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Sustainable management of groundwater extraction: An Australian perspective on current challenges

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A R T I C L E I N F O

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Groundwater management
Sustainability
Research gaps
Implementation

A B S T R A C T

Study region: Australia
Study focus: Our incomplete knowledge of groundwater systems and processes imposes barriers in attempting to manage groundwater sustainably. Challenges also arise through complex institutional arrangements and decision-making processes, and the difficulty in involving stakeholders. In some areas, these difficulties have led to water table decline and impacts on groundwater users and groundwater-dependent ecosystems. However, there is potential to improve the sustainable use of groundwater resources through improvements in management practices. We discuss some of the challenges, and present survey results of research, government, and industry professionals across the groundwater sector in Australia.
New hydrological insights for the region: The highest-ranked challenge identified in the survey was the difficulty in determining regional-scale volumetric water extraction limits. This is surprising given the criticism in the international literature of volumetric based approaches for groundwater management, and the decreased reliance on this approach in Australia and elsewhere in recent

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years. Other major challenges are the difficulty in determining and implementing maximum drawdown criteria for groundwater levels, determining water needs of ecosystems, and managing groundwater impacts on surface water. Notwithstanding these gaps in technical understanding and tools and a lack of resources for groundwater studies, improvements in stakeholder communication should enable more effective decision-making and improve compliance with regulations designed to protect groundwater and dependent ecosystems.

1. Introduction

The last 50 years have seen large increases in global groundwater extraction, principally driven by population growth (Gleeson et al., 2012; Margat and van der Gun, 2013). In Australia, groundwater use increased from approximately 2.6 × 10^9 m^3 y^{-1} in 1983–1984 to 4.2 × 10^9 m^3 y^{-1} in 1996–1997 (NLWRA, 2001), mostly driven by an increase in irrigation water use (Fairweather et al., 2003). By 2015–2016, groundwater use had increased to approximately 5.0 × 10^9 m^3 y^{-1} (Barnett et al., 2020), partly driven by restrictions on surface water extraction. Approximately 70% of groundwater used is for agricultural or pastoral purposes (predominantly irrigation), with the remainder used to support mining activities and for domestic and town water supplies.

In many areas of Australia, widespread groundwater extraction for irrigation of crops commenced before sophisticated groundwater management regimes were in place. Indeed, the slow response times of many groundwater systems can allow unsustainable extraction rates to exist for a period of time before significant impacts are observed either on users or on dependent ecosystems. This has created challenges where management approaches have been imposed on extraction systems that have already been established. In Australia, major policy developments in the mid-1990 s led the way for improvements in groundwater management, including attempts to return unsustainable extraction regimes to sustainable levels (Doolan, 2016). Significant developments have included widespread recognition of the importance of groundwater-dependent ecosystems (GDEs) from the late 1990 s (Hatton and Evans, 1998), a coordinated approach to bore rehabilitation to reduce uncontrolled groundwater loss in the Great Artesian Basin from 2000 (GABCC, 2000), and limits on groundwater pumping in some areas of the Murray-Darling Basin from 2012 (see Box 1).

Despite major steps forward in groundwater management, pressure on groundwater resources has continued, reinforcing the need to manage groundwater extraction to ensure the future sustainability of the resource. Increasing evidence globally of groundwater depletion and environmental impact (Gorelick and Zheng, 2015; De Graaf et al., 2019) suggests either that groundwater use has reached unsustainable levels and/or that our current management approaches are not producing the best outcomes for the resource. The assumption of the current paper is that there is room for improvement in how we are managing groundwater both in Australia and globally. The first step towards improved groundwater management, and the focus of this paper, is an assessment of where the problems lie.

While several recent studies have considered research opportunities in hydrogeology and related disciplines (e.g., Miller and Gray, 2008; Blöschl et al., 2019; Kreamer et al., 2021), few have directly addressed management challenges. Barber et al. (1995) convened a series of meetings with hydrogeological researchers and managers to identify priority water issues in Australia, and the research and development needed to address these national challenges. Lowry et al. (2003) identified 28 gaps that were thought to be hindering effective management of groundwater systems in New Zealand. Their analysis was based on surveys and discussions with groundwater managers, and they identified gaps in information, implementation, and technological and management tools, as well as the understanding of fundamental processes.

Our approach is similar to that of Barber et al. (1995) and Lowry et al. (2003), although more targeted, as we focus on groundwater quantity management and water allocations. We only consider groundwater quality issues that are directly affected by groundwater extraction. We therefore do not consider contamination of groundwater from anthropogenic sources, such as leaching of pesticides and nitrates, or urban and industrial contamination (Li et al., 2021). These are usually managed separately from water allocation, either through licensing of discharge and safety protocols, or through land-use controls and remediation. Also, we do not consider water management issues related to high water tables, water logging and dryland salinity (e.g. Ghassemi et al., 1995). These issues often take precedence in areas of poorer groundwater quality, where there is less demand for groundwater. Rather, we focus on groundwater allocation issues and discuss the main impediments to improving sustainable groundwater quantity management in this context. We also present the findings from a survey of government employees, private industry and the research community. The focus is on Australian conditions, but we expect that many of the issues are universally applicable.

2. Background

A thorough discussion of groundwater allocation management and legislation in Australia is beyond the scope of the current paper, but a very brief introduction is presented here so that the following discussion of challenges and opportunities can be more readily understood. More detailed information can be found in Nelson and Quevauviller (2016), Gardner et al. (2017), Rohde et al. (2017) and Rinaudo et al. (2020).

Each of the six Australian States and two Territories (Fig. 1) allocates groundwater under its own water legislation (Gardner et al.,

Box 1
Cross-Border Arrangements in Australia.

The Great Artesian Basin covers an area of over 1.7 million km^2, spans three states and the Northern Territory and underlies part of the Murray-Darling Basin (Fig. 1). Its aquifers contain approximately 6.5×10^{14} m^3 of groundwater. However, water levels throughout many parts of the basin had been declining since the early part of the 20th century due to uncontrolled flow from more than 4000 artesian bores, most of which had been installed to provide water for cattle grazing. By 1990, 1000 of these had stopped flowing due to a decrease in pressure across the region (Commonwealth Government, 1996).

The Great Artesian Basin Rehabilitation Program started in 1989 and aimed to encourage the capping of bores and piping of water. The cost sharing scheme for bore capping and pipe works was funded 80% by the Commonwealth and States and 20% by water users in NSW and Queensland. The scheme was successful in arresting the decline in water levels across many areas of the basin. The Great Artesian Basin Strategic Management Plan was released in 2000. This is not a statutory document, but rather a framework to foster collaborative management between users to achieve agreed objectives and outcomes. Several cooperative projects been undertaken since the development of the Plan to better understand and manage groundwater in the basin (Commonwealth Government, 2020).

The Murray Darling Basin, which spans five state and territory jurisdictions, is regulated through complex groundwater governance arrangements within the umbrella of the Murray Darling Basin Authority. A cap on surface water diversions from the basin was imposed in 1995. Since the adoption of a Basin Plan in 2012 under Commonwealth legislation, state-level groundwater governance across the Basin has been overlain by nationally adopted 'sustainable diversion limits' on aggregate groundwater withdrawals for each catchment within the basin (MDBA, 2019). This has been accompanied by reductions in water entitlements for irrigators in some areas, and the establishment or further development of water markets and water buy-backs to increase environmental flows (Mendham and Curtis, 2014).

Predating these is the 1986 agreement for managing the groundwater resources across the South Australian - Victorian border. Each State agrees to limit allocations of water in the border zone and to cooperate and subject their other allocation laws to this agreement. In particular, the agreement sets a permissible rate of water table decline for regions within 20 km either side of the border as well as permissible aggregate extraction rates (Government of South Australia, 2022).

2017). The Federal (i.e., national) Government also influences groundwater management in some areas, most notably within the Murray-Darling Basin, which spans several States (Fig. 1 and Box 1), and in the assessment of unconventional gas developments.[1] However, while there are some differences in approaches between the different jurisdictions and between management areas within the jurisdictions, there are many similarities. In 2016, there were 288 groundwater management areas in Australia, covering approximately 75% of the continent. Of these, 136 had volumetric limits on extraction (Barnett et al., 2020). These limits impose upper bounds on the total volume of water that can be taken from the management areas for irrigation, water supply, and commercial and industrial uses (stock and domestic users are excluded from these calculations), and new applications are only permitted if the limits are not exceeded. Some management areas have subzones with their own volumetric limits. Water trading is often permitted once these regional (or subzone) limits are reached (Wheeler et al., 2016), and this enables access for new users.

Areas with high rates of groundwater use often use numerical groundwater models for predicting impacts of groundwater extraction (e.g., Namoi River alluvium; NSW Government, 2019; Walker et al., 2020). These models are sometimes used to assess individual licence applications for very large water volumes, but it is generally considered too costly to run these models for all licence applications. Simpler analytical approaches, such as analytical pumping test solutions, are also sometimes used to assess potential impacts of new licences. Applications can be refused if the estimated drawdown at ecosystems or existing bores exceeds a threshold value.

In some areas, when management plans were first developed, regional limits were set equal to the total water extraction at that time (Barnett and Williamson, 2020). 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 other areas, extraction limits for unconfined aquifers were set equal to the volume of recharge – a practice referred to as 'safe yield'. In recent years, increased recognition that extraction equal to recharge does not prevent impacts on GDEs (Bredehoeft, 1997; Devlin and Sophocleous, 2005), means that it is now more common to allocate a fraction of recharge, with the remaining volume representing a notional allocation to the environment and/or conservative factor that acknowledges uncertainty of our knowledge the groundwater system (Meyland, 2011; MDBA, 2020). The fraction reserved for the environment can be as high as 100% of recharge in areas with high value assets (NSW Government, 2016), but 20–30% is more common (Walker et al., 2020). In some cases, groundwater models are also used for setting regional extraction limits (Pierce et al., 2020). In areas with very low rates of recharge, the extraction limit may be deliberately set above the recharge rate, thus permitting gradual mining of the resource. The Northern Territory Water Allocation Planning Framework links extraction limits to groundwater

[1] https://federalfinancialrelations.gov.au/sites/federalfinancialrelations.gov.au/files/2021–01/coal_seam_gas_mining_devel_np.pdf

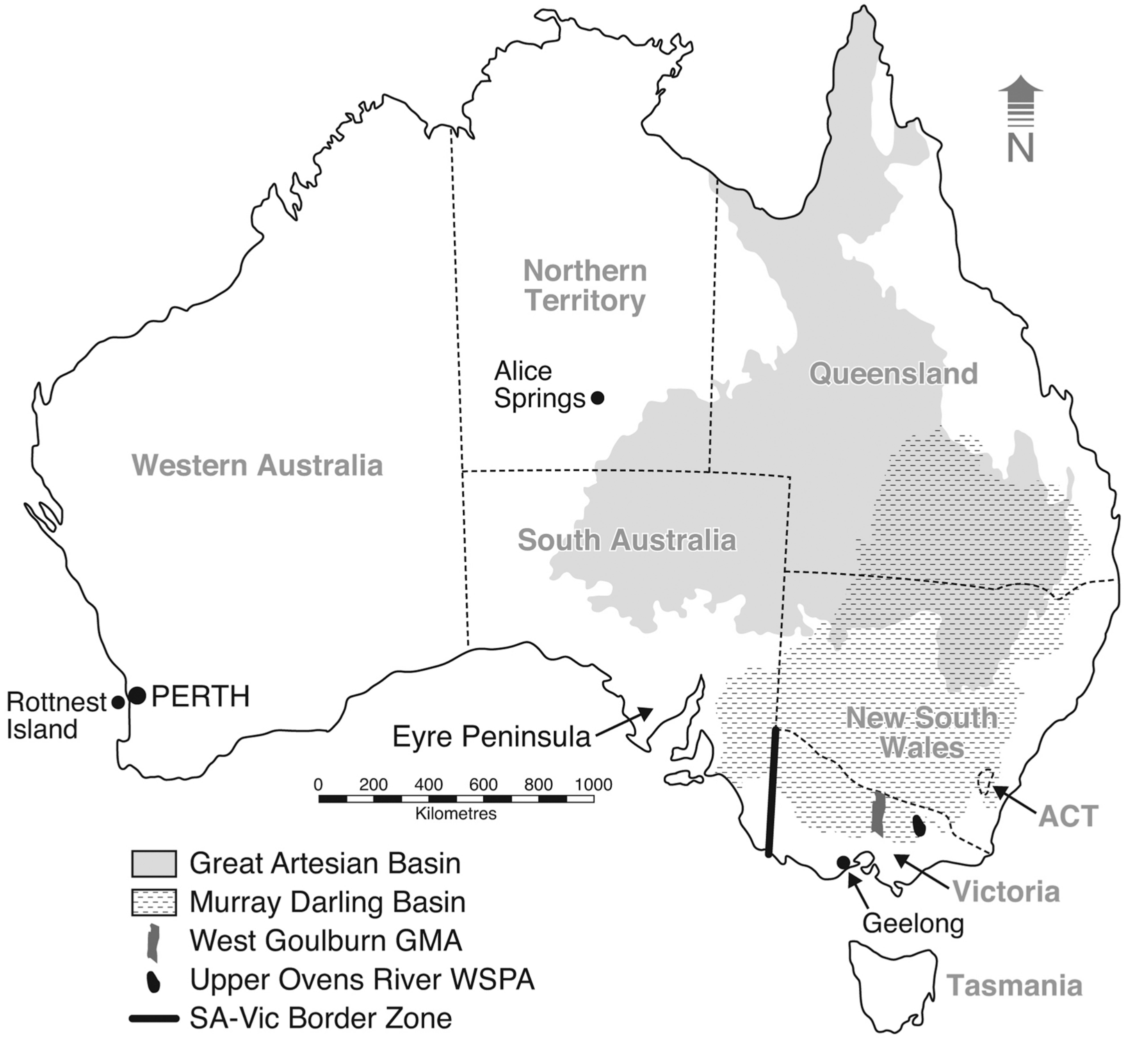

Fig. 1. Location map, highlighting key locations and basins mentioned in the text. Note that ACT refers to the Australian Capital Territory, GMA stands for Groundwater Management Area and WSPA stands for Water Supply Protection Area.

storage rather than recharge rates for the arid zone (DEPWS, 2020). For Alice Springs town water supply, for example, groundwater extraction of 1.3×10^7 m^3 y^{-1} is licenced from aquifers with an annual recharge of only 7.5×10^5 m^3 y^{-1} (DLRM, 2016).

Local management rules are designed to address impacts that cannot be adequately managed using volumetric limits. They include buffer zones that exclude groundwater pumping completely (although licences that pre-date delineation of buffer zones are usually allowed to continue) or regulate pumping depending on proximity to ecosystems or other groundwater users. In some cases, the distance that a bore needs to be from a GDE or other groundwater user is not fixed, but rather varies in proportion to the volume of the water licence (Northern and Yorke Natural Resources Management Board, 2009). Groundwater response triggers are another form of local management rule and use actual groundwater observations (e.g., maximum drawdown or salinity value at key observation bores) to control rates of groundwater extraction (e.g., Goulburn-Murray Water, 2017). Actions following exceedance of trigger values might include temporary or permanent reductions in licenced allocations for some or all groundwater users. It is now becoming more common for jurisdictions to use an adaptive management approach by announcing allocations annually based on groundwater quantity or quality observations (e.g., Eyre Peninsula Natural Resources Management Board, 2016). Announced allocations usually take the form of a percentage of the licenced volume that can be extracted and have proven to be more palatable than permanent reductions in licenced allocations (Pierce et al., 2020). In most States and Territories, legislation gives the Minister responsible for water resources broad powers to consider environmental issues and resource condition in setting water allocations, and to attach conditions to licences to extract water. Most State and Territory legislation also provides for stakeholder consultation, for example, through advisory bodies active in the water planning process; stakeholder consultation in decision-making about issuing and trading allocations and entitlements is less common (Gardner et al., 2017). A recent development is legal provisions requiring special consideration of, and consultation with, First Nations Australians in water planning (MDBC, 2004; Nelson, R, 2022; Productivity

Commission (Australia), 2021).

3. Methods

The collective experience of the authors of this paper, supplemented by discussions with groundwater experts in research institutions, governments and private industry, enabled the identification of 18 primary challenges which need to be overcome to optimally manage groundwater extraction rates. A survey of groundwater professionals was then conducted, where participants were asked to score the challenges on a scale of 1–5, with 1 being 'not an impediment' and 5 being a 'major impediment'. Fractional scores were not permitted. Respondents were also invited to make comments on impediments and list additional impediments or challenges. The survey was distributed through the quarterly newsletter of the National Centre for Groundwater Research and Training, and with direct emails to key groundwater agencies, and was open for a period of eight weeks. Respondents came from State and Federal government agencies, research institutions (universities and CSIRO) and private industry (primarily engineering consulting firms and mining companies). A total of 95 responses were received from the Australian groundwater community. Of these, 35% of respondents (33 responses) were from State Government, 25% (24 responses) were from private industry, 21% (20 responses) were from research institutions, 17% (16 responses) were from the Federal Government (Department of Agriculture, Water and the Environment; Office of Water Science; and Geoscience Australia), and 2% (2 responses) were from other organisations (1 from local government and 1 unspecified). 42% of respondents identified as having more than 20 years of experience, 31% as having between 10 and 20 years of experience, 24% as less than 10 years of experience, and 3% did not complete this question. For each challenge, we present the percent of respondents who ranked it within each of the different categories and calculate an average score. Thus, an average score of 1 means that all respondents rated the challenge as 'not an impediment', and an average score of 5 means that all respondents rated the challenge as a 'major impediment'. The average score would be 3.0 if exactly half the respondents rated the challenge as 'not an impediment', and half rated the challenge as a 'major impediment', although of course an average score of three could also be arrived at in other ways. The average score is analysed for all respondents and for the different groundwater sectors (i.e., State Government, Federal Government, research organisations and private industry). Statistical two-sided T-tests are used to assess significance of differences between responses from the different groundwater sectors.

4. Results

The eighteen challenges identified by the authors through their collective experience and discussions with industry professionals are listed in Fig. 2, where they are also grouped into seven subject areas. Across all challenges and respondents, 28% of responses were a score of 5 (major impediment), 31% were 4, 26% were 3, 13% were 2% and 2% were 1 (not an impediment) (Fig. 3). The average score for each challenge ranged between 3.3 and 4.1 (Fig. 4), indicating that all surveyed issues represented impediments of some concern. The average score across all challenges and respondents was 3.70. In general, respondents from research organisations were the most concerned (average score across all challenges of 3.92), followed by those from Federal Government (3.86), State Government (3.59) and private industry (3.52). The nature of the different impediments and their individual scores from survey responses are discussed below within the subject areas. Differences in the responses between the groundwater sectors are represented in Fig. 5.

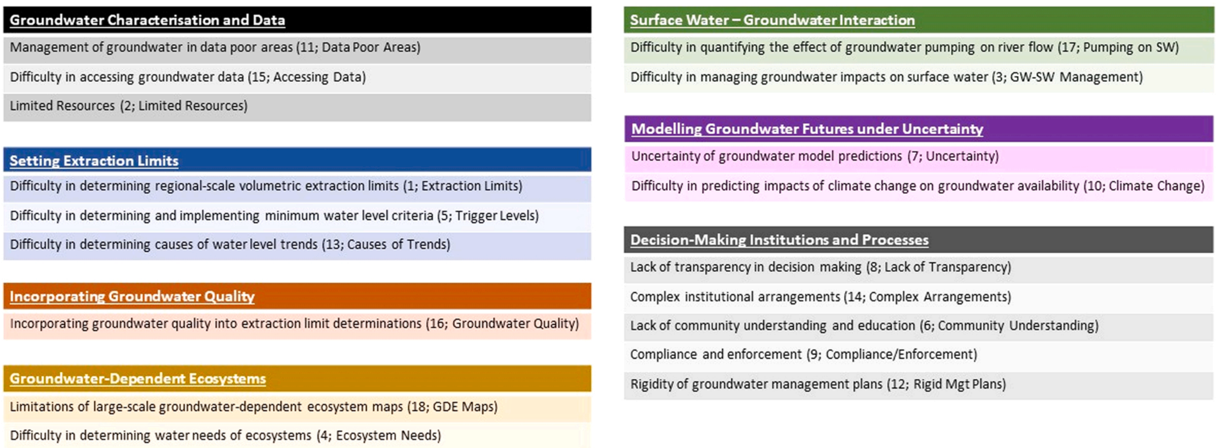

Fig. 2. List of 18 identified challenges, categorised by subject area. Included in parentheses for each challenge is the overall ranking of the question based on the survey, and a short summary title. These are used for brevity in Figs. 3 and 4. The full descriptions of the challenges that were given in the survey is provided in Supplementary Material.

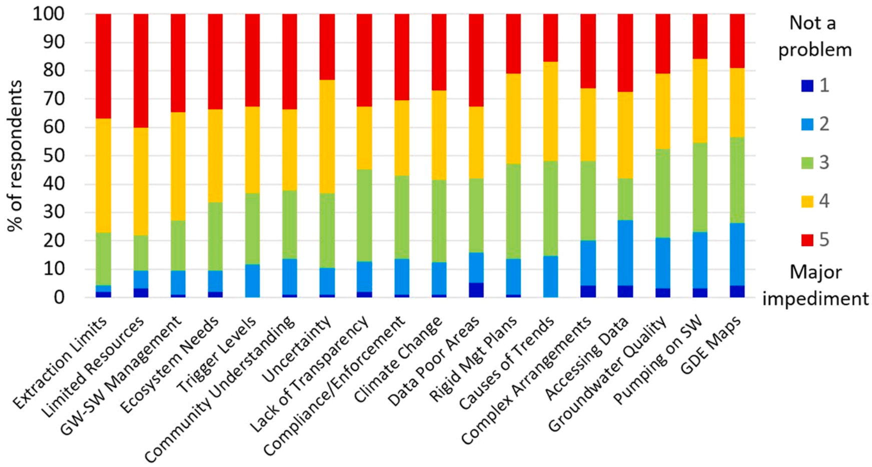

Fig. 3. Percent of survey responses within each category (1−5) for the 18 identified challenges. Shorthand summaries of the challenges are given in the x-axis (Fig. 2), which are arranged from left to right according to their average score. The breakdown by jurisdiction is presented in Supplementary Material.

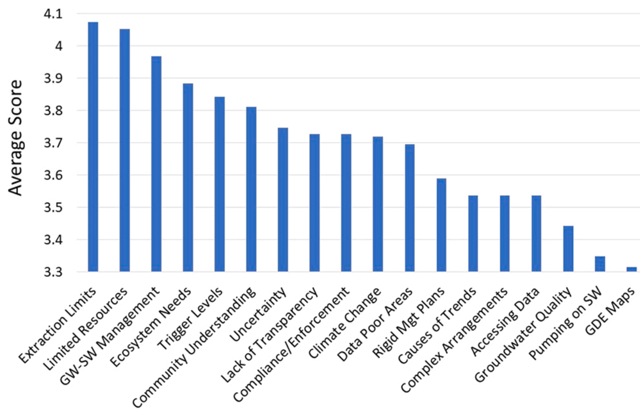

Fig. 4. Average score of different impediments from all respondents. Note the compressed scale of the y-axis. Shorthand summaries of the challenges are given in the x-axis (Fig. 2), which are arranged from left to right according to their average score.

4.1. Groundwater characterisation and data availability

If groundwater decision-making is evidence based, then good decision-making relies on the amount and quality of information that is used for the decision-making process. In Australia, the intensity of groundwater development largely determines the spatial coverage of monitoring networks (Fig. 6). 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 (Fig. 7). Groundwater infrastructure is aging (SKM, 2012), and failed or damaged monitoring bores are not always replaced. Also, a more sophisticated understanding of groundwater systems cannot necessarily be delivered simply with denser monitoring networks and often requires targeted studies into processes such as recharge and discharge, leakage between aquifers, and water requirements of GDEs. These studies are often conducted at small spatial scales and are not uniformly available across different groundwater management areas. While national maps of groundwater attributes have been developed, either by extrapolating data from site-specific studies (e.g., recharge; Leaney et al., 2011) or from remote sensing (e.g., GDEs; Doody et al., 2017), national maps often lack precision and detail in local areas.

There are cases where monitoring networks have been extended and financial resources provided due to a strict environmental regulatory framework around, for example, extensive extraction of mineral resources. Unconventional gas extraction in the Surat Basin, which underlies part of the Great Artesian Basin (Fig. 1), is a good example of this development, where stakeholder pressure on politicians drove investment to improve the understanding of recharge, groundwater flow and inter-aquifer connectivity (Habermehl,

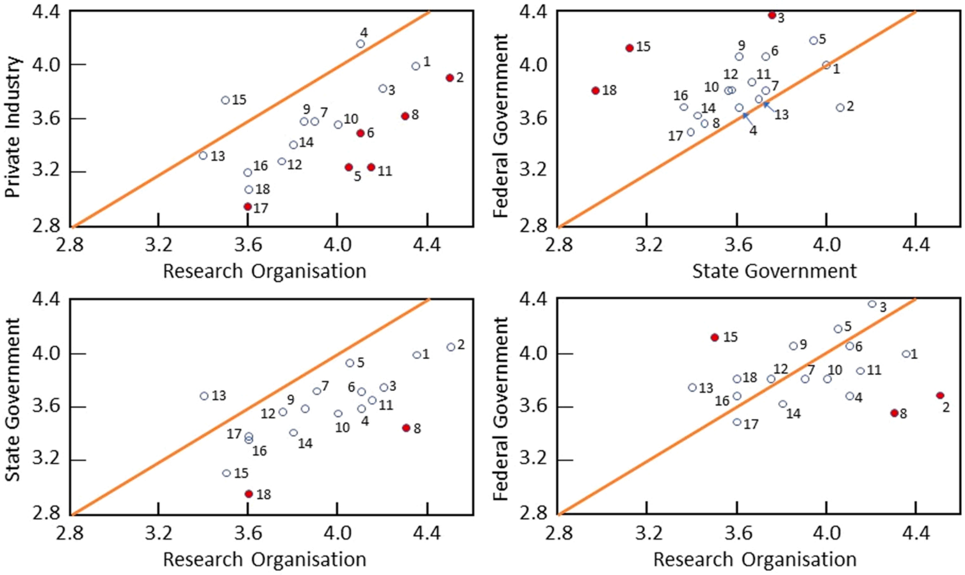

Fig. 5. Comparison of average score for each impediment (1 – 18) given by respondents from different groundwater sectors. Numerals refer to challenges listed in Fig. 2. Red circles denote statistically significant differences at the 10% level (T-test).

2020; Radke and Ransley, 2020; Vink et al., 2020). However, many areas have not benefitted from such programs, and limited resources for groundwater investigations was ranked 2nd overall as an impediment to sustainable groundwater management (Fig. 4), and highest by researchers and State Government survey respondents (Fig. 5). Difficulties in managing groundwater in data-poor areas was ranked 11th overall, but more highly by respondents from State and Federal governments and research organisations (Fig. 5).

Problems can also arise when data sets are split between different agencies. Fundamental groundwater data (stratigraphy, bore construction, hydraulic head, major ion chemistry) are available in State and Territory databases which are publicly available and user-friendly (Sharples et al., 2020). The Bureau of Meteorology has the responsibility of collating groundwater data into a single database (Bureau of Meteorology, 2022), although not all the data in State and Territory databases are represented in the national database. In some jurisdictions, groundwater data were initially held by different government departments, and some information was lost when these databases were merged. Also, data collected by private entities and research organisations are often not replicated in government databases, partly because the latter are mostly limited to certain datatypes, and partly because data gathered by other institutions are often not provided to the database managers. Government departments are increasingly engaging private companies for groundwater monitoring, and this can sometimes make data more difficult to access or require a fee for access. Data collected by some private entities (e.g., mining companies) are often considered to be commercial-in-confidence. While mining companies are required to make some monitoring data available as part of the mining license conditions, detailed studies and specialised data (e.g., geophysical surveys, isotope data) are rarely publicly available. While generally not considered to be a major issue by State agencies, who are often the custodians of key data sets, the difficulty in accessing data has been highlighted by Federal Government and private organization survey respondents in this (Fig. 5) and previous (Nelson, 2019) surveys.

4.2. Setting extraction limits

Setting regional extraction limits to protect groundwater resources, groundwater-dependent ecosystems and existing groundwater users is a challenge and was ranked as the greatest overall impediment to sustainable groundwater management (Fig. 4). In unconfined aquifers, the recharge rate often informs setting of the regional extraction limits, and sometimes limits are set to be a fraction of recharge (which itself may not be well constrained; Crosbie et al., 2012). The fraction of recharge that is allowed to be extracted is usually determined by the perceived value of GDEs within the management area and/or their perceived sensitivity to impact (Doody et al., 2018), but the link between ecosystem value and the environmental allocation is often not well-defined and somewhat subjective. Where a groundwater model is available, it may be used to determine extraction limits that will limit drawdown to acceptable levels (Pierce et al., 2020), but this necessarily involves assumptions regarding the spatial pattern of future groundwater use. Even with carefully determined regional limits, areas of intense development and groundwater drawdown may develop despite average use across a management area being relatively low.

In 2016, 25% of groundwater management areas in Australia were considered to be over-allocated (Barnett et al., 2020), and there are examples where limits have been reduced due to impact of drawdown on ecosystems. In the Barwon River Basin, central Victoria, groundwater extraction from deep aquifers for the water supply of Geelong (population approximately 250,000; Fig. 1) was increased during the 2001 – 2009 drought (Petrides and Cartwright, 2006). Environmental impacts of this extraction included reduced surface water flows in headwater streams with the subsequent drying of swamps, generation of acidic runoff, fish kills, and increased bushfire

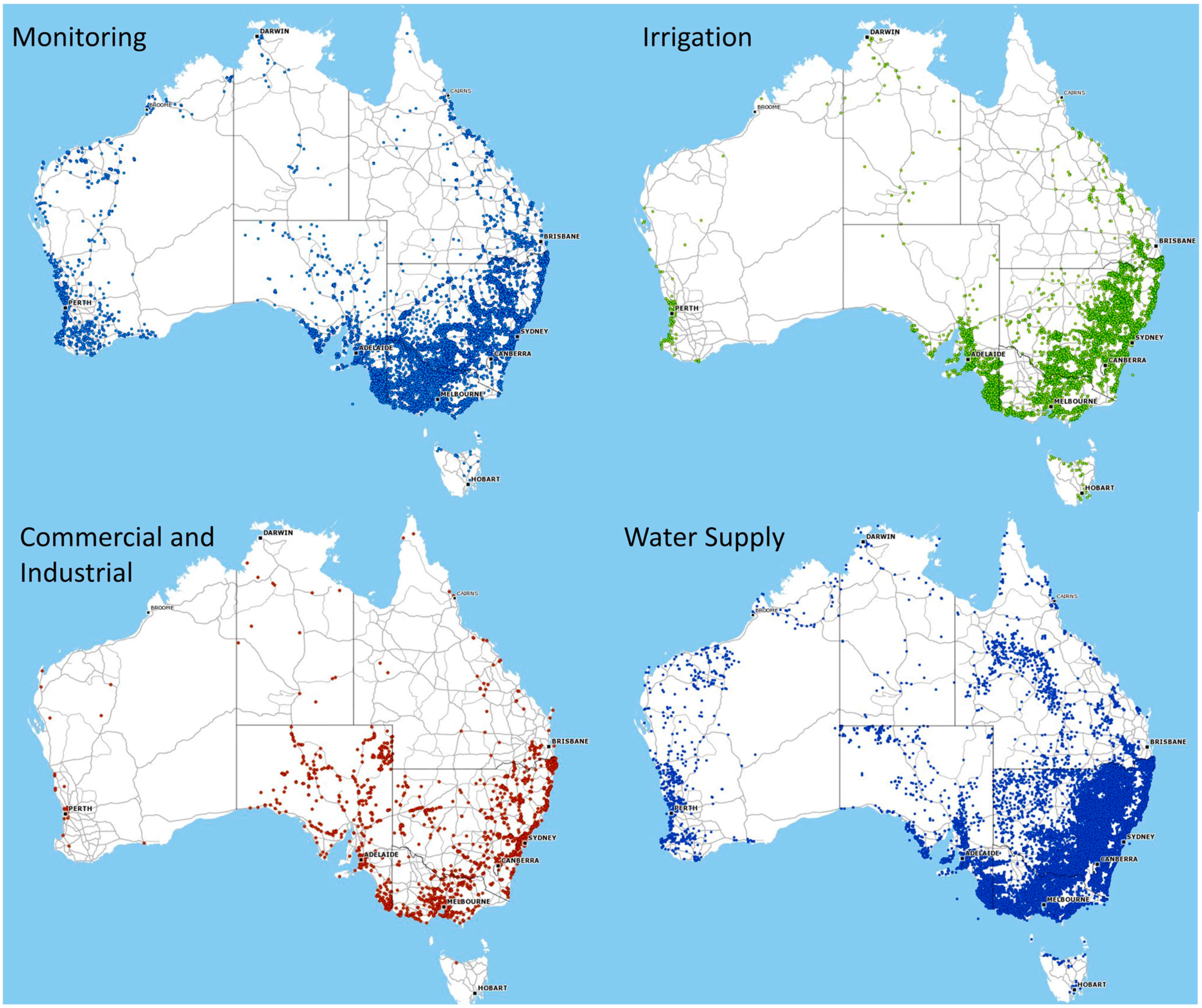

Fig. 6. Distribution of monitoring, irrigation, commercial and industrial and water supply bores across Australia. From Bureau of Meteorology (2022).

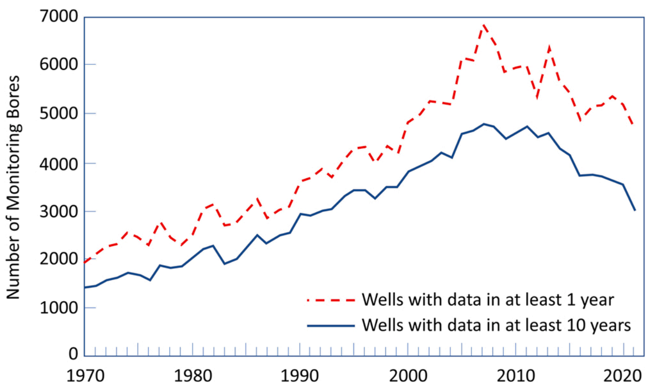

Fig. 7. Groundwater monitoring in South Australia between 1970 and 2021. The plot shows the number of bores monitored for water level in each year. Also shown is the subset of bores monitored each year that have a record covering at least 10 years. The number of bores monitored for water levels increased from the late 20th century through to the early 21st century but has since decreased due to changes in priorities and funding limitations. Data from South Australian Government.

Box 2
The Gnangara groundwater system, Western Australia.

Around 70% of Perth's water is supplied by groundwater, primarily from the 2200 km^2 Gnangara groundwater area (DWER, 2022). The unconfined Superficial aquifer is underlain by two major confined aquifers; the Leederville and Yarragadee aquifers, and water is extracted from these aquifers for public water supply. The Gnangara groundwater system also supports a myriad of GDEs that host a vast range of flora and fauna, and include terrestrial, dampland and aquatic ecosystems (Froend et al., 2018).

The legislative framework for groundwater management allows for statutory planning that includes the identification of environmental values and how water will be allocated to meet environmental needs (Water and Rivers Commission, 2000). Water allocation plans are also subject to the provisions of environmental protection legislation and under this statutory framework, Environmental Water Provisions (EWPs) for the Gnangara groundwater system were established in 1988 as minimum water levels at eight wetlands and then revised in the late 1990 s to include terrestrial vegetation, cave pool and seeps, representing the range of GDEs. Since these criteria were set, Perth's climate has dried, the surface water flow into dams has declined (Petrone et al., 2010), and groundwater storage in the Superficial aquifer has reduced by more than 1.0×10^9 m^3 (DWER, 2022). As a result of the drying climate and groundwater abstraction many of the minimum water levels set as EWPs have not been met (McHugh and Bourke, 2007). To ameliorate negative effects some wetlands have been supplemented by groundwater pumped from the Superficial or Leederville aquifers, and groundwater abstractions for public water supply have been shifted to borefields that are less likely to impact GDEs (McHugh and Bourke, 2007).

In response to the climate challenge, the government identified a range of management options including increasing water recycling and revising groundwater allocations. A managed aquifer recharge system was implemented in 2017, with the injection of recycled water into the confined aquifers. The volume of groundwater abstracted for public water supply was reduced from 145×10^6 m^3 y^{-1} to 120×10^6 m^3 y^{-1} and growth in private abstractions was capped (DOW, 2009). Substantial investments were also made to improve the understanding of the confined aquifers (Meredith et al., 2012; DWER, 2021) and the connectivity of GDEs to the groundwater system (e.g.,Clohessy, 2012;Degens et al., 2012). Using this improved system understanding, numerical modelling of the groundwater system determined that abstraction would need to reduce by 54×10^6 m^3 y^{-1} to maintain groundwater levels and avoid further damage to water quality and environmental health (DWER, 2022). This represents a 20% reduction on the 275×10^6 m^3 y^{-1} abstracted from the Gnangara groundwater system at the time of publication. For most of the 2600 private licenced users their allocations will be reduced by 10% when they apply for renewal of their license (from 2028), resulting in an anticipated abstraction reduction of 9.9×10^6 m^3 y^{-1}. The allocation for public water supply will be reduced by 27%; a reduction of 30×10^6 m^3 y^{-1} (from 110 to 80 $\times 10^6$ m^3 y^{-1}). Domestic garden bore use will be reduced by aligning the current three-days-a-week sprinkler roster for domestic garden bores with the two-days-a-week roster for scheme users, resulting in an estimated reduction of 13.6×10^6 m^3 y^{-1}.

risk. Following community pressure, the agency responsible for water supply withdrew its licence application and committed to restoration works in the impacted streams (BarwonWater, 2020; Nelson, 2022). (See also Box 2.).

In principle, groundwater response triggers (sometimes called resource condition limits) are a better approach for protecting ecosystems and other groundwater users and are usually applied in combination with volumetric approaches. They represent a form of adaptive management, but while the use of trigger levels is conceptually appealing, its ultimate success is determined by the adequacy of observation well coverage, selection of appropriate trigger levels, and ability to observe and quickly respond when trigger levels are exceeded. Even if water level or water quality needs of GDEs are known (see below), determining monitoring bore trigger levels to prevent critical values from being exceeded at the GDE location is difficult (Noorduijn et al., 2019). The problem arises because drawdown cones continue to expand and groundwater levels subside even after extraction ceases. Observation bores therefore need to be located to allow for early warning and provide sufficient time for intervention to prevent the exceedance of maximum permitted declines at the GDEs. The use of triggers is particularly difficult where the intent is to maintain groundwater flow to streams, as a very small reduction in groundwater level near a stream may still result in a reversal of the hydraulic gradient, hence causing a river to change from gaining to losing (McCallum et al., 2013). Currently, the use of trigger levels in Australia is not very sophisticated, and rarely directly linked to the protection of particular ecosystems. For example, in the West Goulburn Groundwater Management Area, which covers an area of 5400 km^2 (Fig. 1), the trigger for possible additional controls on groundwater pumping relies on the average rate of decline in only two observation bores (Goulburn-Murray Water, 2017). Thus, while it provides some control on regional groundwater level decline, it will not prevent local areas of drawdown from occurring and potentially impacting sensitive ecosystems or other groundwater users.

If water level decline is to be used to trigger management intervention, then distinguishing between possible causes (groundwater pumping, land use change, or a prolonged period of low rainfall) becomes important. This can be difficult. Several approaches have been developed for separating water level fluctuations due to rainfall variations from longer-term trends that might be attributed to groundwater extraction or land use change (e.g., Peterson and Western, 2014; Kong et al., 2021), but these models are not widely used. Thus, in the southeast of South Australia, for example, uncertainty over the relative impacts of forestry plantations versus irrigated agriculture has complicated discussions over management intervention to arrest the water table decline (Government of South Australia, 2020).

4.3. Incorporating groundwater quality

In Australia, groundwater salinity exceeds 1500 mg/L across almost 40% of the continent (Harrington and Cook, 2014), and many remote communities in arid areas are exposed to nitrate and uranium in bore water which occurs naturally at concentrations above WHO guidelines (Western Australian Auditor General, 2015; Moggridge, 2020). This limits beneficial use options. The major challenge for groundwater allocation management, however, is understanding when groundwater extraction can lead to deterioration in water quality. Groundwater extraction in aquifer systems of heterogeneous permeability results in changes in the hydraulic gradients between layers, which can increase rates of inter-aquifer mixing or leakage from aquitards (Konikow and Neuzil, 2007). Reversals in the direction of vertical leakage are also possible. If there is contrasting water quality between the different units, this can result in movement of contaminants into water supply aquifers (Hofmann and Cartwright, 2013; Iverach et al., 2017). In the Eyre Peninsula, South Australia (Fig. 1), increases in salinity of groundwater extracted from town water supply bores installed in the unconfined aquifer have been linked to increased leakage from the more saline underlying confined aquifer (DEW, 2020). Where groundwater pumping is for irrigation, recycling of salts can lead to increases in groundwater salinity in the unconfined aquifer (Cook and Keane, 2021; Foster, 2022).

Deterioration in water quality due to seawater intrusion can occur when groundwater extraction occurs in coastal areas (Ferguson and Gleeson, 2012; Werner et al., 2013). Rottnest Island (Fig. 1) is an example of where a freshwater lens has contracted due to a combination of reduced recharge and groundwater extraction (Bryan et al., 2016). Management approaches to seawater intrusion include the setting of level and/or volume-based triggers (Werner et al., 2011), engineered solutions, and ongoing salinity monitoring for advanced warning in dedicated monitoring bores. In Perth, a groundwater replenishment scheme injects treated wastewater into the confined groundwater system to offset groundwater use and ameliorate the threat of seawater intrusion (Smith et al., 2012; Box 2).

Other geochemical processes triggered by groundwater extraction can also impact on water quality. Exposure of sediments to oxygen has led to arsenic and fluoride contamination of groundwater across parts of Asia, Africa, and South America (Ravenscroft et al., 2009; Rodriguez-Lado et al., 2013) and these elements occur at elevated concentrations in some parts of Australia (NHRMC and NRMMC, 2011). A change to more oxic and lower-pH conditions in water supply aquifers can also cause increased mobility of uranium and radium (Lauria et al., 2004; Ayotte et al., 2011). 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 (Ljung et al., 2009; Shand et al., 2018).

In determining water allocation, water quality issues have generally received less attention than water quantity issues, largely because there is often no obvious direct link between extraction and quality change. Where they do occur, 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. 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 (Ayotte et al., 2011).

4.4. Groundwater-dependent ecosystems

GDEs require access to groundwater on a permanent or intermittent basis to meet their water requirements (Eamus et al., 2006), and limitations exist in identifying and mapping GDEs and determining their water needs. Groundwater extraction from unconfined aquifers with shallow water tables poses substantial risks to GDEs and can lead to ecosystem degradation, loss of ecosystem services and environmental damage (Tomlinson and Boulton, 2008; Eamus et al., 2015).

Many approaches have been undertaken to locally identify and map GDEs (Eamus et al., 2006; Doody et al., 2017). 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 (Eamus et al., 2015; Castellazzi et al., 2019). For example, in regions with distinct dry periods, GDEs can be mapped by identifying vegetation which remains green through dry seasons or drought episodes. In Australia, a continental-scale map, the GDE Atlas, has been developed using a combination of local/expert knowledge, and remote sensing of 'wetter' and 'greener' pixels (Barron et al., 2014) or evapotranspiration (Van Dijk et al., 2015; Doody et al., 2017). This map provides a good first step for water managers, but coverage is incomplete and there can be issues of scale and resolution (Brim Box et al., 2022). Of course, the functional dependence of ecosystems on groundwater, as defined by the degree or seasonality of groundwater dependence (Eamus et al., 2006), is difficult to infer from remote sensing analyses which only provide information on 'potential' GDEs. Some jurisdictions have also undertaken their own GDE mapping, using a combination of remote sensing, and mapping of vegetation community structure and depth to groundwater (Kuginis et al., 2016). In New South Wales, mapping of terrestrial (vegetation) GDEs is supplemented by assessments of GDE value, including assessments of distinctiveness, diversity, habitat value, and degree of disturbance (Dabovic et al., 2019).

Once GDEs have been identified, characterising the degree of groundwater dependence or the ecological water requirements of GDEs is challenging and best determined using direct measurement of groundwater use from several lines of evidence (Benyon et al., 2006; Froend and Sommer, 2010). Remote sensing approaches can include the use of flux tower networks, which when positioned in GDEs can provide a measurement of actual evapotranspiration (Cleverly et al., 2006). In the United States, the flux tower network was fundamental for effectively developing remote sensing models of ET (Nagler et al., 2005). In Australia, however, flux tower data in GDEs are limited or unavailable (Glenn et al., 2011), and so other approaches to understand GDE water requirements are required. Toolboxes that describe the different field methods are available (e.g., Richardson et al., 2011), but not all tools are suitable for broadscale application.

Determining the impact of reduced water availability on GDEs is even more difficult. The lack of knowledge of GDE environmental water requirements can be a major impediment to ensuring sustainable groundwater management and is perceived to be a much greater impediment than GDE identification and mapping (Fig. 4).

4.5. Groundwater – surface water interaction

It is now widely understood that pumping groundwater from bores located adjacent to rivers and streams can impact streamflow (McCallum et al., 2013; Gleeson and Richter, 2017). This can be a problem for stream condition, where reduced flows inhibit ecosystem function or result in poor water quality (e.g., stagnant conditions or high summer water temperatures). It is also a problem for downstream water users that are no longer able to extract permitted volumes. Most water resource plans in Australia now require impacts of groundwater extraction on surface water systems to be considered, and surface water and groundwater resources are assumed to be connected unless it can be demonstrated otherwise (National Water Commission, 2009). The predicted impact of groundwater pumping on surface water systems within the Murray Darling Basin was one of the reasons for the adoption in 2012 of a cap on groundwater extraction in the basin (Walker et al., 2020; see Box 1).

Tools for quantifying changes in river flow due to groundwater pumping range from simple stream depletion equations (Glover and Balmer, 1954) to approaches based on numerical models (Leake et al., 2010). The commonly used stream depletion equations typically assume a hydraulic connection between groundwater and rivers (Brunner et al., 2011), and that all groundwater pumping will eventually be sourced from streamflow. They may therefore over-estimate river loss, particularly in areas with shallow water tables where reductions in evapotranspiration loss may also occur (Evans, 2007). While numerical models can consider such processes, parameterising groundwater models to accurately simulate river-groundwater connectivity and changes in evaporative loss is difficult. The impacts of groundwater extraction on intermittent streams (which are especially prevalent in Australia) are particularly poorly understood and difficult to quantify in part due to a lack of gauging stations on these systems (Krabbenhoft et al., 2022). Despite this, estimation of pumping impacts on streams is not generally considered to be a major impediment for sustainable groundwater management (Figs. 3 and 4), possibly due to several recent studies to estimate stream depletion rates (Walker et al., 2020, 2021).

Conjunctive management of groundwater and surface water is more difficult. Approaches for determining the degree of groundwater – surface water exchange that warrants either joint water plans or consideration of the impacts of groundwater pumping on surface water vary across jurisdictions (Nelson, 2013), and in some areas, surface water and groundwater are managed separately even where there is a strong case for joint management. While there have been many studies aimed at quantifying the groundwater – surface water exchange fluxes (e.g., Gardner et al., 2011; Atkins et al., 2016), the current degree of GW-SW exchange is not directly related to the potential for development to alter the exchange rate. It should not therefore limit the need for joint plans.

While most groundwater plans consider impacts on surface water, few surface water plans consider connectivity to be significant or include any assessment of impacts of surface water diversions on groundwater systems (Ross, 2018). There are few examples of truly conjunctive groundwater – surface water management, and it is unclear how conjunctive management should be implemented. Some jurisdictions now consider groundwater licences for bores located close to rivers as part of the surface water allocation limit. However, this approach simply shifts the boundary between the surface water and groundwater domains and does not represent true conjunctive management. Young and McColl (2009) propose that all groundwater licences should involve subtraction of an equivalent amount of water from the surface water cap. This is the case in the Upper Ovens River (northeast Victoria) for groundwater allocations from the coarse-grained alluvial sediments (Goulburn-Murray Water, 2012), for example. However, while this approach offers maximum protection for the surface water system, it may be overly restrictive on groundwater development. In many areas, not all groundwater that is pumped will cause a reduction in streamflow, as some may be derived from reductions in other forms of groundwater discharge (such as evapotranspiration or outflow to the ocean; Evans, 2007). A four-zone system has been proposed, where bores closest to the river are treated as surface water, a second zone where impacts of pumping are transmitted to the river in less than six months (effectively, in the same irrigation season), a zone where impacts take longer than six months and one where pumping effects are never felt at the stream (Evans et al., 2006). While the principle embodied in this approach is sound, zone-based systems can be problematic, as they can allow bores located just outside of a boundary, and which may have a very similar impact to bores inside the boundary, to pump when bores inside the boundary cannot (Nelson, 2013).

Where numerical groundwater models are available, some jurisdictions use these to predict the impact of groundwater pumping on surface water flow when licence applications are made, and hence ensure that the total impact of surface water and groundwater pumping is within acceptable limits. The difficulty is that surface water – groundwater connectivity is a function of time, and so the impact of pumping any bore on streamflow will depend upon the timescale being considered. In many catchments, past lack of consideration of groundwater – surface water interaction will mean that a future reduction in river flow due to widespread groundwater pumping is yet to be realised. Many of the planning tools do not consider long time frames, and do not deal with legacy or future impacts.

4.6. Modelling groundwater futures under uncertainty

Groundwater models are one of the main tools used for forecasting future system states. They provide a means of collating available data and knowledge of how a groundwater system functions and integrating this information to provide predictions. However, uncertainty is pervasive in groundwater modelling and there is no such thing as an “accurate” model. Any model-based prediction is uncertain. Uncertainty stems broadly from three sources: (1) uncertainty in characterizing a groundwater system, (2) simplified representations of the real-world system and (3) uncertainty regarding future conditions. The first two points apply to most groundwater modelling problems. The latter is particularly pertinent where decision-support modelling is undertaken for groundwater management.

Decision-making, whether for environmental management or other purposes, requires knowledge of the risk associated with the decision being taken (Freeze et al., 1990). Characterizing risk requires analysis of the probability of a management action resulting in an undesired outcome. Modelling enables evaluation of the risk associated with a groundwater management action. More importantly, it provides a mechanism for assimilating available information and thus reducing the uncertainty associated with that risk. Knowledge of groundwater systems is always imprecise, and our ability to simulate system and process detail is limited; often requiring rough approximations. These approximations introduce model-induced error. Thus, it is never possible to calculate the outcome of a management action exactly, as these depend on too many unknown (and unknowable) details of the groundwater system. It is, however, possible to calculate probabilistically.

Modelling undertaken to support sustainable groundwater management aims to quantify the uncertainty of management actions not achieving some stakeholder-derived criteria of sustainability. Forecast uncertainty should reflect lack of information as well as inherent model structural defects. Data assimilation may reduce uncertainty derived from hydraulic properties, historical stresses, or multiple conceptual models, and data-worth analysis methods can assist in targeting further site characterisation and data collection (e.g., Kikuchi, 2017; Partington et al., 2020). However, data assimilation cannot reduce predictive uncertainty caused by unknown future conditions.

Given that sustainable management is usually interested in long-term effects, unknown future conditions can contribute significantly to uncertainty of management outcomes. If this is the case, uncertainty of future stresses should be addressed during uncertainty analysis. While models frequently include assessment of the impacts of climate change on groundwater resources, this assessment is often limited to the impact of climate change on groundwater recharge (Crosbie et al., 2012) and less commonly examines changes in irrigation rates that might occur due to reductions in rainfall or increases in evaporation, or even possible changes in crop types and land management (e.g., Stigter et al., 2014; Hugman et al., 2017). Gorelick and Zheng (2015) have emphasised the need for modelling efforts to represent the complex coupled interactions between human and natural systems, and to incorporate uncertainties in economic and policy aspects which may exceed uncertainties in the natural system.

In some cases, irreducible uncertainty may be so high as to preclude the ability to determine whether management outcomes will be effective or not. Nevertheless, decisions must be made. Adaptive management may be employed, specifying reactions to triggers or thresholds to avoid undesired outcomes. In principle, adaptive management provides a framework for uncertainty reduction, with iterative cycles of data assimilation successively improving confidence in predicted management outcomes. Unfortunately, real-world examples of appropriate adaptive groundwater management are rare (Thomann et al., 2020). To the best of our knowledge, there are no demonstrated cases in which modelling provides assurance that an adaptive management plan will reduce the risk of an unwanted outcome.

The science of groundwater data assimilation and uncertainty quantification has matured over the last several decades, and the importance of associating uncertainties with decision-critical groundwater model predictions is rapidly gaining recognition (e.g., Middlemis and Peeters, 2018; IESC, 2018). Documented methodologies and software tools are readily available (e.g., Doherty, 2015; White et al., 2016). Yet, unfortunately, the groundwater industry still lacks personnel with sufficient knowledge and experience in data assimilation and uncertainty analysis. In a recent report, GMDSI (2022) documents the outcomes of a series of discussions with Australian environmental regulators faced with reviewing environmental impact reports informed by groundwater modelling. In these discussions, amongst other things, regulators note the challenge in finding personnel skilled in uncertainty analysis.

Other challenges with groundwater models are scale and resolution. Many of the models that have been developed for groundwater management cover large areas and are not appropriate for making decisions regarding individual licence applications and impacts at individual bores or GDEs. Also, many areas do not have any models or have only models that are insufficiently calibrated for management purposes. In New Zealand, it was estimated that in 1999, only 20% of allocated groundwater was from an aquifer where there was a calibrated numerical model (Fenemor and Robb, 2001). In Australia, the fraction of groundwater withdrawn from an aquifer where there is a calibrated numerical model would likely be higher, but the accuracy of many of our models for decision-making purposes is unproven. Model uncertainty and prediction of climate change impacts were ranked 7th and 10th overall, with similar rankings given by each industry group.

4.7. Decision-making institutions and processes

In Australia, decisions relating to groundwater governance are made by a combination of federal, state and territory governments and non-government organisations including local water boards (Ross, 2016). Groundwater governance is a complex task in part due to the significant time and effort required for multiple organisations, spanning several environment and resource sectors and administrative levels, to address issues (Mendham and Curtis, 2014; Ross, 2016). This fragmented nature of groundwater governance in some parts of Australia has been criticised; however, attempts to improve governance have proven to be difficult due to the diversity of users and complexity of groundwater resources (Ross, 2016). Increased partnerships between governing authorities and the vast array of water users have been identified as potential solutions for improving groundwater governance and reducing regional disparities in management approaches (e.g., Schlager, 2006). Robust management of groundwater resources requires the consideration of land use, biodiversity, and surface water resources. The distribution of these portfolios across Government departments, and effectiveness of the linkages between them, varies across Australia, but where they are managed by different authorities, effective governance of groundwater resources can be hindered (Nelson, 2020).

A transparent and inclusive approvals process provides a genuine opportunity for the best available science to be utilised and for potentially affected stakeholders to be appropriately consulted. In some jurisdictions, important steps have been taken to ensure transparency in the decision-making process relating to groundwater entitlements. For example, the Northern Territory Government has established a Water Licensing Portal (DEPWS, 2021) that provides access to supporting scientific documentation and factors considered when assessing groundwater licence applications. However, this type of information is not uniformly available across all jurisdictions. Yet, the approvals process is delegitimised when the available evidence is not effectively and transparently incorporated (O'Donnell and Nelson, 2020).

The approvals process for groundwater withdrawals, or groundwater-affecting activities, varies depending on the scale of the proposed operation. For major groundwater-affecting projects (e.g., mining applications), Environmental Impact Assessments (EIAs) allow deficiencies in proposed plans, including issues with data gaps, to be identified. They can also highlight points of potential scientific disagreement to be addressed in subsequent investigations. EIAs are the most open and transparent part of the approvals process (Currell et al., 2017), and therefore, a greater emphasis on EIAs may reduce uncertainties in the level and type of impact to groundwater systems at the outset of major projects (Lee, 2014). Currell et al. (2017) suggest that transparency in the approvals process can be improved by ensuring that monitoring criteria and mitigation strategies be made available for scrutiny prior to project approval. Transparency of post-approval operational monitoring data is particularly important to ensure that project proponents are accountable for project impacts, given the hidden nature of groundwater and the likelihood that impacts are not immediately obvious (Nelson, 2019). Transparency in decision making was identified to be a greater challenge by the research community than by other organisations, perhaps partly because the research community are often not connected with decision making processes (Fig. 5).

Groundwater management plans outline long-term management strategies that provide valuable certainty to water users, but they can also lead to inflexible decision-making that is slow to respond to changing knowledge or circumstances (Ross, 2016). The use of rigid groundwater management plans that do not seek to update system understanding based on new knowledge can lead to situations where the potential for lagged aquifer responses is overlooked (Saito et al., 2021). Adaptive management strategies (e.g., Williams et al., 2009) can provide flexibility in the management process, with a focus on uncertainty reduction through management actions. Adaptive management also provides a framework whereby elements of the plan are periodically revisited as new data and improved understanding of system behaviour are identified (Williams et al., 2009). It allows for multiple conceptual models to be considered, along with documented responses to potential future project impacts based on each conceptual model. However, adaptive management can have challenges where it involves changes to be made to volumetric allocations to water users. Reductions in water allocations involves costs in productivity, equity and trust (Iftekhar and Fogarty, 2017; Schuster et al., 2020), and the aim should be to manage groundwater to prevent the need for such reductions. A recent review of its application in groundwater-affecting projects demonstrated that many plans which purportedly used adaptive management deviated significantly from formal definitions of the strategy (Thomann et al., 2020).

For groundwater management plans and water licenses to ensure that water resources are appropriately utilised, compliance of water users and a willingness of, and resources for, administrators to enforce limits is vital. Regulations alone are insufficient to ensure the protection of a resource without the willingness of regulators to enforce their regulatory power (Molle and Closas, 2020). Widespread use of meters for groundwater extraction — critical infrastructure for compliance and enforcement activities — has significantly lagged their use in the surface water context, and in some cases has been met with opposition from groundwater users (Holley and Sinclair, 2013). Ongoing concerns about compliance with groundwater extraction limits and inadequate enforcement programs have drawn the attention of the Australian Competition and Consumer Commission because of the implications for water markets (Commonwealth Government, 2021). In the Murray-Darling Basin, concern about compliance led to a new agreement between Basin States, the Basin Compliance Compact, and the creation of a new federal compliance oversight agency, now known as the Inspector General of Water Compliance. Compliance concerns may also arise in the context of major mining projects that are subject to unclear or ambiguous licence conditions, which may hinder enforcement; insufficient monitoring may also make it difficult to determine if mining projects are causing impermissible impacts, a difficulty which has emerged in the case of coal mining under Sydney's water catchments (WaterNSW, 2018). An approach to establishing and improving compliance with protections for GDEs that is yet to be fully explored in Australia is to establish environmental groundwater entitlements that can be held and enforced by third parties (Nelson, 2022).

The need to build stakeholders' and decision-makers' understanding of hydrogeological concepts is hindered by the complexity of natural systems and organisational complexities that must be overcome to achieve effective groundwater governance. People's intuition about how surface water moves through landscapes is formed by easily observable flows in streams and rivers, while groundwater flow processes are hidden. Studies in Australia (e.g., Mendham and Curtis, 2014) and the United States (e.g., Brasier et al., 2013) have shown that stakeholders' level of groundwater knowledge can be a strong indicator of their perception of risk. Mendham and Curtis (2014) suggest that engaging with stakeholders who are unsure about the risks of potential impacts (as opposed to stakeholders who are strongly for or against a project) early in the project approval process could allow stakeholders to make more informed decisions. Efforts to communicate with stakeholders more clearly are required from across the water sector. Various strategies have been used, and 3D visualisation models have been shown to be highly effective (e.g., Baldwin et al., 2012: Wolhuter et al., 2020).

Ultimately, the decision making and project approval process can be improved through an increased understanding of hydrogeological concepts by stakeholders and decision makers, and consequently groundwater education has been identified as a significant challenge (Figs. 3 and 4). More informed stakeholders will relieve some pressures on decision makers where an understanding of complex groundwater processes is important (Villarroya and Aldwell, 1998). Our survey did not specifically target irrigator groups or other stakeholders (e.g., First Nations, and other communities benefitting from GDEs). The challenge associated with a lack of transparency in the decision-making processes is likely to have rated much higher if it had.

5. Discussion

Sustainable use of groundwater implies the availability of the resource for future generations and that environmental impacts of extraction, both now and in the future, are acceptable and/or manageable. We deliberately avoid using the term 'sustainable yield' in this paper, because the term implies a volume (or at least has been used to mean that), and the spatial and temporal pattern of use is as important as the volume of water extracted. However, if sustainable use of groundwater is a balance between different potential uses and environmental impact, then this is also hard to define as attitudes differ across stakeholder groups and change over time. In Australia and elsewhere, many groundwater systems have areas with declining water levels, with competition between users, reduced streamflow and impacts on groundwater-dependent ecosystems (e.g., Taylor, 2006; Kelly et al., 2013). Of course, there have been many successes, including reductions in allocation in some of the worst affected areas (Schulte and Cuadrado Quesada, 2020; Schuster et al., 2020), the use of water recycling and managed aquifer recharge to increase supply and arrest declining groundwater levels (Keremane and McKay, 2007; Zulfic and Barnett, 2007) and increased participation of stakeholders in setting allocation limits (Pierce et al., 2020). However, interventions have not always been sufficient to arrest declining groundwater levels (Schulte and Cuadrado Quesada, 2020), and management should be seeking to prevent these impacts occurring, rather than respond when groundwater level decline negatively impacts other users or the environment.

Lowry et al. (2003) concluded that gaps affecting management of groundwater quantity in New Zealand were predominantly gaps in information and implementation. Knowledge of groundwater processes was generally considered to be adequate and technical methods and tools were available, even if they were not being widely applied. Of the 18 challenges described in the current paper, seven are principally gaps in information (6, 7, 11, 15, 16, 17 and 18; Fig. 2), six are gaps in implementation (2, 8, 9, 12, 13 and 14), three are gaps in technical tools (1, 3 and 5) and only two are principally gaps in the understanding of fundamental processes (4, 10). However, of those impediments ranked in the top six overall, three are principally gaps with technical tools (1, 3 and 5), with one of each of the gaps in process understanding (4), information (6) and implementation (2).

The highest ranked impediment was the difficulty in determining regional-scale volumetric water extraction limits. This is interesting given the criticism of volumetric based approaches in the international literature, particularly those based on groundwater recharge. While volumetric limits are important, protection of ecosystems cannot be achieved with basin scale limits, and there appears to still be an emphasis on "getting this number right". Other impediments ranked within the top six are the difficulties in determining and implementing minimum water level criteria, in managing groundwater impacts on surface water, and in determining water needs of ecosystems. These issues are at the core of our attempts to balance groundwater allocation with the environment. Also ranked within the top six challenges are stakeholder communication, improving knowledge of groundwater processes within the community, and the limited resources to support groundwater studies. The latter was ranked second overall and applies across all areas of groundwater investigations. Lack of staff and financial resources has also been identified as a major issue for groundwater management in other countries (e.g., Fenemor and Robb, 2001; Zingraff-Hamed et al., 2020).

In addition to the 18 impediments originally identified by the authors, several other challenges and needs were identified by survey respondents. These included the need for more accurate bore metering data and finer temporal resolution of these data, improved consideration of mining issues (in some areas, mine water sits outside the usual water accounting framework; see Timms and Holley, 2016, and Nelson and Quevauviller, 2019), the slow adoption of new research and technologies, and the lack of cost recovery for groundwater management. Future research involving greater numbers and diversity of stakeholder respondents could valuably explore other challenges reported in the literature associated with stakeholders and governance, including insufficient processes for First Nations Australians to engage in, influence and benefit from water allocation and planning (O'Donnell et al., 2022) and larger issues related to governance, accountability and collaborative policy-making (e.g., Zingraff-Hamed et al., 2020).

Strategies to improve groundwater management should include both an assessment of the current impediments, and also an assessment of the ease with which these impediments can be addressed. Stakeholder communication should be a priority as there is high potential for improvement in this area. Community education was identified as a high priority, and is linked to transparency in decision-making, also a major challenge. Decision making is better understood and accepted when groundwater processes and concepts are also well understood and when informed stakeholders are involved in the decision-making process. Limited resources, which is an issue across all areas of groundwater science and management, is often identified as a major challenge in surveys of this type. Improved knowledge of groundwater issues should contribute to increased funding. While the difficulty in determining volumetric extraction limits was identified as the greatest challenge through the survey, in many management areas this challenge is being resolved by announcements of the fraction of a groundwater allocation that can be used in the upcoming season. The use of announced allocations linked to resource conditions (e.g., water levels) reduces the need to carefully define basin volumetric extraction limits. The difficulty in determining water needs of ecosystems (4) and in managing groundwater impacts on surface water (6) are major challenges that do not have simple solutions. Identifying water needs of GDEs remains a critical factor in protecting GDEs, yet most fine-scale available methods are cost and labour-intensive, while broadscale methods can lack precision due to lack of appropriate geospatial data.

As the global population increases, pressures on water resources will also increase. This is likely to see changing emphasis in water resources planning and management, and water allocations to the environment may come under increasing pressure. In Australia, as in many countries, there is not an overall shortage of water. The problem is that water is not available where and when it is needed. There is thus likely to be increased emphasis on engineering interventions, including water supply pipelines to transport water from where it is available to where it is needed, water recycling and managed aquifer recharge. Reduction in water demand, through increased efficiency of water use is also an important part of the solution (Koech and Langat, 2018). The need for water pricing that more accurately reflects its value will also likely receive increased attention. This includes, but is not limited to, recovery of management costs (Commonwealth Government, 2009).

6. Conclusions

This study examined 18 challenges involved in sustainably managing groundwater allocations and conducted a survey of industry professionals to rank these challenges. Of the top six ranked challenges, identifying water requirements of groundwater dependent ecosystems is predominantly a gap in process understanding. Of the others, three are gaps in technical tools, one represents a gap in information, and one is a gap in implementation.

There is scope for improved approaches for managing water levels and surface water – groundwater interaction, and for improved involvement of stakeholders in decision making processes. Importantly, our survey did not include irrigators and other water users. If it had, challenges related to implementation may have rated more highly.

While this study focussed on water allocation issues in Australia, other countries face similar water management issues and many of the challenges are of global interest. Issues related to water allocation (OECD, 2017), management of GDEs (Erostate et al., 2020), groundwater metering (Molle and Closas, 2021), governance (Zingraff-Hamed et al., 2020), water pricing (European Environment Agency, 2009) and provision of sufficient resourcing (Zingraff-Hamed et al., 2020) are receiving increased attention globally. Of course, sustainable groundwater management involves more than water allocation, and there is also scope for further improvements in water efficiency (to reduce demand) and water quality protection both in Australia and globally.

CRediT authorship contribution statement

Cook PG: Conceptualisation, Methodology, Writing – original draft; **Shanafield:** Investigation, Writing – original draft; **Andersen:** Conceptualisation, Methodology, Writing – original draft; **Bourke:** Conceptualisation, Writing – original draft; **Cartwright:** Conceptualisation, Writing – original draft; **Cleverly:** Conceptualisation, Writing – original draft; **Currell:** Conceptualisation, Writing – original draft; **Doody:** Writing – original draft; **Hofmann:** Conceptualisation, Writing – original draft; **Hugmann:** Writing – original draft; **Irvine:** Conceptualisation, Writing – original draft; **Jakeman:** Conceptualisation, Writing – original draft; **McKay:** Conceptualisation, Writing – original draft; **Nelson:** Conceptualisation, Writing – original draft; **Werner:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101262.

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