2017

A global synthesis of managing groundwater dependent ecosystems under sustainable groundwater policy

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10.1111/gwat.12511

Rohde, M. M., Froend, R., & Howard, J. (2017). A Global Synthesis of Managing Groundwater Dependent Ecosystems Under Sustainable Groundwater Policy. *Groundwater*, *55*(3), 293-301. Available here.

Groundwater

Issue Paper/

A Global Synthesis of Managing Groundwater Dependent Ecosystems Under Sustainable Groundwater Policy

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Abstract

Groundwater is a vital water supply worldwide for people and nature. However, species and ecosystems that depend on groundwater for some or all of their water needs, known as groundwater dependent ecosystems (GDEs), are increasingly becoming threatened worldwide due to growing human water demands. Over the past two decades, the protection and management of GDEs have been incorporated into several water management policy initiatives worldwide including jurisdictions within Australia, the European Union, South Africa, and the United States. Among these, Australia has implemented the most comprehensive framework to manage and protect GDEs through its water policy initiatives. Using a science-based approach, Australia has made good progress at reducing uncertainty when selecting management thresholds for GDEs in their water management plans. This has been achieved by incorporating appropriate metrics for GDEs into water monitoring programs so that information gathered over time can inform management decisions. This adaptive management approach is also accompanied by the application of the "Precautionary Principle" in cases where insufficient information on GDEs exist. Additionally, the integration of risk assessment into Australia's approach has enabled water managers to prioritize the most valuable and vulnerable ecologic assets necessary to manage GDEs under Australia's national sustainable water management legislation. The purpose of this paper is to: (1) compare existing global policy initiatives for the protection and management of GDEs; (2) synthesize Australia's adaptive management approach of GDEs in their state water plans; and (3) highlight opportunities and challenges of applying Australia's approach for managing GDEs under other water management policies worldwide.

Introduction

Groundwater is a vital global water resource—it provides the majority of the world's drinking supply (Giordano 2009), supports 43% of irrigated agriculture (Siebert et al. 2010), serves as an emergency reserve during droughts, and sustains important native species and ecosystems. Ecosystems that are maintained by direct or indirect access to groundwater, and rely on the flow or chemical characteristics of groundwater for some or all of their water requirements, are collectively known as groundwater dependent ecosystems (GDEs) (Aldous and Bach 2011; Belvins and Aldous 2011; Brown et al. 2011). GDEs can exist above (terrestrial vegetation, seep/spring, river/stream, wetland, estuary) and within the subterranean

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Article Impact Statement: Global synthesis of opportunities and challenges for managing groundwater dependent ecosystems under sustainable water management policies.

Received August 2016, accepted February 2017.

doi: 10.1111/gwat.12511

(aquifer, cave, hyporheic zone) environment. GDEs above the subterranean environment thrive when natural groundwater levels are maintained such that groundwater is accessible from the land surface, thereby providing a reliable source of water especially when surface water is reduced or absent. GDEs provide valuable ecosystem services, such as supporting biodiversity, providing baseflows in rivers, water purification, pollinator habitat, flood control, water supply, and recreational opportunities. Globally, GDEs are increasingly threatened as human exploitation often exceeds natural recharge rates, particularly in Asia and North America (Gleeson et al. 2015).

The protection of GDEs is particularly challenging due to existing knowledge gaps at the intersection of groundwater hydrology and ecology (Tomlinson 2011). The diversity of GDEs also makes it difficult to provide a one-size-fits-all management solution, since each GDE has different ecological water requirements, contains different species, fosters specific habitat conditions, and can face a variety of threats from groundwater basin activities. Despite these challenges, GDEs are receiving increasing attention through the development of water management policy initiatives around the world.

This article aims to highlight the opportunities and challenges of managing GDEs under sustainable groundwater management policies. The three objectives of this paper are to: (1) compare global policy initiatives for the protection and management of GDEs; (2) synthesize Australia's adaptive management approach of GDEs in their state water plans; and (3) highlight opportunities and challenges of applying similar approaches for managing GDEs policies worldwide.

Existing Policy Initiatives for the Protection and Management of GDEs

Sustainable water management plans aim to adopt sustainable development principles based on achieving a balance between economic, social, and environmental needs, such that "development meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al. 1987). Although environmental considerations have become increasingly incorporated into water management policies worldwide, emphasis has been on protecting ecosystems dependent upon surface water. GDEs have been partially protected in those policies that recognize a link between groundwater and surface water; however, specific reference to ecosystems dependent upon groundwater within sustainable water policies has only been incorporated into a handful of legislation in the United States (California), the European Union (EU), South Africa, and Australia. Among these, Australia has implemented the most comprehensive framework to manage and protect GDEs through its water policy initiatives.

California

Recognition of GDEs in California falls under the Sustainable Groundwater Management Act (SGMA) of 2014. Prior to SGMA, groundwater law was almost entirely driven by court decisions to govern the use of groundwater in the absence of a comprehensive statutory and regulatory regime. In recent decades, state legislative efforts have increased to encourage and incentivize local groundwater management. SGMA was passed during an historic drought period (starting in 2011), and although California was the last state within the United States to pass comprehensive groundwater legislation, it remains the only state within the United States to specifically recognize GDEs in its groundwater legislation.

GDEs have been defined by the California Department of Water Resources as "ecological communities of species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface" (State of California 2016). Although GDEs have only recently been mapped in California (Howard and Merrifield 2010), local agencies (known as Groundwater Sustainability Agencies) are required under SGMA to identify and consider impacts on GDEs when reporting in 5-year Groundwater Sustainability Plans (State of California 2014, 2016). In addition to the explicit mention of GDEs within the statute and regulations, GDEs also fall under the broader California regulatory definition of "beneficial uses and users of groundwater."

European Union

Recognition of GDEs in the EU falls under the Water Framework Directive (WFD) of 2000 (European Union 2000). The WFD is a legislative framework for EU member states to protect surface water (inland, transitional, coastal) and groundwater. Environmental objectives within the WFD build upon community policies established in Article 174 within the EU Treaty to preserve, protect, and improve the quality of the environment by exercising the "precautionary principle" and rectifying environmental damage at the source through the polluters-pay principle.

GDEs in the EU are referred to as "groundwater dependent terrestrial ecosystems" and are defined as terrestrial ecosystems that are sustained by groundwater bodies and are directly dependent on the quantity (flow, level) or quality of groundwater bodies for a significant period of the year (Schutten et al. 2012). Nations within the EU are required to maintain groundwater quantity and quality based on threshold values established to prevent "any significant damage to terrestrial ecosystems which depend directly on the groundwater body" (Annex V, Table 2.1.2 in European Union 2000). Similarly, the chemical composition of groundwater must not cause "any significant diminution of the ecological or chemical quality of such [surface waters] nor in any significant damage to terrestrial ecosystems, which depend directly on the groundwater body" (Annex I, Table 2.3.2 in European Union 2000).

South Africa

Consideration for GDEs in South Africa falls under the National Water Act of 1998. Although there is no explicit mention of GDEs in the Act itself, this environmentally progressive Act guarantees water (surface water and groundwater) to be reserved for human and environmental needs. To address environmental needs, objectives known as "resource directed measures (RDM)" are made based on an optimal balance between consumptive use (taking water out of the system) and nonconsumptive use (leaving water in the system) (Seward 2010). RDMs are based on three concepts: (1) that an optimal level or range exists for achieving benefits for both consumptive and nonconsumptive uses; (2) thresholds exist and if consumptive use exceeds this level, then adverse impacts will occur to environmental resources or the water resource itself; and (3) public participation is essential in deciding upon optimal ranges and thresholds, so that public values can be integrated (Seward 2010).

GDEs are defined in a report to the Water Research Commission in South Africa as "terrestrial ecosystems that depend on groundwater such that the ecosystem would be significantly altered and even irreversibly degraded if groundwater availability (quantity & quality) was to change beyond its 'normal range of fluctuation'" (Colvin et al. 2003). Although water allocations for ecosystems is required, a lack of differentiation between groundwater and surface water resources and an emphasis on surface waters has limited the consideration of GDEs in water management (Aldous and Bach 2011). In addition, a shortage of technical capacity and long licensing wait times have also weakened the effectiveness of the legislation resulting in limited implementation of sustainable groundwater use for the environment (Seward 2010).

Australia

The management of GDEs in Australia falls under the National Water Initiative (NWI) of 2004, an intergovernmental agreement, that shaped water reform in Australia by taking a "whole of water cycle" approach to protect its water resources at the federal and state levels (Bates et al. 2010; Richardson et al. 2011a). The NWI has served as the basis for the recognition of environmental and ecological values of water in all Australian state and territorial jurisdiction water plans (Tomlinson 2011). The NWI was instituted in the middle of a significant 12-year drought period (1997 to 2009) to increase sustainability and include provisions for the environment.

GDEs are defined by the Australian government as "ecosystems that require access to groundwater to meet all or some of their water requirements so as to maintain the communities of plants and animals, ecological processes they support, and ecosystem services they provide" (Richardson et al. 2011a). At the federal level, the NWI requires state entities to tailor the inclusion and protection of GDEs in state water plans, but Australia's state entities have the authority to identify ecological objectives, quantify environmental water provisions, and determine water allocation provisions.

Australia's Approach for Managing GDEs

Adaptive management is at the core of Australia's approach for managing GDEs, as required under the NWI. This adaptive management framework enables water managers to make water allocation decisions based on routine monitoring and targeted scientific investigations to determine the hydrologic conditions and thresholds required to maintain a GDE. Since uncertainty in determining thresholds can be high, particularly during the early management years, some states within Australia have integrated risk assessments to minimize adverse impacts to the most valuable and vulnerable GDEs in the interim period. This section introduces Australia's adaptive management framework for GDEs, the scientific underpinnings in identifying GDE thresholds, and how risk assessment is used to minimize adverse impacts to GDEs as a result of groundwater resource use.

Adaptive Management Framework

Adaptive management is a "learning by doing" management strategy that utilizes ongoing monitoring and research to inform management decisions (Richardson et al. 2011a). In the case of GDEs, this iterative process (Figure 1) helps water managers to ensure ecological values are identified and considered in management plans in the early management years when there is uncertainty in the cause and effect relationship between the hydrologic regime and ecological response (Richardson et al. 2011a; Serov et al. 2012). The consideration of environmental water needs during water allocation decisions in Australia requires a determination of ecological water requirements for GDEs. Ecological water requirements are based on the best available scientific information made available through monitoring and targeted research that can identify which aspects of the hydrologic regime are most important in supporting the structure and function of an ecosystem. In the context of GDEs, ecological water requirements would include depth to the water table targets, water quality standards, and flow dynamic criteria at the boundary of interconnected surface water bodies.

In 2007, the Australian government commissioned the development of a practical "toolbox" of suggested approaches ("GDE Toolbox") to assist Australian state agencies in the identification and management of GDEs for water plans (Clifton et al. 2007). The GDE Toolbox (Table S1, Supporting Information) was updated in 2011 (Richardson et al. 2011a, 2011b) to offer a range of methods for determining ecosystem reliance on groundwater and to help water managers conduct the necessary technical investigations and monitoring protocols to develop ecological water requirements for GDEs. Local data and information generated through monitoring programs and best available science from the GDE Toolbox provides information to revise conceptual models, identify threshold responses, and appropriately signal to water managers when intervention is necessary. By incorporating biotic and abiotic indicators into monitoring programs, water managers are better able to respond to hydrological changes that affect the GDE's

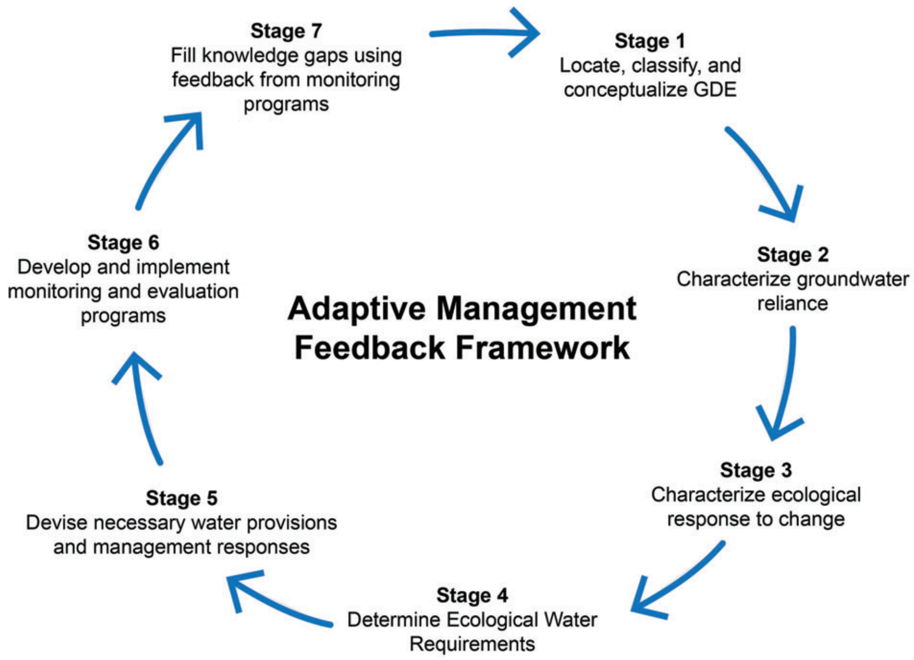


Figure 1. Conceptual framework for GDE management in Australia (modified from Richardson et al. 2011a).

condition (Richardson et al. 2011a). Determining GDE water allocation draws upon the "precautionary principle" to ensure that, in the absence of extensive scientific certainty, preventative measures are taken to reduce harm done to GDEs. The "precautionary principle" is an internationally recognized concept that has been integrated into some legally binding international treaties such as the Rio Declaration and the Kyoto Protocol.

Scientific Basis for Thresholds

Determining thresholds for GDEs is key when integrating environmental considerations into sustainable groundwater management. The inherent diversity of GDEs requires thresholds to be locally determined due to differences in species composition, reliance on groundwater, and adaptive capacities to varying threats. General patterns have, however, begun to emerge from Australian research and their science-based adaptive management efforts.

In general, changes in groundwater availability have been found to progressively impact the biotic indicators such as growth, reproduction, recruitment, mortality, and ecosystem structure and function (Eamus et al. 2006a). GDEs include organisms that have evolved complex physiological and biochemical adaptations to adjust and adapt to short-term water-deficit stress. However, if the stress is prolonged or extreme, these adaptations become inadequate and result in populations progressively declining, and a shift in the composition and function of ecosystems (Figure 2). Although monitoring protocols will vary across GDE types based on local habitat conditions and reliance on groundwater, choosing appropriate indicators to reflect the biological response functions (growth, reproduction, recruitment, mortality, and ecosystem structure and function) to changing groundwater conditions is key. Monitoring these response functions for individual species is better understood than monitoring response functions for entire ecosystems, due to variation in species responses (Eamus et al. 2015). The identification of key species within a GDE that can serve as an indicator of biotic responses to groundwater drawdown helps in detecting ecosystem change. Nevertheless, the incorporation of ecosystem metrics in monitoring regimes, such as ecosystem vigor (physiologic capacity such as productivity and growth), organization (species composition, richness, biodiversity and structural traits for a community), and systematic resilience to environmental stressors (climate change, wild fires, anthropogenic impacts) (Costanza and Mageau 1999) are important to enhance our collective understanding of the causal mechanisms between groundwater basin management activities and GDEs.

Remote sensing applications (e.g., Landsat NDVI and NDMI) provide approaches to incorporate ecosystem metrics into monitoring programs and access historical data to assess resiliency to environmental stressors (Li et al. 2014; Eamus et al. 2015). Functional relationships between integrated ecosystem-scale responses to changes in groundwater availability have been hypothesized to be linear, curvi-linear or step-wise related (Leffler and Evans 1999; Eamus et al. 2006b). However, in reality these relationships are most likely case-specific due to localized differences in the species composition, historical conditions, hydrogeologic regime, among other factors.

The rate, magnitude, and duration of groundwater changes will determine the short- and long-term impacts to a GDE (Scott et al. 1999; Shafroth et al. 2000), so both absolute and relative changes to groundwater availability are both important factors in determining a GDE's

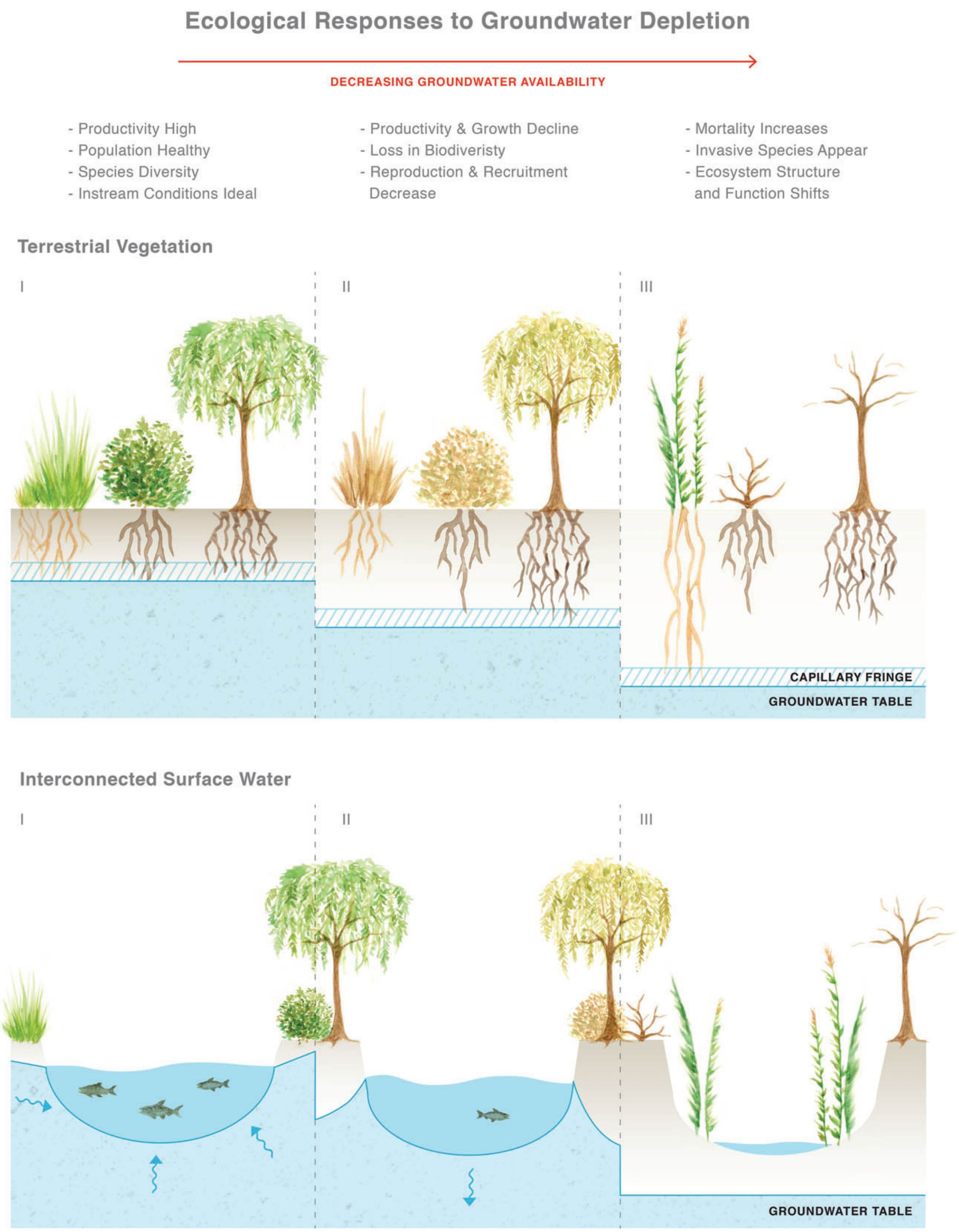


Figure 2. Ecological responses to decreases in groundwater availability within Terrestrial Vegetation and Interconnected Surface Water systems.

ecological response. In the case of groundwater dependent vegetation (phreatophytes), root distribution and function will reflect groundwater regimes during development (Canham et al. 2012), and if water table levels change rapidly, root systems may not adequately adapt (Canham et al. 2015), resulting in functional responses ranging in severity from declines in productivity to mortality (Figure 2). Gradual changes in the water table provide a greater opportunity for plants to adapt to the effects of water stress, but in the process can cause changes in the ecosystem structure and community composition (Froend and Sommer 2010). Gradual increases in depth to groundwater within a GDE with historically shallow groundwater levels tends to result in an altered species composition due to the migration of more opportunistic invasive species that have deeper rooting systems and are better adapted to deeper groundwater conditions (Keddy and Reznicek 1986; Moore and Keddy 1988; Sommer and Froend 2014).

Risk Assessment

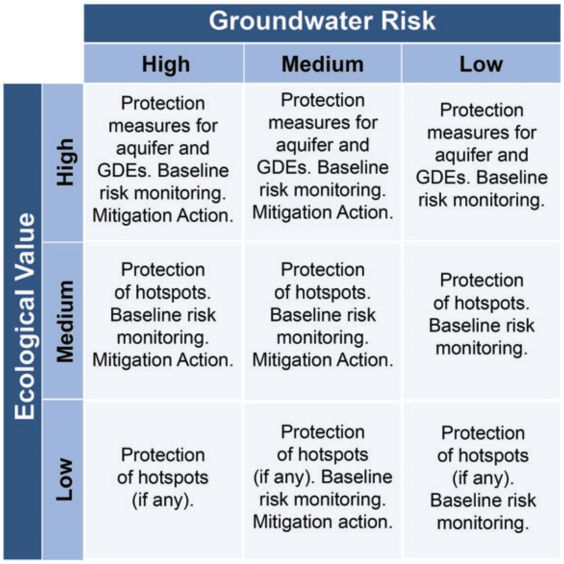
New South Wales adopted the most specific and comprehensive statewide approach for managing GDEs in Australia (Tomlinson 2011). Their approach builds upon adaptive management strategies required in the NWI by incorporating ecological valuation and risk assessment to better recommend management strategies despite uncertainties around GDEs. Although adaptive management strategies use monitoring programs to reconcile knowledge gaps and uncertainties, management actions may still be required in the interim to prevent adverse consequences. By understanding the ecological value and susceptibility of a GDE to groundwater use activities, management actions can be prioritized so that risk is minimized as monitoring programs work to reduce uncertainty. To determine how human activities can impact a GDE, the existing functional and biodiversity values of the ecosystem and their susceptibility to human activities is assessed so that appropriate management actions needed to protect these valued attributes of the ecosystem can then be determined. Assessing whether proposed or current groundwater use activities are likely to have an impact on GDEs helps prioritize which GDEs are most likely to be impacted and the necessary mitigation practices. Prioritization is beneficial not only from an inventory perspective, but also because management efforts can strategically target GDEs that require the greatest need of attention. This is especially true when large uncertainty exists in the early management years and limited financial resources are available for monitoring.

Ecological valuation is a two-stage process that begins with a "desktop" approach and ends with a more in depth analysis. Stage one is designed to rapidly identify high-value GDEs known to have (1) high conservation value (e.g., critical habitat for endangered or threatened species); (2) protection under other legislative or regulatory programs (e.g., national park system); and (3) obligate or entirely dependent ecosystems and species (e.g., ecosystems present in subsurface environments containing stygofauna/stygobite species, and even ecosystems containing species entirely dependent on springs or seeps). Stage two includes a more detailed approach for identifying ecological value and includes evaluating the following four criteria: (1) the landscape context (surface and subsurface) for the GDE environment; (2) rarity of dependent biota or physical features within the watershed and/or hydrologic unit (as appropriate); (3) diversity within the watershed and/or hydrologic unit (as appropriate); (4) special features that provide important and unique habitat within a watershed and/or hydrologic unit (as appropriate) (Dunn 2000). Ecological values for individual GDEs are determined through a series of questions and characterized as having a high, moderate, or low value. The ecological value determined for a GDE is then used in the risk assessment process.

The risk assessment process relies on an understanding of a GDE's reliance on groundwater and what tolerances and sensitivities exist for the ecological assets comprising the GDE. Impacts of current or proposed activities to a GDE can then be determined. Similar to the ecological valuation assessment, New South Wales uses a series of questions to help water managers utilize monitoring data and modeling results to assess the likelihood of risk (high, medium, low, or insufficient data/unknown) occurring to GDES from current or proposed activities. For example, one question used to assess water quantity risk to GDEs is: "What will be the risk of changing base flow conditions on GDEs?", where High Risk is "Permanent reversal of base flow conditions"; Medium Risk is "Temporary reversal of base flow conditions exceeding seasonal variation"; and Low Risk is "No change in direction of flow" (Serov et al. 2012). This process highlights where information gaps exist and how monitoring can be enhanced. After GDEs are assessed for ecologic value and risk, both metrics are incorporated into a risk matrix (Figure 3). The risk matrix prioritizes GDEs with high value and high risk. GDE prioritization via the risk matrix enables water managers to develop strategies to maintain or improve the ecological value of a GDE within an aquifer, and reduce the impact risk that human activities can have on GDEs.

Opportunities and Challenges for Policy Applications

Australia's adaptive management framework of using scientific data and research to inform management decisions is a key step toward achieving sustainable water management. Knowledge gaps and uncertainties are bound to exist around GDEs during the early management years. Monitoring programs may take years to reduce uncertainty on how reliant GDEs are on groundwater or what the quantitative groundwater needs are. This leaves GDEs vulnerable to incurring adverse impacts from groundwater use activities and changing groundwater conditions that may be irreversible or difficult to mitigate. Taking a precautionary approach during resource planning and incorporating risk assessment into an adaptive management framework can help water managers prioritize



Ecological Value		Groundwater Risk		
		High	Medium	Low
	High	Protection measures for aquifer and GDEs. Baseline risk monitoring. Mitigation Action.	Protection measures for aquifer and GDEs. Baseline risk monitoring. Mitigation Action.	Protection measures for aquifer and GDEs. Baseline risk monitoring.
	Medium	Protection of hotspots. Baseline risk monitoring. Mitigation Action.	Protection of hotspots. Baseline risk monitoring. Mitigation Action.	Protection of hotspots. Baseline risk monitoring.
	Low	Protection of hotspots (if any).	Protection of hotspots (if any). Baseline risk monitoring. Mitigation action.	Protection of hotspots (if any). Baseline risk monitoring.

Figure 3. Risk matrix with short-term management actions for each outcome (modified from Serov et al. 2012).

resources, reduce risk, and avoid adverse impacts, despite uncertainties. However, depending on the knowledge gaps and the ecological value of the GDE, it might become necessary to conduct targeted research to investigate cause and effect relationships using more advanced methods (e.g., plant water-use modeling, environmental or isotopic tracers, numerical groundwater modeling) in addition to routine monitoring (e.g., groundwater levels, water quality metrics, instream flow criteria, vegetation growth).

These GDE management concepts offer key lessons for successfully implementing water management policies. While ecosystem protection is included under water management policies in California, the EU, and South Africa, specifics on GDE management are lacking. Adopting a risk-based adaptive management framework, similar to Australia, that revises the allocation of water to the environment based on scientific research and monitoring can improve the management of GDEs. Australia's adaptive management framework aligns well with California's SGMA legislation since local agencies are required to reconcile knowledge gaps and uncertainties through monitoring programs, thereby giving them the opportunity to acquire new information and amend planning and management actions (Department of Water Resources 2016; State of California 2016). In addition, SMGA requires local agencies to achieve groundwater sustainability by avoiding undesirable results (i.e., chronic lowering of groundwater levels, reduction of groundwater storage, seawater intrusion, degraded water quality, land subsidence, and depletions of interconnected surface water), considering potential effects on GDEs and other beneficial uses, and setting sustainable management criteria (i.e., basin sustainability goal, minimum thresholds, measurable objectives, and interim milestones) using the "best available information and best available science" (State of California 2016).

Determining thresholds for GDEs still remains a challenge for many water agencies worldwide, largely due to knowledge gaps in ecohydrology. Scientific research on ecological thresholds can certainly aid water managers in meeting their legislative requirements to identify thresholds for GDEs. However, it is important for water management agencies to integrate both abiotic (e.g., groundwater levels, water quality metrics (e.g., nutrients, temperature, pH, salinity), and groundwater-surface water flow criteria) and biotic (e.g., growth, reproduction, species composition, ecosystem structure, ecosystem function, and mortality) indicators into local monitoring networks, determine locally appropriate thresholds, and allocate accurate and locally appropriate sustainable environmental water provisions for GDEs. Water managers can achieve these local needs by leveraging additional assistance from third party institutions (e.g., academia, NGOs, think tanks) via partnerships and by building transparency into data collection and reporting standards to promote necessary research on GDEs.

Legislation written at the National (Australia and South Africa), intergovernmental (European Union), and even subnational (state) level (California) requires top-down support and guidance during implementation on the ground, as well as bottom-up community involvement and local acceptance. To ensure overall success of legislation, a coordinated approach of common frameworks and methodological approaches need to be developed to reduce the burden on water managers and promote overall success in implementation of legislation. This may explain Australia's relative success in implementing GDE management in comparison to its counterparts.

Conclusion

GDEs possess an incredible range of important habitat that if not managed properly can incur severe consequences that are difficult, if not impossible, to recover. Australia's adaptive management approach in considering GDEs in their state water plans offers a blueprint for how water managers around the world can deal with uncertainty by using the best available science and targeted research in monitoring programs, applying the "precautionary principle" when uncertainties exist, and using risk assessments to prioritize and manage valuable and vulnerable GDEs. The Australian case also illustrates the importance of developing a common management framework in conjunction with the legislative language that can leverage best available science and regional datasets. This ensures that implementers of the legislation receive the necessary technical guidance and support to manage GDEs. Adoption of a common approach across jurisdictional boundaries also helps to facilitate transparency, accountability, and knowledge sharing opportunities. Such guidance is mutually beneficial for central agencies and water managers as it helps to reduce costs, streamline the review process, and promote overall success of sustainable water management legislation.

Acknowledgments

The authors would like to thank Dr. Thomas Harter and two anonymous reviewers for their insightful comments, which greatly improved this manuscript. The lead author would like to thank the Bechtel Foundation for their financial support to The Nature Conservancy's ongoing groundwater research on GDEs in sustainable groundwater management.

Authors' Note: The authors do not have any conflicts of interest or financial disclosures to report.

Supporting Information

Additional Supporting Information may be found in the online version of this article. Supporting Information is generally *not* peer reviewed.

Table S1. GDE Toolbox: a summary of the methods and approaches to identify GDEs and determine their reliance on groundwater.

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