provides a good first step for water managers, but coverage is incomplete and there are limitations with satellite approaches. Knowledge and cultural values attributed to GDEs not included in the GDE Atlas.

There is a need to improve the use of satellite data for both identifying GDEs and assessing their water use. There is also a need for rapid field assessment tools to ground truth satellite data. We also need better tools for distinguishing between ecosystem that are dependent on groundwater only during droughts, versus those that are dependent seasonally or all the time. Marine ecosystems are not included in national GDE maps, and are another area where research is urgently needed. Groundwater discharge to the ocean can create important ecosystems that support marine fish production.[32]

***Research Priority 2-1.* Improve remote sensing techniques for identification of GDEs, and rapid field assessment tools to ground truth satellite data.**

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[27] Eamus et al., 2006. A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. *Australian Journal of Botany,* 54, 97-114. DOI: 10.1071/bt05031.

[28] Doody et al., 2017. Continental mapping of groundwater dependent ecosystems: A methodological framework to integrate diverse data and expert opinion. *Journal of Hydrology: Regional Studies*, 10, 61-81. DOI: 10.1016/j.ejrh.2017.01.003.

[29] Eamus et al., 2015. Groundwater-dependent ecosystems: recent insights from satellite and field-based studies. *Hydrology and Earth System Sciences*, 19, 4229-4256.

[30] Doody et al., 2017, op. cit.

[31] GDE Atlas (Bureau of Meteorology)

[32] Fujita et al., 2019. Increase in fish production through bottom-up trophic linkage in coastal waters induced by nutrients supplied via submarine groundwater. *Frontiers in Environmental Science*, 7.

2.2.3 GDE Response to Stress

How GDEs will respond to changes in their water regime is poorly known. Many large trees access groundwater, and the maximum rooting depths of different tree species are poorly known, as are root distributions and how tree water use changes as a function of depth. We need to know when trees are accessing groundwater, and the ability of trees to extend their roots to manage water table decline and maintain water use. What magnitude of water table decline leads to significant declines in tree health, vegetation assemblages and ecosystem function? For lakes and wetlands, large declines in groundwater levels can cause permanent lakes and wetlands to become ephemeral, with dramatic changes to their ecology. For lakes and wetlands that are naturally ephemeral, reductions in groundwater levels can reduce the frequency that these surface water systems hold water. We need to better understand the role that groundwater plays in these ecosystems and how changes in groundwater levels affect their permanence. Sources of groundwater to springs can also be difficult to identify in multi-layered aquifers, and the link between change in aquifer pressure and change in spring flow is difficult to predict.

We also need to understand the sensitivity of ecosystems to climate change. This information is critical for understanding potential impacts. Our ability to predict impacts of water level change on ecosystems would also be improved by clearly documenting observed impacts where they arise. Measurement of such impacts needs to be quantitative and objective, rather than anecdotal. From a management perspective, there is a need for a practical approach to better connect the science of GDE response to stress with decision making on when and how to intervene.

***Research Priority 2-2.* Develop a database of ecosystems historically impacted by groundwater decline and tools for predicting future impacts.**

2.3 Incorporating Indigenous Cultural Knowledge and Values[33]

Indigenous People have an intimate connection with surface water and groundwater, and how it connects with the land. The health of traditional lands, of which water is an intrinsic and sacred part, is intimately linked to the cultural and spiritual identity of Indigenous People and communities. Groundwater dependent cultural values and groundwater dependent cultural sites include non-physical sites such as creation sites and sites recorded in creation stories or songlines, physical sites where resources are collected (e.g., food, medicines) or manufactured (e.g., tools, musical instruments), and burial or occupation sites.[34] Many groundwater-dependent ecosystems (e.g., springs, ephemeral and permanent wetlands) will also have knowledge and cultural values attributed to them, meaning that the protection of GDEs may provide some degree of protection to cultural values. Cultural water requirements have been defined for some areas and provision of cultural water allocations may provide a mechanism for incorporating cultural values into existing water allocations. Australian governments have recently committed to developing targets to measure (and presumably increase) water allocations to Indigenous groups.[35] However, existing western water management is based on the concept of 'acceptable impacts', whereas protection of cultural values may require that places are protected in their natural form and any impact may be unacceptable. Despite the challenges, groundwater ownership by Indigenous groups is currently very small. In the Murray-Darling Basin, for example, groundwater entitlements held by Indigenous groups constitute 0.02% of all available groundwater[36], indicating that there is a long way to go in water planning and sharing across all stakeholders.

In 2009, Australia endorsed the United Nations Declaration on the Rights of Indigenous Peoples[37], which universally acknowledges Indigenous Peoples' rights, including the rights to water and the right to determine priorities and strategies for the development or use of their resources. Underpinning this is the need to incorporate Indigenous knowledge and values to support holistic water management and policy. The State of Environment Report acknowledges there is currently a lack of regard for Indigenous knowledge for influencing

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[33] This section draws heavily on Moggridge and Thompson, 2021, Cultural value of water and western water management: an Australian Indigenous perspective. *Australasian Journal of Water Resources*, 25:1, 4-14, doi:10.1080/13241583.2021.1897926.

[34] Moggridge, 2020. Aboriginal People and Groundwater. *Proceedings of The Royal Society of Queensland*, 126, 11-27.

[35] Hartwig et al. , 2021. Benchmarking Indigenous water holdings in the Murray-Darling Basin: a crucial step towards developing water rights targets for Australia. *Australasian Journal of Water Resources*, DOI:10.1080/13241583.2021.1970094

[36] Hartwig et al., 2021, op. cit.

[37] United Nations Declaration on the Rights of Indigenous Peoples. New York : United Nations Department of Economic and Social Affairs, 2007.

water policy and legislation[38] . While there are examples of progress in some areas of surface water management (i.e., The National Cultural Flows Research Project[39]), groundwater examples are scarce.

The scientific community is increasingly recognising the value of incorporating Indigenous knowledge into research, acknowledging that greater research impact and value are achieved when science is interwoven with the knowledge, intuition, and capability of Traditional Owners[40]. However, there is an urgent need for the development of meaningful partnerships across all organisations involved in science research, including groundwater, and a shift from 'consultation' towards co-designed and co-led research and supporting Indigenous-led research that informs groundwater policy and management.

Seven research areas for progressing the incorporation of Indigenous knowledge and cultural values in water management have been identified:

(i) Understanding Indigenous Peoples' values and traditional management roles relating to water.[41]

(ii) Improving the accessibility of language and communication around water issues (water literacy). The language of western water management is often not accessible to Indigenous People, and cultural values are not well understood by water managers.

(iii) Differentiating Indigenous water from environmental water needs. There is a misconception that the needs for cultural water may be met through environmental water provisions to ecosystems.

(iv) Improving the ownership and economic value of Indigenous groundwater entitlements. Currently the level of Indigenous ownership is minimal.

(v) Determining the water needed to protect cultural values. This is analogous, but different to determining water provisions for protection of GDEs. It is not clear that cultural values can be satisfied by volumetric allocations.

(vi) Inclusion of cultural values in an already over-allocated water market. Provision of water to sustain cultural values may require reduction in allocations to other users.

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[38] Australian Government, Department of Agriculture, Water and the Environment, 2021. State of the Environment Report 2021. https://soe.dcceew.gov.au/.

[39] MLDRIN, NBAN & NAILSMA (Murray Lower Darling Rivers Indigenous Nations, Northern Basin Aboriginal Nations & North Australian Indigenous Land and Sea Management Alliance), 2017. Dhungala Baaka: rethinking the future of water management in Australia. Report prepared by the Cultural Flows Planning and Research Committee, National Cultural Flows Research Project, Australia.

[40] Evans-Illidge et al., 2020. AIMS Indigenous Partnerships Plan - from engagement to partnerships.

[41] MLDRIN, NBAN & NAILSMA, 2017, op cit.

(vii) Developing new governance approaches to water management that incorporate Indigenous Peoples' governance and capacity building.

Research Priority 3-1. Create a framework to support explicit groundwater management/allocation to protect Indigenous cultural values.

Research Priority 3-2. A shift in the groundwater research community from a 'consultation' approach towards supporting co-designed/co-led research and Indigenous-led research that informs groundwater policy and management.

2.4 Characterising and Modelling Groundwater Systems

2.4.1 Background

In Australia, the intensity of groundwater development largely determines the spatial coverage of monitoring networks. Large sedimentary basins, alluvial aquifers, areas of high population density and regions of high economic interest (large scale irrigated agriculture, oil and gas extraction, mining operations) often have higher data density than areas where groundwater may only support small communities (e.g., hard rock geology areas with low population density). Monitoring may be available over long periods of time (sometimes multiple decades), but periods of 'network rationalisation' and cost-cutting have led to incomplete monitoring data for many bores and sometimes to an overall reduction in monitoring programs. Groundwater infrastructure is aging[42], and failed or damaged monitoring bores are not always replaced. However, understanding groundwater systems requires more than monitoring bores, but necessitates targeted studies into processes of recharge and discharge, leakage between aquifers, and aquifer residence times. These studies are often conducted at small spatial scales and are not uniformly available across different groundwater management areas.

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[42] SKM, 2012. An assessment of groundwater management and monitoring costs in Australia, Sinclair Knight Merz, Waterlines report, National Water Commission, Canberra.

2.4.2 Characterising Groundwater Systems

Characterising groundwater systems to the point where they can be modelled with sufficient precision is a major challenge. Much of our information on groundwater systems is derived from bores, and understanding aquifer hydraulic properties and groundwater chemistry between observation bore sites is difficult. We need improved characterisation of groundwater systems across their spatial domain. This will probably rely on development of new geophysical and geochemical methods, as well as increased application of existing tools together with improved interpretation methods for these existing tools. It will require improved communication with other earth science disciplines so that hydrological studies can benefit from up-to-date geological knowledge. This is most important in areas of complex geology, where structural controls such as dykes, faults and folds influence groundwater flow.[43] However there is also a need for better knowledge of layering and connectivity of depositional units within sedimentary aquifers as these determine the anisotropy of hydraulic properties. We need more use of groundwater models that describe heterogeneity in a geologically realistic manner. This will allow us to see how different conceptualisations of aquifer systems affect model predictions. It is not expected that these types of models will be routinely applied, but they will allow us to develop a better understanding of the uncertainty associated with incomplete aquifer characterisation.

***Research Priority 4-1.* Develop tools to better characterise geological controls on groundwater flow.**

2.4.3 Surface Water – Groundwater Interactions

Methods for estimating the connections between surface water and groundwater are available, but these approaches are usually implemented in intensive, small-scale field studies, whereas groundwater management requires basin-scale estimates. Partly for this reason, estimates of the impacts of groundwater pumping on rivers are not available across most of Australia. The impacts of groundwater extraction on intermittent streams (which are especially prevalent in Australia) are particularly poorly understood and difficult to quantify. How changes in river management and climate change impacts on river flows will affect groundwater systems is still unknown.

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[43] 2nd EAGE Workshop on Fluid Flow in Faults and Fracture - Modelling, Uncertainty and Risk. 15-16 August 2023, Canberra, Australia.

***Research Priority 4-2.* Quantify groundwater – surface water exchange at basin scales.**

2.4.4 Groundwater Recharge

Groundwater recharge estimates are crucial for aquifer water balances, understanding of salinisation processes and robust calibration of groundwater models. Rates of groundwater recharge underpin volumetric allocation limits in many areas of Australia, yet recharge rates are often poorly known and subject to significant uncertainty. There is a need for improved estimates of recharge, and improved understanding of the assumptions and uncertainties of the different recharge estimation methods. There are significant gaps on the importance of focussed recharge to Australian groundwater systems (e.g., recharge due to infiltration from rivers), and the balance between diffuse and focussed recharge. There is also a lack of information on how groundwater recharge varies over time. We need to have better method for estimating how much recharge occurs from floods, as climate change is likely to lead to more severe and longer droughts but also more extreme rainfall events. Simulating flood recharge is likely to be difficult with existing groundwater models.

Root zone drainage and aquifer recharge is a key component of water balances in irrigated regions, and current approaches to estimating irrigation recharge use broad assumptions on crop water use (and root zone drainage), irrigation-region scale water balances and/or inverse modelling through groundwater model calibration. These techniques are limited where the watertable is deep and the geology in the unsaturated zone is complex (e.g., less permeable layers rejecting recharge). This can lead to poor assumptions on the recharge rate and the time for root zone drainage to recharge a deep aquifer. Ultimately this uncertainty leads to less reliable estimates of impacts from irrigation. Further development of analytical methods for estimating recharge beneath irrigated areas is needed.

***Research Priority 4-3.* Quantify uncertainty in groundwater recharge estimates, including flood recharge from rivers, and recharge beneath irrigation areas.**

2.4.5 Groundwater Modelling

Groundwater modelling is the main tool for predicting how different stressors (groundwater extraction, climate change) and different groundwater management approaches are likely to affect groundwater systems and dependent environments. Our ability to model groundwater systems far exceeds our ability to characterise them, and there are challenges associated with predicting impacts on uncertain systems. Groundwater models need to include relevant geological heterogeneity and be sufficiently complex to make reliable predictions. It is important to know the level of complexity that needs to be incorporated into models in different environments and for different purposes. The effect of our uncertain knowledge of aquifer systems can be estimated through model uncertainty analysis, but currently uncertainty analysis is mostly limited to assessing effects of variation in aquifer parameters (e.g., hydraulic conductivity). Effects of uncertainties in groundwater conceptualisations are seldom considered but are probably the greatest source of uncertainty. We therefore need to better understand the trade-off between model simplicity and complexity and develop tools for assessing the required level of complexity of groundwater models along with tools that help us understand what type of modelling is appropriate, given model objectives and risk posed by a model stress. The role of machine learning in groundwater modelling is also largely unexplored as is the potential for predictive models to update themselves automatically as new data becomes available.

Groundwater models also need to link with surface water, climate and socio-economic models to provide whole of water cycle models. To support decision-making, model predictions need to consider future water demands for urban, agriculture and mining industries, ecosystem needs, and changes in water availability.

Research Priority 4-4. **Quantify the uncertainty of groundwater models that is due to uncertain conceptualisation and characterisation of groundwater systems.**

2.5 Protecting Water Quality

2.5.1 Background

In regional Australia, water quality issues have generally received less attention than water quantity issues. Groundwater salinity exceeds 1500 mg/L over much of inland Australia[44], and many remote communities in arid areas are exposed to nitrate and uranium in bore water which occurs naturally at concentrations above WHO guidelines.[45,46] Water quality guidelines are available for drinking water, recreational water use, livestock and irrigation.[47,48] Such guidelines specify recommended maximum concentrations for salinity, various dissolved ions and metals, biological parameters, pesticides and organic contaminants, and radionuclides. Water treatment or provision of alternative supplies is required where water quality is less than required for its intended use. Equally or more important, though, is preventing deterioration in water quality due to human activities.

There are many processes that can lead to deterioration in groundwater quality, and so determining the cause in each case can be difficult. Where changes in land use cause increases in recharge rates, this can sometimes cause water tables to rise to close to the land surface. Evapotranspiration from shallow water tables will increase groundwater salinity. Where groundwater pumping occurs for irrigation, evaporation and transpiration of water applied to the crop increases salinity, and so water that moves down to the aquifer is more saline that the original groundwater that was extracted. This process also can lead to increases in groundwater salinity over time. Groundwater extraction can also cause poor quality groundwater to move into productive aquifers. In coastal areas, groundwater extraction can result in seawater moving into the aquifer to replace the water that is extracted.

Nitrate pollution can occur from fertilisers, feedlots, diary and sewerage effluent, and agricultural activities can also cause groundwaters to be contaminated with herbicides and pesticides. Geochemical processes can also impact on water quality. Exposure of sediments to oxygen has led to arsenic and fluoride contamination of groundwater in many parts of

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[44] Harrington and Cook, 2014, op. cit.

[45] Western Australian Auditor General, 2015. Delivering Essential Services to Remote Aboriginal Communities. Office of the Western Australian Auditor General, May 2015, 30pp.

[46] Moggridge, 2020, op. cit.

[47] Australia and New Zealand Guidelines for Fresh and Marine Water Quality.

[48] ANZG (2023). Livestock drinking water guidelines. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra.

the world and these elements occur at elevated concentrations in some parts of Australia[49]. In coastal areas, the release of sulfuric acid due to lowering of the water table and oxidation of sediments containing sulfides can lead to reductions in groundwater pH, and mobilisation of heavy metals and other trace elements to the point where they are hazardous to human health and/or ecosystems.[50]

2.5.2 National Water Quality Trends

Other than for salinity, there are no readily available maps of groundwater quality across Australia. Sometimes, declines in groundwater quality over time are observed in monitoring bores or bores that are used for water supply. Declines in water quality have been documented in the Namoi[51] and Lower Murray[52] groundwater systems, in NSW, in Eyre Peninsula, South Australia[53], and many other areas. However, there are no statistics on rates of water quality decline nationally, or national maps showing areas where declines in water quality are widespread. The extent of the problem is therefore currently unknown.

Water quality changes are typically slow and lag behind water level changes, and water quality monitoring is more difficult and expensive than water level monitoring. It is not clear that our monitoring systems for water quality are sufficiently robust to detect small changes that might provide early warning of more serious impacts, or that all appropriate parameters are being measured. In many cases, identification of water quality changes is hampered by a lack of sufficient baseline (pre-development) water quality data. There also is a shortage of information on water quality risks to groundwater resources, and there is no national-scale data on how water quality is changing over time.

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[49] NHMRC, NRMMC, 2011. Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra.

[50] Shand et al., 2018. National Acid Sulfate Soils Guidance: Guidance for the dewatering of acid sulfate soils in shallow groundwater environments, Department of Agriculture and Water Resources, Canberra, ACT.

[51] NSW Government. Lower Namoi Groundwater Source. Preliminary analysis of water quality 2003-2019.

[52] NSW Government. Lower Murray Groundwater Source: preliminary analysis of water quality (2003-2015).

[53] Department for Environment and Water (DEW) 2020. Uley South groundwater model, DEW Technical report 2020/37, Government of South Australia, Department for Environment and Water, Adelaide.

***Research Priority 5-1*. Review baseline water quality data and water quality status and trends across Australia. Assess the suitability of current water quality monitoring.**

2.5.3 Predicting Water Quality Changes

Predicting water quality changes is challenging, and when declines in groundwater quality are observed, differentiating between different possible causes of the water quality decline is difficult. In some cases, this has resulted in a lack of ameliorative action when declines in water quality have occurred. Understanding the link between groundwater extraction and water quality change and incorporating the knowledge into comprehensive and effective monitoring schemes and into the setting of sustainable extraction limits remains a challenge and further research is required. A re-assessment of the risk of groundwater quality decline due to salinisation processes associated with past and future land use and land management changes should also be undertaken. Such predictions were undertaken in the 1990s and revisiting and updating these models is overdue.

***Research Priority 5-2*. Better understand the link between groundwater extraction and water quality change and incorporate this knowledge into comprehensive and effective monitoring and management schemes.**

2.5.4 Use of Saline Groundwater

Much of Australia is underlain by brackish or saline groundwater. Groundwater salinity exceeds 1500 mg/L (the limit for drinking water and irrigation of most crops) over more than one third of the continent, and in the area where groundwater is the only available water resource half of the groundwater resource is saline.[54] In the USA, about 13 percent of all water used is saline water, including approximately five percent of water used for

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[54] Harrington and Cook, 2014. Groundwater in Australia, National Centre for Groundwater Research and Training, Australia.

industrial purposes and 53 percent of all water used for mining.[55] Figures on saline water use are not available in Australia.

Further research is needed on the potential productive use of this resource, including the potential to substitute saline water for existing freshwater use in industry and mining. There is also potential to irrigate crops with saline water, and it has been suggested that seven million hectares of the Murray hydrogeological basin in the southern Murray-Darling Basin may be suitable for irrigation with saline groundwater.[56] Use of inland saline groundwater for commercial aquaculture has also been reviewed[57] and proposed.[58] Rules for accessing brackish and saline groundwater resources perhaps should be different to those for native fresh groundwater, particularly in areas with high water tables. Financial or other incentive systems could be considered for substitution of saline water use for freshwater use. There is therefore an urgent need for better characterisation of Australia's saline groundwater resources and for policy research around the use of brackish and saline groundwater.

***Research Priority 5-3.* Explore the potential productive use of saline groundwater, including the potential to substitute saline water for existing freshwater use in industry and mining.**

2.6 Monitoring Systems and Data Sharing

Sound groundwater management relies on the amount and quality of information that is available in the decision-making process. Traditionally, groundwater monitoring focusses on manual measurements of water levels in dedicated monitoring wells. However, recent years have seen the availability of automatic sensors and dataloggers that have increased our ability to capture larger amounts and different types of data. Access to real-time

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[55] United States Geological Survey. Is saline water used for anything?

[56] Ranatunga et al., 2010. Potential use of saline groundwater for irrigation in the Murray hydrogeological basin of Australia. *Environmental Modelling and Software*, 25(10), 1188-1196.

[57] Barron et al., 2021. Review of low-cost desalination opportunities for agriculture in Australia. A report to the National Water Grid Authority. CSIRO Land and Water, Australia.

[58] Awal et al., 2016. Investigation into the potential use of inland saline groundwater for the production of live feeds for commercial aquaculture purposes. *Journal of Aquaculture and Marine Biology*, 4 (1), 21-27.

groundwater data has the potential to increase our ability to respond to changes in groundwater systems and adapt management approaches as necessary.

Satellite sensors are also increasing the volume of ancillary data that is available for understanding groundwater systems and their interaction with the environment. There is a need for a modern water data infrastructure system that harnesses the new and emerging data and supports open data sharing. Research is also needed on the development of new sensors and improvements in existing sensors. With the increase in data volumes, automated tools and protocols will be needed for quality assurance and quality control (QA and QC) and identifying data errors.

Assessment of cumulative impacts would benefit from access to data beyond that collected by State and Territory water management agencies. Important groundwater data (particularly related to water chemistry) is held by other agencies (EPA, CSIRO, GA, universities, irrigation companies, private engineering firms, mining companies and landowners). This data is often not available through the primary State, Territory and Commonwealth databases. There is a need for a national database that provides information on data that is collected and stored by different organisations. Where it is not commercial-in-confidence, systems could be developed to make this information publicly available.

***Research Priority 6-1*. Develop automated tools and protocols to manage and make available increasing data volumes. Develop rules to encourage data sharing and a national database to capture data that is collected and stored by different organisations.**

2.7 Groundwater for Mining and Energy

2.7.1 Background

Mining export revenue exceeded $400 billion in 2021-22 and is forecast to grow to more than $450 billion in 2022-23.[59] The mining sector is a large industrial user of water, and across much of Australia the industry is groundwater dependent. The industry is estimated

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[59] Australian Government. Department of Industry, Science and Resources, Resources and Energy Quarterly, December 2022.

to use approximately 1.3 billion litres of water per year[60], much of which is derived from groundwater. Mining, manufacturing and other industries have a high gross value added per gigalitre of water consumed, with a dollar contribution to GDP per litre of water used approximately ten times greater than that of irrigated agriculture.[61]

Groundwater issues related to mining and energy resources have particular characteristics that differ from other groundwater developments. Groundwater extraction usually only occurs for a finite period of time (often a few decades), but the impacts of these developments on groundwater systems can be felt over much longer time periods. In areas where mining occurs, it is often the largest water user, and dewatering to create a dry mining environment can cause reductions in groundwater levels over areas of hundreds or even thousands of square kilometres. Acid mine drainage is a problem around coal and metal mines[62], and these issues have not been satisfactorily managed in the past. The boom in coal seam gas (CSG) developments in Queensland and New South Wales poses additional challenges for water management, with large volumes of sometimes highly saline wastewater requiring treatment or disposal, and the location of CSG developments in important agricultural areas.

2.7.2 Closure of Open Pit Mines

Many existing open pit mines will cease operations within the next 10 – 20 years. This represents a huge challenge for water management, and predicting impacts of mine closure on the environment requires information across all areas of hydrogeology. In landscapes where there are large numbers of pits, predicting the cumulative impact of these pits on the groundwater system is likely to be a challenge, particularly as some pits will be closing when others are still dewatering. Evaporative loss of groundwater may be significant in arid landscapes with high pit densities. Salinity buildup in evaporating pits is not well understood, nor is the potential for density-dependent flow to transport salt into adjacent aquifers. In the future, mines will be much deeper than they are today, perhaps extending to depths more than a kilometre. It may take many decades for groundwater systems to recovery from dewatering operations.[63] Thus, for many mines, groundwater management will need to continue for many years after production ceases in order to protect ecosystems

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[60] Australian Bureau of Statistics. Australian Water Account 2021-22.

[61] Deloitte, 2013, op. cit.

[62] Khanal and Hodgkinson, 2021. Subsidence prediction versus observation in Australia: A short comment. *Environmental Impact Assessment Review*, 86, 106479, 6p.

[63] Bozan et al., 2022. Groundwater level recovery following closure of open pit mines. *Hydrogeology Journal*, https://doi.org/10.1007/s10040-022-02508-2.

and manage water quality. This will create significant challenges, the implications of which are yet to be fully acknowledged.

***Research Priority 7-1*. Develop tools to better predict and manage impacts on groundwater from mining operations, including cumulative impacts where multiple mines, some closed and some operational, are within a single catchment.**

2.7.3 Geomechanics and Groundwater

Understanding the link between geomechanics and groundwater is important in mine landscapes, in coal seam gas operations and in other areas where groundwater pumping leads to large reductions in aquifer pressures. Reductions in aquifer pressures can lead to the downward movement of the ground, and this can cause damage to bridges, roads, railroads, drains and sewers, as well as to private and public buildings, and changes in land slope resulting in changes in surface runoff patterns. In Australia, subsidence is most commonly reported in association with coal mines, including those in the LaTrobe Valley, Victoria[64], and Sydney and Gunnedah Basins, NSW[65]. The national cost of subsidence due to groundwater pumping has not been estimated, although mine subsidence damage was reported to have cost the NSW Government $8.7 million between 2009 and 2014 for purchase of affected residential properties alone[66], while another report states that mine subsidence and tunnel failure damaged or destroyed an estimated 30 buildings during the period 2000-2011, with an estimated cost in 2010 dollars of approximately $6.5 million.[67]

Understanding subsidence issues is critical in underground and open pit mining and unconventional gas developments. Improvements in our ability to predict subsidence resulting from groundwater withdrawals are needed. We also need to understand how subsidence affects aquifer hydraulic properties and where it may therefore impact groundwater flow. It is possible that the measurement of subsidence may provide valuable

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[64] Waghorne and Disfani, 2019. Land subsidence/rebound change after Hazelwood mine rehabilitation. In AB Fourie and M Tibbett (eds) Mine Closure 2019.

[65] Khanal and Hodgkinson, 2021. Subsidence prediction versus observation in Australia: A short comment. *Environmental Impact Assessment Review*, 86, 106479, 6p.

[66] https://www.australianmining.com.au/8-7-million-spent-on-subsidence-in-the-hunter-2/

[67] https://knowledge.aidr.org.au/resources/ajem-jan-2013-impact-of-landslides-in-australia-to-december-2011/

information on the groundwater system. Slope stability in open cut mines is another area where improved knowledge of the link between groundwater and geomechanics is important. Increasing pit wall slopes can potentially save billions of dollars by reducing the volume of material that must be excavated to access ore.

***Research Priority 7-2*. Develop improved tools to understand the influence of subsidence on the groundwater resource and dependent users and ecosystems, and on aquifer properties.**

2.8 Science Communication

There is a need for a better coordinated, national effort to raise the profile of groundwater and its growing importance to the economy with groups across government, industry and community sectors. There is also a need for improved communication and collaboration amongst groundwater research providers.

Improved understanding of groundwater processes at all levels will improve our ability to manage groundwater resources effectively and sustainably. Groundwater is generally hidden from view, and there is a need for better communication methods and mechanisms. Some excellent products have been produced by some State and Territory governments[68,69], including animated videos and storymaps, and there has also been some development of teaching materials for schools[70]. However, there is a need to coordinate and better disseminate this information. There is also a need to better promote the importance of groundwater to Australia's economy, to mining, industry, agriculture and pastoral land users, as well as to Indigenous communities and the environment. The profile of groundwater research can be raised by publicising how effective groundwater management helps to solve Australia's challenges. Uncertainty in understanding groundwater systems and the risk that this poses also needs to be better understood and communicated.

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[68] NSW Government .What is groundwater?

[69] Queensland plan to protect our Great Artesian Basin. Queensland Government. https://storymaps.arcgis.com/stories/259e2ef480944f799fb2465ba2821877

[70] https://www.ga.gov.au/education/classroom-resources/water

***Research Priority 8-1*. Develop methods and materials to support building community knowledge of groundwater systems, risks and uncertainty.**

3. CONCLUSIONS

Groundwater supplies between one fifth and one third of Australia's water consumption, and is central to our water, food and energy security, Indigenous culture and our natural environment. It accounts for more than 90% of all water used across almost 50% of Australia's land area and is the main water source over more than 80% of the country. It is used in agricultural and pastoral activities, regional and remote Indigenous communities, for mining, manufacturing, and industry, and for urban or household supply. Yet, today, one quarter of Australia's 288 groundwater management areas are over-allocated, and we are not ready to manage the large increase in demand for groundwater that is anticipated to occur within the next few decades. The Australian population is projected to grow to between 37.4 and 49.2 million by 2066, and climate change is predicted to reduce groundwater recharge in many of Australia's productive agricultural regions over the same time frame. Yet, Australia's future reliance on groundwater to support its projected population and economic growth will increase as surface water resources become less reliable with a drying climate.

To secure environmentally sustainable groundwater supplies we need pro-active investment in groundwater science and its adoption in future water management solutions.

We need to better manage our groundwater resource to ensure Australia's food, water and energy security and protect the environment.

This report has identified eighteen research priorities across eight management and research themes to prepare for a growing demand on groundwater (Table 1). **The identified research priorities are based on current limitations to our groundwater knowledge and the collective capacity to meet the likely future increased reliance on groundwater as a water supply.** They include the need to improve our knowledge of our groundwater systems, the need to develop better approaches for predicting the impacts of groundwater extraction, and the need to develop better management systems that can rapidly respond to changing water demands and groundwater conditions.

Table 1. Groundwater management imperatives and associated research priorities.

Management Imperatives	Research Priorities
1. Groundwater Management, Climate Change and Water Security. Effective & flexible management of groundwater resources where climate change is driving changes to demand.	1-1. Develop methods to identify stressed groundwater resources and tools to manage local impacts.
	1-2. Understand the impacts of climate change on groundwater recharge, water demand, and cropping systems.
	1-3. Develop better conjunctive surface water and groundwater management approaches.
2. Protecting Groundwater-Dependent Ecosystems. Many ecosystems are dependent on groundwater and are impacted when groundwater is extracted. There is limited knowledge on how to manage groundwater to protect GDE values.	2-1. Improve remote sensing techniques for identification of GDEs, and rapid field assessment tools to ground truth satellite data.
	2-2. Develop a database of ecosystems historically impacted by groundwater decline and tools for predicting future impacts.
3. Incorporating Indigenous Cultural Knowledge and Values. Groundwater is intrinsically linked to Indigenous cultural values and extends beyond just the use of water.	3-1. Create a framework to support explicit groundwater management/allocation to protect Indigenous cultural values.
	3-2. A shift in the groundwater research community from a ‘consultation’ approach towards supporting co-designed/co-led research and Indigenous-led research that informs groundwater policy and management.
4. Characterising and Modelling Groundwater Systems. Sound groundwater management relies on our ability to characterise all aspects of groundwater systems as well as the availability of tools to predict future impacts.	4-1. Develop tools to better characterise geological controls on groundwater flow.
	4-2. Quantify groundwater – surface water exchange at basin scales.
	4-3. Quantify uncertainty in groundwater recharge estimates, including flood recharge from rivers, and recharge beneath irrigation areas.
	4-4. Quantify the uncertainty of groundwater models that is due to uncertain conceptualisation and characterisation of groundwater systems.

Management Imperatives	Research Priorities
5. Protecting Water Quality. Over most of Australia, groundwater quality limits the range of potential uses and groundwater quality decline is declining in many areas.	5-1. Review baseline water quality data and water quality status and trends across Australia. Assess the suitability of current water quality monitoring.
	5-2. Better understand the link between groundwater extraction and water quality change and incorporate this knowledge into comprehensive and effective monitoring and management schemes.
	5-3. Explore the potential productive use of saline groundwater, including the potential to substitute saline water for existing freshwater use in industry and mining
6. Monitoring Systems and Data Sharing. Increasing use of satellite and telemetry data collection systems will potentially lead to better understanding of groundwater systems. A national approach to data sharing will lead to increased availability of this and other data and therefore to more consistent and transparent reporting.	6-1. Develop automated tools and protocols to manage and make available increasing data volumes. Develop rules to encourage data sharing and a national database to capture data that is collected and stored by different organisations.
7. Groundwater for Mining and Energy. Management of groundwater in catchments with multiple mining operations creates complex challenges related to cumulative impacts during mining and following closure.	7-1. Develop tools to better predict and manage impacts on groundwater from mining operations, including cumulative impacts where multiple mines, some closed and some operational, are within a single catchment.
	7-2. Develop improved tools to understand the influence of subsidence on the groundwater resource and dependent users and ecosystems, and on aquifer properties.
8. Science Communication. Extending knowledge of how groundwater systems work to a broad range of community stakeholders is critical when determining appropriate management objectives and building trust in decision-making.	8-1. Develop methods and materials to support building community knowledge of groundwater systems, risks and uncertainty.

However, this report is incomplete, and there are many areas that were not covered in this assessment. Most notably, we have not considered the contamination of groundwater in urban environments and regional areas that are linked to manufacturing and defence industries. Additional research priorities are linked to our ability to manage groundwater contamination by PFAS or other industrial chemicals. The report seeks to identify *research priorities*, but there is a need for increased resources across many areas of groundwater investigation and management. There is a need to replace aging bore infrastructure[71], and to arrest the decline in numbers of monitoring bores.[72] These issues are not directly discussed. There is also a pressing need to increase the number of trained hydrogeologists to deliver on these and other challenges, and to manage our growing reliance on groundwater.

Investment in groundwater science has the potential to unlock new opportunities as well as optimise groundwater's contribution to future integrated water management.

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[71] SKM, 2012. An assessment of groundwater management and monitoring costs in Australia, Sinclair Knight Merz, Waterlines report, National Water Commission, Canberra.

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ACKNOWLEDGEMENTS

Numerous people contributed to this report, in addition to those who are named as authors. This includes several researchers at CSIRO and GeoScience Australia, and those who attended the online Groundwater Research Priorities workshop and asked questions or submitted online comments.

APPENDIX: WORKSHOP PRESENTERS AND PANELLISTS

Online Meeting – 7 June 2023

Moderator: Stuart Richardson
S.B. Richardson Consulting
Chair, NCGRT Advisory Board

Introduction: Peter Cook
NCGRT, Flinders University

Presenters:

1. Rob Vertessy (Global Change Advisory)
2. Kelly Strike (Department of Climate Change, Energy, the Environment and Water)
3. Blair Douglas (BHP)
4. Jo Searle (Department for Water and Environmental Regulation, WA)
5. Elisabetta Carrara (Bureau of Meteorology)

Discussion panel:

1. Rick Evans (Jacobs)
2. Patrick McKelvey (Shell QGC)
3. Peter Baker (Department for Environment and Water, SA)
4. Sue Hamilton (NSW Department of Planning and Environment)
5. Shane Papworth (NT Power and Water)
6. Sanjeev Pandey (Office of Groundwater Impact Assessment, Qld))
7. Shane Trott (Rio Tinto)
8. Rebecca Nelson (Melbourne University)