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Water rights for groundwater environments as an enabling condition for adaptive water governance

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ABSTRACT. Despite now widespread scholarly scientific acknowledgement of the ecological importance of groundwater, progress on protecting groundwater-dependent ecosystems (GDEs) in practice has been slow. Extending the legal concept of environmental water rights from the surface water context to groundwater may help to accelerate protections and to promote adaptive water governance, particularly when combined with regulatory rules. Although some groundwater law frameworks have developed regulatory rules to protect GDEs that mirror those for surface water, they have yet to develop frameworks to support environmental groundwater rights that mirror environmental surface water rights, i.e., in-ground flow rights equivalent to in-stream flow rights. These rights are generally quantified, transferable, allow in situ use or withdrawal, and are held and enforced by an identified public or private entity. Here, I first conceptualize environmental groundwater rights and then evaluate the conceptual and practical advantages and challenges for adaptive water governance of a legal framework to support them, in a way that is intended to be relevant to diverse jurisdictional contexts. To do so, I use two existing theoretical frameworks: one for evaluating alternative approaches to providing environmental water, and the second for considering the roles of law in adaptive water governance. I find that water markets and some environmental crises may present windows of opportunity for establishing environmental groundwater rights and, thereby, local-scale thresholds of minimum protection. These rights may circumvent barriers to adaptive governance that often characterize water law. They may also facilitate adaptive governance by allowing learning, revision, flexibility, and experimentation about the environmental water requirements of GDEs to fill critical knowledge gaps. A legal framework for environmental groundwater rights can also harness and legitimize local environmental and Indigenous voices and increase access to resources. When combined with larger scale regulatory rules, such a legal framework can also help to facilitate multiscale governance.

Key Words: *adaptive water governance; environmental flows; groundwater; groundwater-dependent ecosystems; in-stream flows; law; water entitlements; water law; water rights*

INTRODUCTION

Groundwater supports diverse ecosystems (groundwater-dependent ecosystems, or GDEs) and provides baseflow to rivers, springs, groundwater-dependent terrestrial vegetation, and even aquifer-dwelling microfauna (Tomlinson 2011). This provision secures ecosystem services, including contaminant biodegradation, nutrient cycling, flow maintenance, flood mitigation, and aesthetic and recreational benefits (Tomlinson 2011, Griebler and Avramov 2015). Human alteration of hydrological systems, including groundwater systems (Stewardson et al. 2017), has triggered the need to protect water for these environmental purposes. Water laws that facilitate protections for GDEs must necessarily adopt an adaptive water governance (AWG) approach, i.e., “governance that allows adaptive processes to emerge ... [enabling] society to navigate the dynamic, multiscale nature of social ecological systems” (Cosens et al. 2014:9). In the context of GDEs, adaptive processes that may be facilitated by governance arrangements include adapting water management to new knowledge about the ecological thresholds of GDEs and changed environmental conditions, including climate change (Kløve et al. 2014, Elshall et al. 2020), and adapting associated legal mechanisms to promote these processes. Adaptive governance for GDEs needs to be flexible, allowing experimentation, learning, monitoring, and revision in relation to different management options and scientific information, including often uncertain ecological thresholds (Elshall et al. 2020, Saito et al. 2021), which are embedded in legal mechanisms. AWG for GDEs should also empower diverse stakeholders, including local and nongovernmental organizations, who may

pursue local-scale environmental values. These prescriptions are well established in contexts that emphasize surface water and legal frameworks (e.g., Huitema et al. 2009, Pahl-Wostl et al. 2013, Cosens et al. 2014, Arnold 2015). They also mirror relevant adaptive governance requirements advanced for groundwater in the context of conflict resolution, groundwater ecosystem services, and groundwater more generally (Susskind 2005, Gleeson et al. 2012, Knüppe and Pahl-Wostl 2013, Saito et al. 2021).

As well as advancing these prescriptive requirements for AWG, existing groundwater-focused AWG literature emphasizes factors that tend to be more prominent in groundwater compared to surface water systems, for example, long time scales (e.g., Knüppe and Pahl-Wostl 2013, Thomann et al. 2020) and decentralized and local-level decision-making within management that integrates spatial scales (e.g., Knüppe and Pahl-Wostl 2013, du Bray et al. 2018). Discussions of adaptive strategies that are delivered through regulatory and planning approaches tend to dominate the existing literature (e.g., Knüppe and Pahl-Wostl 2013, Thomas 2019, Thomann et al. 2020, Saito et al. 2021). Though legal scholars have helped to build the AWG literature (e.g., Arnold and Gunderson 2013, Cosens et al. 2014), the legal views of AWG tend to focus on surface water, leaving a gap in understanding how AWG for GDEs might be facilitated through wider legal approaches beyond regulation and planning. Here, I address this gap in three ways: by considering desirable elements of AWG, with a focus on GDEs; by exploring the potential for approaches based on water rights to act as enabling conditions for AWG, contrasting these rights approaches with the regulatory

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approaches that are more commonly discussed; and by exploring how combining both approaches could further facilitate AWG by promoting multiscale governance and implementing lessons learned from local experimentation.

Globally, the ecological elements of water laws have traditionally focused on protecting streamflows, rather than groundwater, and associated legal mechanisms for streamflows are well established (Le Quesne et al. 2010), although the terminology and legal details vary. Common terms include “environmental water entitlements”, “environmental flows”, “minimum instream flows”, “instream flow water rights”, and latterly, “rights for rivers” (Amos 2006, Covell et al. 2017, O’Donnell 2018; *Water Act* 2007 (Commonwealth); together, here termed “environmental water”). These legal mechanisms seek to ensure that there is enough water in rivers to satisfy identified environmental purposes. In some cases, water law-based “rules” based on regulations and plans prevent additional water from being withdrawn; in other cases, legal “rights” to water are acquired and dedicated to environmental purposes. The latter rights approach to protecting environmental surface water tends to be considered more flexible and adaptive than rules (Horne et al. 2017a); indeed, water law rules and legal doctrines are notoriously rigid and face political barriers to change and adaptive approaches in diverse jurisdictions (Arnold 2015, Craig 2020, Alexandra 2021).

In at least some jurisdictions, water law and policy have started to recognize the importance of GDEs (Nelson and Quevauviller 2016, Rohde et al. 2017). This recognition has tended to occur through rules that constrain groundwater pumping for consumptive uses so that GDEs can access the water “left behind”. Legal development has been slower in relation to what is here termed “environmental groundwater rights”, that is, enforceable, transferable, legal rights to a volume or level (or both) of groundwater of specified quality, held by a public or private entity to achieve environmental purposes in a specific location by leaving the water in situ or withdrawing it to apply to ecosystems directly. Such rights would be roughly analogous to surface water environmental rights in some jurisdictions. This approach would both protect water left behind by consumptive users and facilitate acquiring water from existing consumptive users and managing it to meet ecological thresholds.

Scientists recognize that adapting groundwater management to climate change will likely require changes to institutional and regulatory frameworks (Kløve et al. 2014). As water law increasingly recognizes GDEs, the adaptive benefits of rights in the surface water context, relative to rules or a lack of protective mechanisms, warrant investigation in the groundwater context. A rights approach could facilitate adapting to climate change by promoting experimentation and filling knowledge gaps about meeting GDE water requirements as they change with climate change, and piloting local management approaches that may be future candidates for broadly applicable legal rules that are more difficult to introduce and amend than acquiring rights. A rights approach also allows for more direct involvement by local and environmentally motivated nongovernmental organizations, who hold or manage the rights.

Here, I offer a conceptualization of environmental groundwater rights and evaluate the potential for corresponding laws to promote and play other hypothesized roles in AWG (Cosens et

al. 2014), including by combining rights with rules to protect GDEs. This analysis is intended to be relevant to diverse jurisdictions, acting as a foundation for further, jurisdiction-specific investigations. In some jurisdictions, the legal change required to support such rights would be minimal, and rights could support AWG pragmatically by extending well-established legal tools. In other jurisdictions, a rights approach would represent a significant change that may not be feasible or reasonably compatible with existing legal regimes or cultural norms. In searching for ways to promote adaptation and resilience, scholars have pointed to the importance of exploring the untapped potential of existing tools of environmental law (Garmestani et al. 2019) and “bridging existing governance to proposed approaches” (Cosens et al. 2014:5). Rights approaches are one such tool that deserves exploration as an enabling condition that could support AWG for GDEs.

I next provide background, briefly describing: the importance of GDEs and the significance of climate change for groundwater systems; the development of environmental surface water rules and rights; and how corresponding groundwater mechanisms are emerging. I construct an argument from first principles about legal elements necessary for the law to promote AWG for GDEs based on the characteristics of groundwater and GDEs, climate change, and basic lessons from the development of environmental surface water. I then conceptualize an approach to environmental groundwater rights in more detail and discuss how existing legal frameworks might be used or adapted to establish rights in practice. Finally, I position these initial discussions in theoretical context, applying two existing analytical frameworks to evaluate the jurisdictional conditions in which an environmental groundwater rights approach may achieve benefits for AWG that are less likely under a rules-based approach, and to analyze the various roles that a legal framework for environmental groundwater rights could play in AWG. Appendix 1 illustrates the jurisdiction-specific benefits and challenges of the proposed approach to environmental groundwater rights with reference to a current conflict over damage to GDEs brought about by pumping for municipal purposes in Victoria, Australia, a jurisdiction that already provides a basic level of rules-based protection for GDEs.

To ensure accessibility to a wide audience, acknowledging that terminology used in the environmental water context varies significantly around the world, I use accepted jurisdiction-neutral terms unless referring to a specific jurisdiction: “environmental water”, “environmental water rights”, and “permit” (termed a “license” in some jurisdictions) for the administrative authorization related to a water right (termed an “entitlement” in some jurisdictions).

BACKGROUND

Importance of groundwater-dependent ecosystems and the need to experiment and adapt to new knowledge about ecological thresholds

Groundwater supports terrestrial vegetation; springs, rivers, and wetlands to which it discharges; and subterranean biota (Tomlinson 2011, Rohde et al. 2017). GDEs include high-profile and iconic ecological and landscape features such as the Old Faithful geyser in Yellowstone National Park, Wyoming, USA

(Stevens et al. 2021), Central Europe's groundwater-fed floodplain oak forests (Skiadaresis et al. 2019), and the revered, millennia-old mound springs of Australia's arid Great Artesian basin (Arthington et al. 2020). GDEs are also much more widespread than this list suggests, as shown by large-scale efforts to map the probability of their occurrence across continents, nations, and provinces (Colvin et al. 2003, Howard and Merrifield 2010, Richardson et al. 2011, U.S. Department of Agriculture, Forest Service 2012, Doody et al. 2017).

Groundwater and GDEs support ecosystem services that benefit human communities, including water supply, water purification, flood mitigation, nutrient cycling, drought attenuation, and cultural services (Tomlinson 2011, Griebler and Avramov 2015, Rohde et al. 2017) related to groundwater-dependent species and features, from coho salmon in North America (Larsen and Woelfle-Erskine 2018) to caves in France (Hérivaux and Grémont 2019). Policy interest in an ecosystem services approach to GDEs is increasing (e.g., in China, France, and Australia; Commonwealth Scientific and Industrial Research Organisation 2012, Hérivaux and Grémont 2019, Yang and Liu 2020).

Physically, ecological thresholds for GDEs relate to groundwater levels and quality, including temperature (Tomlinson 2011). However, precisely characterizing groundwater dependence is challenging: data are frequently lacking, and there can be long distances in space and time between actions such as pumping for consumptive purposes and the effects becoming apparent in natural systems (Elshall et al. 2020, Saito et al. 2021). These uncertainties and evolving knowledge highlight the importance of mechanisms for protecting GDEs to adapt in response to new information. Indeed, adaptive systems should promote experimentation that produces the necessary information, for example, facilitating experimenting with protecting different groundwater characteristics (e.g. level, quality) to understand relevant ecological thresholds and how best to meet them.

Climate change, groundwater, and adapting management to new circumstances

Climate change is likely to increase threats to groundwater, GDEs, and groundwater-supported ecosystem services in many ways. These threats include effects on groundwater recharge rates, changes to groundwater quality through mechanisms such as increased seawater intrusion into freshwater aquifers, increased groundwater pumping to counter increasingly variable streamflows, potentially increased evapotranspiration, and changes to afforestation and deforestation that will affect groundwater availability (Kløve et al. 2014, Elshall et al. 2020). However, key research gaps remain, and predicting precise effects in a particular region is difficult (Kløve et al. 2014). Accordingly, protecting GDEs in the climate change context requires adaptive governance to respond to new information about changed groundwater dependence of GDEs (e.g., if evapotranspiration changes), changed groundwater availability for GDEs (e.g., caused by changes to recharge), and changed threats (e.g., increased human groundwater use reducing availability or affecting groundwater quality).

Climate change has already driven management changes to support important GDEs. For instance, in southwest Western Australia, a striking climate shift has significantly reduced recharge, creating policy support for artificially supplementing

wetlands and rehydrating cave systems for environmental benefits (Department of Water 2009, Clifton et al. 2010, Department of Water and Environmental Regulation 2021). More generally, decision-making frameworks for adaptive governance to respond to climate change may span resisting, accepting, and intervening responses to direct ecological transformation to ensure ecological resilience (Schuurman et al. 2020). Legal approaches for protecting GDEs should ideally support flexible management options across this spectrum. For example, in some circumstances, local "ecological irrigation" using groundwater pumping is one option for resisting a trajectory of change, maintaining or restoring historical ecosystem processes or features that are considered critical or iconic, are required under a legal conservation mandate, or require active support for a defined period (say, assuming successful future climate change mitigation measures, or for the duration of a temporary nearby groundwater-using project). Ecological irrigation may also provide a way to directly facilitate ecological adaptation. For example, withdrawn groundwater could support efforts to establish novel ecological conditions that are preferred over those that would emerge via merely accepting change, where those new conditions are intended to become self-sustaining in a climate-changed world but require initial intervention.

Implications for adaptive water governance for groundwater-dependent ecosystems

The foregoing discussion underscores that adaptive legal mechanisms for GDEs should first facilitate monitoring and learning about relevant ecological thresholds and how they change, implementing and revising them through associated legal mechanisms ("learning and revision"); and second, facilitate experimentation and give managers flexibility by providing multiple options to meet these thresholds and address risks to meeting them, including by limiting groundwater pumping for consumptive use or allowing groundwater pumping for local ecological purposes ("experimentation and flexibility"). A third desirable feature relates to barriers to achieving the first two features illuminated by experience in implementing environmental water protections: the need to involve diverse actors such as local nongovernmental organizations ("diverse actors"), which also helps implement a fourth feature desirable for AWG: governance at "multiple scales". Both of these features are discussed below (*Background: Environmental rules and rights for surface water: Adaptive water governance and the benefits of rights-based approaches in the surface water context*). Each of these four features may have varying importance and strike varying barriers in different places and at different times. I next provide background on existing legal approaches to environmental water and the extent to which they support these features. I then explore these factors further in the groundwater context.

Environmental rules and rights for surface water

Legal approaches to protecting surface water for ecosystems provide a framework for considering how legal rules and rights would support AWG for GDEs, considering similarities and differences between surface water and groundwater, and conceiving of environmental groundwater rights in a way that is informed by the surface water experience. Extensive technical and legal literatures describe and analyze protections for streamflows (e.g., Dyson et al. 2008, Arthington 2012, Pahl-Wostl et al. 2013, Covell et al. 2017, Horne et al. 2017b, Ziemer et al. 2020). National

and subnational water allocation regimes have created diverse mechanisms that fall into two broad legal categories. The first category of mechanisms “establish[es] a legal right to water for the environment itself” (here termed “rights-based”), and the second “impose[s] conditions on other water users”, for example, rules about minimum flows that constrain consumptive use (here termed “rules-based”; Horne et al. 2017a:361).

Environmental rules for surface water

Legal rules for environmental surface water confer a power to manage water in certain ways, limit activities to avoid harming water environments, or both (O’Donnell 2018). Examples are dam operating rules or release requirements, limits on aggregate withdrawals of water for consumptive purposes, and limits on individual applications to divert or transfer water, so that the environment receives the remaining water (rules-based protections).

These rules take different forms depending on the jurisdiction. Australia’s “sustainable diversion limits” cap aggregate extractions at the basin and sub-basin scales in the agriculturally important Murray-Darling Basin (Basin Plan 2012 legislation <https://www.legislation.gov.au/Details/F2021C01067>). In many western U.S. states, often undefined public-interest criteria influence whether public agencies approve applications to appropriate or transfer water (Bell and Taylor 2008, Squillace 2020). Granting rivers legal personhood (e.g., New Zealand, India, Colombia, Bangladesh, and Australia; O’Donnell and Talbot-Jones 2018) is a more recent form of rules-based protection, given that, strikingly, these rivers lack rights to their own water (O’Donnell 2020). Rather, compared to holding water rights, legal personhood allows river representatives less direct influence over land-use planning and broader water management (O’Donnell 2020).

Environmental rights for surface water

By contrast, rights-based mechanisms for environmental surface water typically consist of transferable legal rights, held by or on behalf of the environment, in relation to a quantified volume of water at a particular place (O’Donnell 2013, 2018). Although first established in the United States, they now occur in diverse allocation regimes (e.g., Mexico, Chile, South Africa, Canada, and Australia; O’Donnell 2013, Horne et al. 2017a). Various actors may hold these rights, although some jurisdictions restrict eligible holders (Covell et al. 2017, O’Donnell and Garrick 2017).

Legal frameworks for water rights differ around the world, so rights-based mechanisms for environmental surface water look different in different places. For example, the water rights doctrine of prior appropriation applies in most of the western United States (Thompson et al. 2018), creating a system of heterogeneous, perpetual water rights. Under conditions of scarcity, rights developed earlier in time are satisfied before “junior” rights developed later in time (Thompson et al. 2018). By contrast, Australian water rights frameworks involve both perpetual and time-limited rights to withdraw water. Water scarcity triggers proportional reductions in seasonal water “allocations”, spread equally across all water “entitlements”, or across large categories of entitlements (e.g., “high security” and “low security”; Gardner et al. 2018). The holder of a water right in these systems holds a right to use the water subject to conditions, including

environment-oriented conditions, and the right may not necessarily amount to a property right (Gardner et al. 2018).

Depending on the jurisdiction, acquiring an environmental water right can involve temporarily leasing or purchasing water rights outright or realizing savings from water efficiency projects (Covell et al. 2017). Using an environmental surface water right may involve leaving it in situ (after releasing it from an on-stream dam, where such exists, or merely constraining consumptive pumping to protect natural flows) or actively pumping and using infrastructure to divert streamflow to target ecosystems, for example, floodplain wetlands (Haas 2008, Murray-Darling Basin Authority 2015, Murray Irrigation 2019). This use can require changes to water rights frameworks, for example, clarifying that in situ use is “beneficial” (Bell and Taylor 2008).

Adaptive water governance and the benefits of rights-based approaches in the surface water context

Rights-based approaches have been characterized as more flexible and adaptive than rules-based mechanisms (Horne et al. 2017a). As a generalization, environmental surface water rights allow both in situ use and diversion for ecological use, promoting experimentation and flexibility in meeting ecological thresholds, whereas rules-based mechanisms typically envision in situ ecological use only. In addition, rights are held by an identified public or private entity that manages and may enforce them, diffusing power beyond government. Because politics can obstruct actions to defend dependent ecosystems, particularly during drought (O’Donnell 2012, Horne et al. 2017a), it is advantageous for holders of environmental water to have some independence from government to reduce the likelihood of political barriers to management adaptations. Private parties, public-private partnerships, and specially created independent statutory entities all have some element of independence. Some actors may receive the support of formal advisory groups and a legislated funding source or tax benefits for water rights donors (O’Donnell and Talbot-Jones 2018, Ziemer et al. 2020). In directly involving these diverse actors, rights-based approaches contrast with the dependence of rules-based mechanisms on action by public agencies that may be more politically constrained. Experience shows that political context can render rules-based protections more vulnerable to change that compromises the meeting of ecological thresholds, or can lead to a lack of enforcement or simply non-enactment in response to pressures to maintain or increase consumptive allocations (Le Quesne et al. 2010, O’Donnell and Garrick 2017). Nongovernmental actors may also be more open to experimentation than more typically risk-averse governments.

Combining rules and rights for environmental surface water for a multiscale approach

Rights- and rules-based approaches may coexist. In Australia’s Murray-Darling Basin, the use of agricultural water rights “recovered” (bought back) for environmental purposes is subject to participatory prioritization processes, management, monitoring, and reporting under legal rules contained in a statutory basin-scale plan (Basin Plan 2012 legislation <https://www.legislation.gov.au/Details/F2021C01067>). Other regimes provide for environmental surface water rights under a state- or basin-scale water plan (e.g., Washington state: Schromen-Wawrin 2013; Idaho: Covell et al. 2017). Conceiving of rights within a planned

approach allows for water governance at multiple scales: the local, at which individual rights are delivered; and the basin, at which the management of multiple rights is coordinated, potentially alongside rules-based restrictions on consumptive use.

Environmental rules and environmental rights for groundwater: state of play

Environmental rules for groundwater

Legal efforts to protect GDEs are emerging in several jurisdictions (Thompson 2011, Nelson and Quevauviller 2016, Rohde et al. 2017). Implementation often lags policy aspirations (Rohde et al. 2017). Protections usually appear as rules that restrain groundwater withdrawals, rather than rights. Infrastructure-based initiatives also occur, such as relocating boreholes away from sensitive GDEs (e.g., Beauce Aquifer, France; Verley 2020) and piping free-flowing artesian bores (e.g., Great Artesian basin, Australia; New South Wales Government 2016, 2019). Commentators also tend to recommend rules and management plans to protect GDEs, including modeling, thresholds for avoiding adverse impacts, triggers for action, large-scale monitoring, and good stakeholder engagement (Noorduijn et al. 2019, Elshall et al. 2020, Thomann et al. 2020, Gage and Milman 2021, Saito et al. 2021).

Rules for GDEs tend to control consumptive pumping in one of three ways (Nelson 2013). The first is imprecise but easy-to-administer “simple numerical” limits on pumping (e.g., a lateral no-pumping buffer distance from a river or other GDE, other area-based pumping embargo, a permissible volume of aggregate annual withdrawals in the form of “safe” or “sustainable” yield, or a percentage of recharge or storage set aside for ecological purposes). This approach is reflected in South Africa’s “ground water ecological reserve”: water that may not be allocated for consumptive use, rather than water covered by a volumetric right (Seward 2010, Gannon 2014). Rules-based volumetric limits on extractions (often called “caps”) are considered unlikely to be sufficient by themselves to protect GDEs (Pierce and Cook 2020). The second is “complex numerical thresholds”, which take more time and resources to administer but more precisely limit the modeled impacts of a pumping proposal (e.g., limits on maximum allowable decreases in aquifer levels, spring flows to support wetlands, or surface water that would be captured from a stream). The third is “principle-based thresholds” that use broadly worded considerations like the “public interest” or impacts on unspecified “ecosystems” to guide statutory permitting of consumptive water rights (Nelson 2013, Noorduijn et al. 2019). In the United States, the public trust doctrine is a common law mechanism with the potential to protect GDEs that is broadly analogous to this third approach (Thompson 2011, Gannon 2014).

All of these mechanisms are rules-based: they appear in statutes, regulations, legally binding management plans or guidelines that are often subject to regular revision, and occasionally, judge-made law in common law systems. They constrain consumptive withdrawals to an ecologically informed limit through decisions about permits. They are typically implemented by state agencies rather than delivered through a water right managed by an identifiable entity, and involve simply leaving groundwater in situ, rather than allowing more flexible management options. Unlike surface water reservoirs, there is no option to actively release water to deliver it to ecosystems without rights, so rules-based

approaches to environmental groundwater offer less flexibility to meet environmental needs than rules-based approaches to environmental surface water.

In theory, regularly reviewed rules provide scope for experimenting and adapting pumping limits to new knowledge about GDE needs. However, challenges in establishing, amending, and implementing these rules may arise in practice. As for surface water, it may be politically difficult to revise rules, and stakeholders may challenge rules that reduce access to groundwater and raise potential equity issues (Noorduijn et al. 2019). In some jurisdictions, constitutional protections for private property (e.g., the “takings” clause in the United States; Squillace 2020) may hinder the adoption of rules that would constrain pumping. These political and legal obstacles, as well as the rigidity of existing water and administrative law regimes, may pose “serious impediments that generally prevent governmental water agencies from engaging in scientifically valid adaptive management” of groundwater, including as to ecological protections (Craig 2020:11). In jurisdictions that require stakeholder consensus to institute legal management plans or other rules, progressive, quantified protections may simply never eventuate (Gage and Milman 2021). In practice, groundwater plans tend to adopt an ad hoc rather than a structured approach to adaptive learning (Thomann et al. 2020). Sometimes knowledge gaps about ecological needs and thresholds may have a chilling effect on reforms to rules (Gage and Milman 2021), obstructing the AWG goal of encouraging experimentation to build knowledge.

None of this information means that it is impossible effectively to establish, amend, and implement rules-based approaches. Rather, it is to recognize that, depending on the jurisdiction, relying on rules alone can significantly obstruct AWG, which warrants considering the potential for combining rules-based and rights-based approaches to better facilitate AWG of GDEs.

Environmental rights for groundwater: the emerging picture

Although it seems that no scholarly work comprehensively considers the extent of rights-based approaches to environmental groundwater, it appears they are emerging ad hoc. In some jurisdictions, rights allow for both in situ preservation and active withdrawal of groundwater for ecological purposes. Significant works on environmental flows and allied concepts of the public interest in water allocation explicitly exclude groundwater from their scope, though they recognize its importance (e.g., Owens 2016, Squillace 2020). The scholarly and gray literatures reveal some instances of groundwater rights being used for environmental purposes. In Australia, an AUD \$13 billion government program has bought back water for environmental purposes in overallocated parts of the multistate Murray-Darling Basin. The purchased water rights are now held by an independent statutory entity, the Commonwealth Environmental Water Holder (*Water Act 2007* ss. 104-113). As of August 2020, it holds 46.8 GL of groundwater entitlements in two states, equating to 1.6% of its total water holdings (Australian Government 2020a). However, its extensive current management plan for its holdings does not describe its approach to its groundwater rights (Australian Government 2020b), which are presumably left in situ, although rights allow pumping. There appears to be little attempt to coordinate environmental groundwater rights with the

dominant rules-based approach to protecting GDEs in this case. In Australian states, expanding the use of environmental groundwater rights would require little legal change, but rather, greater awareness, investigation, and funding by nongovernmental organizations and statutory entities.

In the United States, rights to groundwater may also help protect GDEs in limited situations: for example, in national parks, for federally recognized tribes, and for endangered species under both federal law and state water allocation laws (Leshy 2008, Thompson 2011, Gannon 2014, Womble et al. 2018). A prominent example is the Barton Springs Edwards Aquifer Conservation District in Texas, which holds a volumetric “conservation permit” that consists of permanently retired consumptive use groundwater permits. The conservation permit is dedicated to protecting spring flow for federally listed endangered salamanders, and withdrawing it is prohibited (Barton Springs Edwards Aquifer Conservation District 1988, as revised 2019, in Texas rules and by-laws <https://bseacd.org/uploads/RULES-and-BYLAWS-Final.pdf>). In other situations, groundwater rights allow extractive ecological use. A water rights settlement for the federally recognized Zuni Pueblo grants water rights, including to groundwater, that are actively used to restore ecologically and culturally important wetlands (Zuni Indian Tribe Water Rights Settlement in the Little CO River Basin, CV 6717, Superior Court of Arizona, Apache County [7 June 2002] <http://hdl.handle.net/1928/21893>). Some U.S. state water laws explicitly mention wildlife purposes in the statutory provisions that apply to granting groundwater permits (e.g., North Dakota Century Code Annotated § 61-04-02 (West)), though it is unclear how widely this occurs in practice and whether in situ use is allowed (extraction would typically be required).

The slow emergence of environmental groundwater rights appears ad hoc and often restricted to rare situations, rather than being the product of sustained policy consideration and legal facilitation. Questions then arise as to the potential to develop law and policy frameworks proactively for environmental groundwater rights to complement existing specific mechanisms and rules-based approaches (Table 1), what these rights would ideally look like, and how they could promote AWG.

Table 1. Environmental rules and rights for surface water and groundwater: status and opportunities.

Law aspect	Surface water	Groundwater
Environmental rules	Well established in many jurisdictions	Established in some jurisdictions
Environmental rights (volumetric)	Well established in many jurisdictions	Emerging ad hoc in some jurisdictions in limited situations [†]
Combining rules and rights	Present in some jurisdictions; facilitates multiscalar governance	No known development; requires a legal framework to derive greatest benefit by linking rules and rights [†]

[†]Key areas of opportunity for further development.

CONCEIVING AND ESTABLISHING ENVIRONMENTAL GROUNDWATER RIGHTS

The analysis I have provided suggests that an appreciation of groundwater, GDEs, the risks of climate change, and the

challenges experienced in protecting environmental surface water mean that AWG for GDEs requires legal mechanisms that embrace learning and revision, experimentation and flexibility, and governance that involves diverse actors pursuing actions at multiple scales. It suggests that, at first sight, rights-based mechanisms may support these features to a greater degree than rules-based mechanisms in some jurisdictions, and combining rights and rules would further benefit AWG by allowing a multiscalar approach. To evaluate environmental groundwater rights from an AWG perspective, I next conceptualize and justify the key ideal features of environmental groundwater rights and how legal systems would need to be adapted (or not) to establish them. I later evaluate this conceptualization against established analytical frameworks.

What would environmental groundwater rights look like?

An environmental groundwater right would most simply involve a right to a volume of groundwater to be withdrawn or used in situ for ecological purposes (these options facilitating experimentation and flexibility), held by an entity in an analogous way to the holding of environmental rights to surface water. This definition raises an initial question of ecological fit, that is, the closeness of the link between a quantified volume of groundwater and ecological outcomes where the water is held in situ, given that more complex characteristics of groundwater regimes (flux, level, pressure, and quality) are ecologically relevant. Without actively pumping groundwater and applying it to ecosystems, declining groundwater levels will eventually deprive a GDE of groundwater that is subject to a right. Accordingly, an ecologically oriented volumetric specification of a right would ideally be accompanied by a legal requirement of others to maintain an ecologically reasonable groundwater level at a relevant location, perhaps by reference to a rule that specifies such levels for local contexts (see *Conceiving and Establishing Environmental Groundwater Rights: Combining rules and rights for environmental groundwater to promote multiscalar adaptive governance*). Volumetrically specified groundwater rights in some jurisdictions already include a requirement to maintain a “reasonable” groundwater “level”, although “reasonableness” relates more to considerations of pumping cost, which have little relevance to sustaining ecosystems in situ (e.g., Kansas, USA; Griggs 2014). An ecological version could specify reasonable levels in a precautionary way, including a rate of change component, allowing for temporal variation in levels if evidence were available that it was ecologically justified, as where terrestrial vegetation can withstand periods of reduced access to groundwater (Noorduyn et al. 2019).

Though the link between a purely volumetric right and ecological outcomes may seem attenuated, it is clearly enough to justify the existing ad hoc emergence of environmental groundwater rights described above. It is also worth noting that the same question of ecological fit also arises in the case of environmental surface water rights. In that context, flow-related ecological functions include longitudinal and lateral connectivity and more complex “hydrographic signatures”, rather than volume per se (Thoms and Sheldon 2002), despite volume often being the way the legal right is specified.

An alternative to a volumetric specification may be a right to a quantified groundwater level at a particular location, enforceable by an identified public or private entity. This right would differ from rules-based approaches that limit allowable decreases in

aquifer levels by allowing a dedicated advocate to enforce the meeting of agreed ecological thresholds, diffusing power beyond government. This approach would be more compatible with some legal systems than others. It would be a comparatively small extension for systems that specifically recognize the need to protect ecosystems and currently or feasibly could provide rules-based mechanisms for doing so. It would be much harder to implement in systems that do not usually provide special mechanisms for protecting ecosystems that trump consumptive uses, such as in the prior appropriation systems of the western United States (Covell et al. 2017). It would also be highly contentious where GDEs are very sensitive to reductions in aquifer levels or pressures, as in arid regions (Saito et al. 2021), because it would preclude any significant groundwater withdrawals for consumptive purposes. However, this option would be relatively straightforward to enforce because measuring water levels is relatively easy and takes into account the cumulative effect of human groundwater uses, including those that do not require authorization through a permit or license (Richardson 2012), and other changes to recharge and discharge, including those caused by climate change.

Two common factors characterize these two alternative approaches to environmental groundwater rights. The first factor is the quantified nature of the subject of the right, expressed either as a groundwater level or volume. This factor provides a clearly defined legal mechanism to implement knowledge about ecological thresholds. A right specified as a level directly limits allowable drawdown of an aquifer. A volumetric right may indirectly limit depletion by reducing the allocable water that would remain within the jurisdiction's mechanism for determining the "safe", "sustainable", or "acceptable" yield of the aquifer (Elshall et al. 2020, Pierce and Cook 2020). Alternatively or additionally, the presence of a volumetric groundwater right at a location may carry with it a requirement not to reduce aquifer levels to "unreasonable" levels. Quantifying groundwater rights facilitates enforcing them, as well as making markets possible in the case of volumetric rights (Theesfeld 2010), which in turn promotes revision to levels of protection in changing circumstances.

The second common factor is the presence of formal, legally empowered and politically independent public or private rights holders, advocates for GDEs, which rules-based approaches lack. "Adaptive law" benefits from diffusing power among diverse actors (Cosens et al. 2014, Arnold 2015). These advocates may help combat common challenges to enforcing groundwater rights, including uncertainty about enforcement responsibilities, water agency cultures that downplay enforcement, insufficient state resources, and political cultures in groundwater irrigation communities that prefer "collective and deliberate inaction" in response to depletion (Productivity Commission 2003, Holley and Sinclair 2012, Griggs 2017:37, du Bray et al. 2018). New actors may also bring additional resources to support protection efforts that rely on resource-poor community groups (see Appendix 1 for an example). Private rights holders may be more open to experimentation with extractive use for environmental purposes to resist or direct ecological responses to climate change (Schuurman et al. 2020). They could also acquire environmental groundwater rights to prevent overpumping groundwater before adverse impacts manifest, whereas governments may be more

reluctant to act to impose rules-based mechanisms without a clear crisis, especially where agencies perceive themselves to be facilitators of water use rather than environmental stewards (Nelson 2014, Griggs 2017). The high degree of discretion often available to water administrators exacerbates this problem in the case of GDEs that receive protections only from vague legal principles such as the "public interest" (Nelson 2014, Squillace 2020).

Only volumetrically specified rights provide the choice of in situ and ex situ use, with corresponding benefits for flexibility and experimentation. Because this approach offers significant additional scope for adaptation and represents a striking omission from established legal frameworks (particularly in contrast to surface water), I focus on this form of environmental groundwater rights for the remainder of this article.

Adapting legal regimes to establish environmental groundwater rights: allocation and reallocation as "windows of opportunity" for adaptive water governance

In different places, there will be different requirements and costs to adapt a legal framework to support and encourage environmental groundwater rights. In some jurisdictions, establishing these rights will be straightforward using preexisting legal structures such as water markets or requirements related to biodiversity protection. In others, growing pressures to meet social needs may be allied with GDEs, such as greater Indigenous control over water. In these jurisdictions, it will be more a question of adapting how existing mechanisms are used, rather than adapting the mechanism itself in ways that require significant legal change. In common with rules-based approaches, highly allocated groundwater systems involve the greatest challenge because creating environmental groundwater rights (or imposing new rules) is likely to affect existing uses.

Water markets

The Cosens/Gunderson/Chaffin framework for AWG hypothesizes that law can "creat[e] either a disturbance or a window of opportunity in which adaptive forms of governance may emerge" (Cosens et al. 2014:6). In fully allocated systems, existing laws that support water markets may present such a window of opportunity. Aspiring rights holders with resources can acquire groundwater rights for environmental purposes (as occurs for surface water; Owens 2016).

Transferable groundwater rights, required for groundwater markets to operate, are becoming more common around the world (Charalambous 2013). In prior appropriation systems, the most reliable senior rights are likely to be the most costly to purchase, presenting a financial hurdle for aspiring purchasers. Although purchasing cheaper, junior rights may not provide as much theoretical security for their beneficiary ecosystems, lower rates of administration according to priority (i.e., curtailment of junior rights) in the case of groundwater may reduce the difference in practice (Schlager 2006, Griggs 2017) but also may raise concerns about enforceability. However, relying on voluntary sales of groundwater from consumptive users to environmental holders entails risks that there may be no willing sellers, as recent Australian experience illustrates (Australian Government, Department of Agriculture, Water and the Environment: Groundwater purchasing, <https://www.agriculture.gov.au/water/markets/commonwealth-water-mdb/groundwater-purchasing>).

“Crisis” legal requirements

Legal requirements to protect biodiversity in crisis, i.e., groundwater-dependent endangered species (Thompson 2011), may also theoretically prompt the development of frameworks for environmental groundwater rights, even in fully allocated systems, especially if such requirements trigger larger, collaborative problem-solving policy processes (Gosnell et al. 2017). Similarly, situations of critical environmental degradation that trigger legal remediation requirements, for example, to address water quality concerns (e.g., Appendix 1) could conceivably trigger the development of environmental groundwater rights. However, these comparatively rare and more extreme situations seem unlikely to spur reforms that would make such rights generally available.

Nonlegal factors may open or constrict windows of opportunity

Nonlegal factors may also create windows of opportunity for environmental groundwater rights. It may be possible to create rights by increasing water-use efficiency and capturing the savings as a water right (Horne et al. 2017a), though some efficiency measures may also reduce leakage or recharge that supports GDEs (Victorian Ombudsman 2011). In systems that are not fully allocated, political pressure and advocacy may cause governments to consider granting water to nongovernmental organizations to be managed for environmental and Indigenous-environmental purposes (e.g., Woods et al. 2022).

Compared to environmental surface water rights, the sociopolitical challenges of reallocating groundwater in fully allocated systems may constrict these windows of opportunity to a lesser degree. Groundwater users typically own and control their own infrastructure. As a result, reducing irrigation would not create a “Swiss cheese effect” as has occurred in some surface water irrigation communities. In that context, government buy-backs of water for environmental purposes can reduce irrigator numbers and leave those remaining to bear increased costs of maintaining shared infrastructure such as irrigation channels (Wheeler et al. 2013). Though reduced economic activity associated with irrigation might have some local economic effects, remaining groundwater users would pay lower pumping costs if more groundwater were left in aquifers and levels rose (Konikow and Kendy 2005, de Graaf et al. 2019).

Combining rules and rights for environmental groundwater to promote multiscale adaptive governance

As for surface water, a jurisdiction could combine rights- and rules-based approaches for GDEs. Formalizing links between these approaches, and the scales at which they operate, offers a key benefit for AWG of developing legal frameworks for environmental groundwater rights or promoting awareness of them where they are already appearing ad hoc. Environmental groundwater rights at the local scale could complement rules for protecting GDEs, which often apply at large geographic scales, in several ways:

1. By addressing areas of local decline within basins protected by large-scale, rules-based caps on extraction, where it is not legally or politically possible to institute local-scale rules to constrain extractions based on protecting water levels. Basin-scale volumetric limits alone are unlikely to protect a local feature such as a groundwater-dependent wetland from local declines (Pierce and Cook 2020). Acquiring existing

consumptive groundwater rights around that wetland for ecological uses could support local groundwater levels (although surrounding groundwater withdrawals would continue to have some effect) and provide a source for experimenting with and using active pumping and supplementary watering in times of peak stress;

2. Similar to (1), by achieving a higher level of protection for local GDEs than is legally or politically possible through rules that constrain extraction by reference to quantified aquifer levels, even where they exist, or through broadly worded principle-based thresholds. State-sanctioned local rules may allow more GDE degradation than the community is willing to accept. More diverse actors such as Indigenous or local communities may highly value a particular groundwater-dependent waterhole or common species for cultural or recreational reasons that do not meet formal indicia of “value” or “public interest” that would trigger strict rules-based protection;
3. By facilitating local knowledge-building about GDE ecological thresholds where uncertainty about these thresholds may compromise the effectiveness of rules-based approaches that seek to set boundaries to protect them. Acquiring consumptive groundwater rights and leaving them in situ can encourage learning and revision by testing hypotheses about the effects on GDEs of further constraining pumping without engaging in complicated rule change procedures, and the resulting knowledge could be used to justify later changes to rules that would protect that ecosystem type at a large scale;
4. By taking the first step toward rules-based approaches in jurisdictions where the latter have never been used. Adapting a legal regime by introducing entirely new rules can be contentious, legally complicated, and time-consuming. Most jurisdictions globally do not protect GDEs using water law rules, but if they already provide for transferable volumetric groundwater rights for consumptive purposes, it would be a comparatively small step to allow these rights to be transferred to ecological uses. This development could be used to pilot-test the effects of broader scale rules.

ASSESSING THE BENEFITS AND RISKS OF ENVIRONMENTAL GROUNDWATER RIGHTS FOR ADAPTIVE WATER GOVERNANCE AND THE ROLES OF LAW

Here, I use two analytical frameworks advanced in the existing literature to evaluate the concept of environmental groundwater rights, including roles that rights could play in enabling AWG, the jurisdictional conditions in which an environmental groundwater rights approach may achieve benefits for AWG that are less likely under a rules-based approach, and approaches to adapting governance systems to establish these rights. Applying the first framework (hereafter the Horne/O’Donnell/Tharme framework; Horne et al. 2017a) helps to evaluate the questions: Under what conditions would environmental groundwater rights benefit AWG, relative to rules, considering differences between groundwater and surface water, and in what jurisdictional contexts (e.g., surrounding physical and governance contexts and other factors) is a rights approach pragmatic and compelling? Notably, the relative benefits for AWG of an environmental

groundwater rights approach may not universally outweigh its risks and costs or be reasonably compatible with existing legal regimes or cultural norms. Applying the second analytical framework (hereafter the Cosens/Gunderson/Chaffin framework; Cosens et al. 2014) helps to evaluate the question: What roles could law that supports environmental groundwater rights play in AWG for GDEs? In general, law is hypothesized by this framework to create windows of opportunity for adaptive governance, set boundaries that protect ecological systems, remove current legal barriers to AWG, and facilitate AWG. The latter three roles are explored below. Finally, I further contextualize how a combination of rules and rights could enable AWG by facilitating multiscale governance, sociocultural benefits for Indigenous peoples, and experimentation with ecological thresholds that could inform rules-based mechanisms.

Table 2 summarizes the results of this analysis using both analytical frameworks. The following explanatory text considers each element, drawing on and expanding the first principles discussion of GDEs and AWG advanced earlier, which centers around learning and revision, experimentation and flexibility, diverse actors, and multiscale approaches that combine rights and rules. I summarize and highlight interactions and complementarities between rules and rights.

Initial conditions and constraints

The first evaluation element of the Horne/O'Donnell/Tharme framework focuses on the surrounding hydrological, institutional, legal, and scientific conditions that influence the benefits for AWG and challenges of rights- and rules-based approaches to environmental water. Extending the framework beyond its original surface water context, I explore how each of these subcategories of conditions could play out differently in different groundwater contexts, indicating conditions under which environmental groundwater rights would be more or less likely to benefit AWG.

Hydrological conditions and constraints: implications for setting boundaries and meeting ecological thresholds

Important hydrological conditions relevant to ecological thresholds for GDEs include the possibility of groundwater-surface water connections and the unique characteristics of some groundwater systems as to recharge: both aspects suggest the benefits of a rights-based approach. A GDE that relies on both surface water and groundwater (as many do; Tomlinson 2011) may be protected in a coordinated way using both environmental surface water and groundwater rights to protect baseflow at critical locations. It is difficult to protect these ecosystems with surface water rights alone where laws do not recognize the connections between surface water and groundwater, which is a relatively frequent situation (Arnold 2015, Jakeman et al. 2016, Closas and Villholth 2020). Rights holders may be powerless to defend against the impacts of groundwater pumping on river conditions. Groundwater rights could provide a source of water to tide over in-stream refugia in times of peak stress in the absence of other legal options to protect baseflows.

Nonrecharging and slowly recharging groundwater systems pose unique challenges that demonstrate the advantages for meeting ecological thresholds of a rights-based approach for groundwater. Groundwater may be nonrenewable where an aquifer receives little or no modern-day recharge, as in the Great Artesian basin

of Australia, the Nubian Sandstone in northern Africa, and the Basin and Range Aquifers in the U.S. state of Arizona (Margat and van der Gun 2013). Where GDEs depend on depleted or slowly recharging groundwater resources, rules that reduce aggregate withdrawals will not prevent declining water levels and pressures if withdrawals still exceed low rates of recharge. Recovering GDEs may take a long time if left to occur naturally, although it may be feasible in some circumstances (New South Wales Government 2016, 2019). Restoring these ecosystems may require artificial recharge and more complex legal frameworks for facilitating recharge using water held subject to water rights, as well as safeguarding the stored groundwater using environmental groundwater rights. The time lags inherent in groundwater systems make it difficult to conceive of ways to achieve such restoration by relying on rules that simply constrain pumping for consumptive purposes; valued ecosystems may be lost by the time underlying groundwater systems recover naturally.

Institutional and legal initial conditions and constraints: rights circumventing barriers to adaptive water governance for groundwater-dependent ecosystems

Potentially low political and agency motivation to introduce, amend, and enforce new rules to protect GDEs are further important initial conditions as obstacles to adopting legal rules. These obstacles may be higher for rules about groundwater than those about surface water. Groundwater overuse is less visible than surface water overuse, and the political imperatives to protect GDEs may be weaker than for rivers, with lower awareness of the ecological value of groundwater (Ekmekçi and Günay 1997, Boulton 2009, Nelson 2013, Cuadrado-Quesada and Rayfuse 2020). This situation is changing, however, with some notable nongovernmental organization contributions to advocacy and science (e.g., The Nature Conservancy's Groundwater Resource Hub: <https://groundwaterresourcehub.org/>).

An important benefit of groundwater environmental rights over rules-based mechanisms is in diversifying the actors directly involved in setting and enforcing ecological boundaries to support GDEs, circumventing political barriers to government action. The degree to which a jurisdiction has active and well-resourced nongovernmental organizations or genuinely independent statutory water rights holders will affect the degree to which these actors may effectively acquire and use groundwater environmental rights.

Long-established flaws in existing legal frameworks can obstruct AWG, but environmental groundwater rights may present a way to circumvent some of their ill effects. Water laws that commonly, but not universally, separate regulation of water quantity and quality (Arnold 2015, Rohde et al. 2017, Thompson et al. 2018) cannot easily use rules to constrain pumping that creates or exacerbates pollution that may threaten GDEs, such as pollution from acid sulphate soils, liberation of naturally occurring arsenic or fluoride in groundwater, and seawater intrusion (Margat and van der Gun 2013). While amending legal regimes to remove this regulatory separation and barrier to AWG may be difficult, strategically acquiring and protecting rights in situ could help prevent extraction-related groundwater quality problems from arising or increasing at a local scale.

The development of environmental surface water rights has sometimes required controversial legal change to remove legal barriers (Ziemer et al. 2020). Depending on the jurisdiction,

Table 2. Benefits and challenges of environmental groundwater rights (“rights”). Insights from applying the Horne/O’Donnell/Tharme framework (Horne et al. 2017a; columns) and implications for adaptive water governance as per the Cosens/Gunderson/Chaffin framework (Cosens et al. 2014; rows). See Appendix 1 for an example of a case scenario that investigates how some of these factors might arise in practice.

Cosens/Gunderson/Chaffin framework		Horne/O’Donnell/Tharme framework		
		Initial conditions and constraints: hydrology, institutions, law, science	Environmental values and sociocultural preferences	Responsiveness to variability and change
Creates a window of opportunity in which adaptive governance may emerge		Existing water markets open a window to reallocation through volumetric rights purchases; endangered species or environmental remediation requirements may do so more rarely	Without structural support, local capacity to pay for rights to protect environmental values may not be enough to open the market window	Opportunities to enter the water market may change with market conditions over time and rules-based restrictions [†]
Sets boundaries by identifying approaching ecological thresholds or tipping points		Existing rules-based legal management plans may set boundaries, e.g., using large-scale caps on pumping; rights earmark boundaries at the local scale, and enforcing them prevents overshooting local boundaries [†]	Boundaries inherent in rights can reflect local values and preferences to complement those expressed at a higher scale through basin-scale rules-based mechanisms [†]	Boundaries set by rights can be readily adapted in response to new knowledge about tipping points through rights transfers, e.g., acquiring further rights needed to protect groundwater-dependent ecosystems
Presents barriers (–) or removes barriers (+) to adaptive water governance		(+) Rights facilitate actively restoring aquifers with low recharge and managing groundwater-surface water and quantity-quality links in legal regimes that lack these links (–) Full benefits of rights may require legal adaptations to support water quality component of rights, enable transfers, allow in situ use, etc.	(–) Socio-legal preferences for centralized public action in some jurisdictions may obstruct development of rights held by local actors at local scale (+) Legal rights legitimize protection of groundwater-dependent ecosystems but (–) may invite backlash if consumptive users perceive a competitive threat (–) Financial resources are needed to buy rights through markets and fund any regulatory holding costs	(+) Provides an alternative or (ideally) complement to rules-based approaches that are difficult to adjust in response to changing conditions and new information about environmental requirements [†]
Facilitates adaptive water governance	Structures that facilitate multilevel and multiscale governance	Presence of rules-based approaches, e.g., management plans allow for links between local rights and basin-scale rules [†]	Rights holders may be local-scale and/or private entities as well as centralized public entities; local rights holders may gain a seat at the table in larger scale debates about water policies and rules [†]	Rights allow more responsive local adaptation than is possible through basin-scale rules that may not prioritize local values; local knowledge built through experimentation can inform basin-scale rules [†]
	Increased capacity of actors to respond to change and to play a role in decision-making	Rights can grant local actors legal capacity to protect groundwater-dependent ecosystems, avoiding political barriers to government action inherent in rules-based mechanisms	Rights allow prioritization of groundwater-dependent ecosystems based on local and Indigenous values, adding to priorities set using rules at higher scales [†] ; institutionalizing rights may increase access to resources	Rights introduce capacity for active groundwater management and ex situ use to resist or direct trajectories of ecological change
	Process elements that encourage problem-solving and collaboration	Institutionalizes interest in collecting and acting on groundwater-dependent ecosystems-related science	Basin-scale rules and management plans can structure coordination of local rights to achieve synergies in use of rights [†]	Rights allow experimentation and problem-solving (including though ex situ use), building knowledge about environmental water requirements, informing rules [†]

[†]Interactions and complementarities exist between rights and rules.

similar barriers may also require attention to facilitate environmental groundwater rights. Relevant legal changes have included allowing water rights for in situ use rather than requiring diversion, allowing consumptive uses to be changed to instream use, and enabling permanent and temporary transfers of water (including that saved by irrigation efficiencies) for instream uses (Ziemer et al. 2020). In some cases, the different situation of groundwater may mean that existing laws present fewer barriers to environmental groundwater rights as a form of adaptive governance. For example, nonuse of groundwater is arguably less

likely to constitute impermissible “waste” because groundwater flows more slowly than surface water and may largely remain in place for future use (Griggs 2014). In any case, removing these barriers in jurisdictions that already have frameworks for volumetric groundwater rights and administrative permitting systems is likely to be much less contentious than introducing entirely new rules for protecting GDEs that would mandate reductions in consumptive use. Some western U.S. states may well belong to this category. Where jurisdictions have not developed transferable or volumetric water rights, a nonvolumetric approach

to environmental groundwater rights (such as third-party rights to enforce specified aquifer levels necessary for ecological purposes or, alternatively, rules-based approaches to protecting GDEs) would likely be more feasible and less administratively costly to develop.

Data and knowledge conditions and constraints

Finally, building ecological information about groundwater dependence is expensive and often suffers from knowledge gaps (Rohde et al. 2017, Gage and Milman 2021). While government capacity and enthusiasm for getting this information can wax and wane, in jurisdictions with well-resourced nongovernmental organizations or statutory water holders, these entities have a direct and ongoing interest in collecting GDE information, acting on it by securing rights, and experimenting using volumetric rights to build knowledge about ecological thresholds.

Philosophy on environmental values and sociocultural preferences

The second major evaluation factor in the Horne/O'Donnell/Tharme framework focuses on the environmental philosophy underlying a water rights system and sociocultural leanings toward rules- or rights-based protections. Diverse social, cultural, and political preferences are evident globally in relation to groundwater (Gleeson et al. 2020). Where rights-based approaches are philosophically and culturally acceptable, environmental groundwater rights arguably have the potential to give voice to more diverse local norms and preferences, with corresponding benefits for AWG, particularly where rights are supported by capacity-building initiatives for local actors.

Sociocultural preferences for centralization vs. localism and implications for adaptive water governance through facilitating multiscale governance

At first glance, the decentralized nature of a rights-based approach to protecting GDEs is aligned with social and political norms that value localism. Closer analysis shows that rights can also be consistent with a centralized approach and, indeed, can facilitate multiscale governance when combined with rules. Localism is clearly valued where local aquifer management organizations have developed alongside markets and groundwater property rights, as in Chile (Donoso et al. 2020). The same is true where private sector autonomy is culturally preferred (Arnold and Gunderson 2013) and private actors may hold environmental water, as in some U.S. states (Covell et al. 2017). However, a rights-based approach may also lend itself to cultural preferences for larger scale, public-sector driven environmental protection where statutory entities hold the relevant rights (e.g., those listed in O'Donnell 2013).

Environmental groundwater rights allow for the expression of local values and preferences, which are central to AWG (Cosens et al. 2014). State and federal laws may prioritize protection of GDEs by relying on existing environmental designations that reflect state, national, or even international values (e.g., wetlands of international importance in Australia's Murray-Darling Basin or federally listed endangered species reliant on Texas' Edwards Aquifer; Nelson 2014). However, important ecosystems and species other than endangered species rely on groundwater too. Admittedly, water planning processes may allow local stakeholders to participate in prioritizing local GDEs for protection through rules (Nelson and Quevauviller 2016, Squillace 2020). However, the link with local values and

preferences is more direct in the case of local actors (including nongovernmental organizations) directly lobbying for, purchasing, holding, and managing environmental groundwater rights to protect local groundwater-dependent values. Local-scale rights could complement and interact with rules-based management plans at larger basin scales, allowing multiscale governance that is also sought by AWG theories (Cosens et al. 2014). These plans could create synergies and support higher scale values from the coordinated exercise of multiple local-scale environmental groundwater rights. This process is analogous to collaboration to maximize the benefits of environmental surface water by coordinating its use with other water sources (Docker and Johnson 2017).

Sociocultural benefits for Indigenous peoples: facilitating adaptive water governance by diversifying actors and sources of knowledge

As well as legitimating protection for GDEs and attendant ecosystem services, better protecting groundwater and GDEs through rights may have social and cultural benefits for groups historically excluded from water policy discussions. It could give greater voice to Indigenous worldviews, as in tribal rights to groundwater (Womble et al. 2018). Indigenous water rights holders may gain a seat at the table in regulatory discussions about water management rules (Jackson and Langton 2011) and in broader water protection and management discussions (Ratcliff 2016). Developing a legal framework for environmental groundwater rights would support the recognition, legitimacy, and development of Indigenous capacity, as can occur in analogous river basin settings (Cosens and Chaffin 2016). If environmental groundwater rights support Indigenous peoples to secure a seat at the table, it could lead to more transformative engagement with Indigenous values, for example, in rules-based approaches, broader water allocation processes, landscape management, and Indigenous-settler relations (Nelson et al. 2018, O'Donnell et al. 2021).

Sociocultural and socioeconomic barriers to using environmental groundwater rights effectively

Ironically, the surface water experience suggests that the strength of water rights for environmental purposes can attract social challenges. Environmental objectives can shift from being perceived as special, and deserving of protective rules, to just another user of water, and even the largest irrigator in the system, with implications for perceptions of adversity and competition, and reduced need for state support (O'Donnell 2018:140). However, granting rivers legal personhood has sometimes prompted similar backlash (O'Donnell 2020); this risk can affect rights- and rules-based approaches alike. Comparatively lower community support and advocacy about GDEs may lower this risk for environmental groundwater rights compared to surface water rights.

Practical economic challenges could also arise even where there is community support for environmental groundwater rights. Market-based reallocation requires funding to buy groundwater rights, and even where rights are granted by government free of charge, they may be accompanied by annual holding fees and other transaction costs (Ziemer et al. 2020). Formal legal frameworks for environmental groundwater rights could use existing institutional arrangements for statutory environmental

water holders or introduce new supportive financial mechanisms. Policy interest in payments for ecosystem services presents one theoretical but apparently little-implemented way of funding groundwater protections (Knüppe et al. 2016), including funding to acquire and use groundwater rights. Even with initial resources to acquire and hold rights, a right may amount to little more than “paper” water without ongoing resources to develop infrastructure to use it, which is a common challenge across Indigenous contexts (Womble et al. 2018). This barrier may similarly obstruct active *ex situ* use of an environmental groundwater right that requires infrastructure, reducing benefits to AWG of experimentation and flexibility if this option cannot be used in practice.

Responsiveness to new knowledge, variability, and climate change: learning and flexibility to meet ecological thresholds

When in volumetric form, environmental groundwater rights allow more flexibility than rules-based approaches, which can be more difficult to adjust (Horne et al. 2017a), obstructing problem-solving that is central to AWG (Cosens et al. 2014). A rights holder may buy groundwater in periods of critical need or temporarily sell groundwater when alternative supplies are available for environmental purposes. This process occurs in some environmental surface water contexts, subject to statutory constraints (O'Donnell and Garrick 2017). This flexibility to adapt is particularly valuable given that much remains unknown about the water requirements of GDEs. A rights-based approach enables a fast response to new information about ecological thresholds if the holder can access water markets to secure additional water to meet these thresholds. It also enables local experimentation in response to hypothesized ecological thresholds. This local knowledge-building can then inform rules-based mechanisms to protect GDEs at larger scales. By contrast, even where rules-based mechanisms such as water plans must be reviewed, multiyear review timelines are not conducive to fast responses to experimentation or new information, including in relation to climate change. Even with substantial investments in scientific studies, adapting environmental water rules to accommodate climate change can be politically difficult (Alexandra 2021).

An environmental rights-based approach that enables *ex situ* use could also provide for flexible adaptation to severe climate change effects that necessitate actively applying groundwater to benefit GDEs stressed by severe climate variability. This approach helps keep open and adaptable the decision space for these “resist” and “direct” approaches to conservation in the face of transformational climate change (Schuurman et al. 2020). The same is true of more temporary stresses, where active use of groundwater may help reduce ecological vulnerability to drought. This situation may, in turn, reduce ripple effects of change from ecological change to ecosystem services and dependent human systems (Crausbay et al. 2017). By increasing groundwater storage (even if only temporarily in the case of usually extractive ecological use), developing environmental rights for groundwater also provides broader benefits for human drought resilience, for example, by reducing pumping costs for other users.

SYNTHESIS AND CONCLUSION

Despite the now widespread scholarly scientific acknowledgement of the ecological importance of groundwater, progress on actually

protecting GDEs using law has been slow. Inadequate protections for GDEs risk unregulated harms to ecosystems under normal conditions, and more severe harms where climate stresses reduce recharge or lead to increased consumptive withdrawals.

Extending the legal concept of a water right for the environment from the surface water context to groundwater may help accelerate protections and promote AWG. While some groundwater law frameworks have developed rules to protect GDEs that mirror those for surface water, they have yet to develop frameworks for allowing and facilitating the use of environmental groundwater rights, though examples are emerging *ad hoc*. Such frameworks would allow for enforceable, transferable water rights based on quantified volumes (or potentially water levels, or both), allowing for both extractive and *in situ* use, held by an identified public or private entity. Beyond simply allowing for such rights, legal frameworks could encourage protecting GDEs in this way using similar mechanisms to those in place for surface water in various jurisdictions, including secure funding sources, tax benefits for water donors, and institutional support.

I have demonstrated that conceptually, a rights-based approach to protecting GDEs offers three groups of distinctive and linked benefits for AWG, particularly when combined with rules-based approaches. First, as conceived here, the concept of environmental groundwater rights promotes AWG by diffusing power among multiple actors, allowing nongovernmental organizations as well as independent statutory authorities to hold and manage water rights that are dedicated to ecological purposes. Interested actors may include Indigenous groups seeking to protect culturally important values, who may value the legitimizing effects of water rights in dominant cultural contexts and find their voices amplified in debates about rules. This power diffusion also facilitates actors pursuing different priorities for ecological protection at more local scales than those usually reflected in government rules, complementing rules-based approaches at a higher spatial scale.

Second, rights-based approaches support learning about ecological thresholds of GDEs and implementing and revising ecologically informed limits on groundwater withdrawals at multiple scales. When combined with rules-based approaches that tend to protect GDEs at a high spatial scale, for example, through basin-wide limits on extraction, the local character of a water right facilitates protecting and building knowledge about locally significant GDEs and experimenting with approaches to protection that could later be adopted in generally applicable rules. This characteristic is especially valuable for GDEs about which little is known, where experimentation can build knowledge about how they respond to changes in water availability and other climate change effects and readily adapt to this knowledge by acquiring or disposing of unneeded rights. Conversely, basin-scale plans can usefully interact with rights by coordinating the use of multiple local-scale rights to achieve synergies, including as between the use of environmental surface water and groundwater rights, especially in legal regimes that do not otherwise recognize groundwater-surface water connections. Similarly, rights could also help to circumvent legal barriers to AWG, such as often legally rigid regulatory divides between water quantity and quality, which can leave ecosystems vulnerable to harm from uncontrolled extractions that cause or exacerbate pollution.

Third, environmental groundwater rights may help to counter some of the administrative, sociopolitical, and physical barriers inherent in attempts at AWG that depend solely on rules-based approaches to protecting ecosystems and on improving rules. These barriers include the vagueness with which some rules are specified (e.g., those that constrain withdrawals by considering the “public interest”), which makes them difficult to administer in a way that results in consistent protection. Protections based on rights can be more easily adopted and amended than rules, where legal systems already have basic frameworks for rights. Political difficulties can arise where legislative and regulatory attempts to amend rules to improve GDE protections or respond to new knowledge about GDEs would reduce economically important withdrawals. The quantified nature of rights and the potential for them to be acquired, held, and enforced by environmentally motivated actors that lack conflicting political objectives help to avoid these difficulties. In slowly recharging or depleted groundwater systems, water rights that allow extraction also physically provide scope for artificially restoring ecosystems while the underlying groundwater systems recover. This approach overcomes the natural time lags between ceasing or reducing pumping (for example, under rules-based approaches) and groundwater levels recovering. Active pumping and application to ecological assets could also assist sensitive GDEs or GDEs experiencing peak stress and help a valued ecosystem adapt to a climate-changed future while retaining desirable functions. Rights increase flexibility for experimentation and problem-solving in management that responds to stressors such as climate change.

Depending on the specific jurisdictional context, legally supporting environmental groundwater rights may require only policy change and encouragement (especially where the rights are emerging ad hoc) or relatively minor legal change (for example, to clarify that in situ use of a groundwater right is allowed and to provide for institutional support or incentives). Equally, the benefits to AWG and risks of such a framework are likely to vary according to the preexisting legal and institutional context and groundwater conditions. Costs, risks, and political barriers are likely to be lowest where relatively little legal and policy change is required. Established frameworks for legally transferable water rights and water markets, and existing “crisis” legal requirements in relation to biodiversity or water quality, may act as windows of opportunity for developing environmental groundwater rights to protect GDEs. Obstacles to using rights to protect GDEs include inadequate funding where a system requires rights to be purchased and where high infrastructure and operational costs are associated with ecological pumping, and the influence of perceptions that GDEs are competing with consumptive use.

An environmental groundwater rights approach is unlikely to work everywhere and likely works best when combined with a rules-based approach. My conceptual analysis suggests that, in some jurisdictions, it will promote AWG to a degree worth investigating further. With climate stresses looming ever larger, the time has come to tap the adaptive potential of current governance approaches to more fully protect our water environments.

Responses to this article can be read online at:
<https://www.ecologyandsociety.org/issues/responses.php/13123>

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Data Availability:

Data/code sharing is not applicable because no data/code were analyzed in this study.

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APPENDIX: CASE STUDY: ACID WETLANDS VS DRY TAPS IN VICTORIA, AUSTRALIA

To illustrate the challenges and benefits of environmental groundwater rights in a real-world context, this appendix presents a case study of a current controversy over the effects of groundwater pumping on GDEs in Victoria, Australia. The surrounding jurisdictional circumstances of the case study make groundwater environmental rights plausible, requiring a smaller step away from existing approaches than in other places. Victoria has an established statutory entity for holding environmental water, legal frameworks for environmental surface water rights are well developed, GDEs are formally recognized as important and rules-based protections for GDEs already exist in the jurisdiction. Australia is recognized to have the world's most comprehensive policy protections for GDEs, and the paradigm for protecting GDEs already promotes an iterative adaptive management framework (Rohde et al. 2017).

The events central to this case help illustrate important challenges noted above: links between groundwater quantity and quality and between groundwater and surface water; and protections for 'regular' GDEs that do not benefit from special status as habitat for endangered species, or a national park or other protective mechanism. The events also have high political salience, pitting municipal groundwater use in a large regional city against wetlands, streams and a major river — and their dependent irrigators — that have suffered from contamination with acidic water and heavy metals connected to municipal groundwater use.

Existing governance framework for water in Victoria

As in other Australian states, water in Victoria is owned by the Crown, which may authorize a person to use that water under an administrative licensing system (Gardner et al. 2018). Legislation provides for groundwater pumping to be authorized mainly using renewable 15-year, volumetric 'take and use' licenses (sections 51, 56, *Water Act 1989* (Vic) ('Water Act')). Licenses are usually issued by a delegate of the Water Minister, being the regionally-based water corporations that also provide revenue-raising rural water services in addition to carrying out regulatory functions with the objective of environmental protection. This creates the theoretical potential for conflicts of interest. A license is associated with a particular parcel of land, and license conditions may specify the purposes of use (section 56, *Water Act*). When considering an application for a take and use license, the delegate of the Water Minister must ensure that aggregate extractions from a basin do not exceed an aggregate cap on pumping known as a 'permissible consumptive volume' for the basin (Minister for Water 2014). The delegate must also consider potential effects on 'high-value' GDEs using a risk assessment approach (Minister for Environment 2015). However, this approach may not apply to areas that have a statutory or informal 'local' management plan in place and only applies to narrow categories of 'high value' GDEs that tend to reflect a surface water focus (e.g. Ramsar wetlands, areas prioritized by waterway managers) (Minister for Environment 2015). Some management plans apply binding rules-based protections for GDEs, such as pumping restrictions near rivers or permissible consumptive volumes (section 22A, *Water Act*), but may rely heavily on assumptions about GDEs from remotely sensed data, and simply note that further investigation of GDEs is required (Goulburn-Murray Water 2012a). Most do not manage surface water and groundwater together, though there is one notable exception in the state's north (Goulburn-Murray Water 2012b).

Surface water is managed differently to groundwater across much of the state. In unregulated surface water systems (those without significant on-stream storages), the same take-and-use licenses apply as for groundwater. In regulated systems, surface water rights are disaggregated

into three types of entitlements that relate to a share of the delivery capacity of a system, a share of the volume of water available in the system, and authorization to use the water on a specific parcel of land (State of Victoria 2016) (for convenience, ‘surface water rights’). An independent, expertise-based state agency, the Victorian Environmental Water Holder, holds surface water rights and actively manages the rights in conjunction with local entities and Aboriginal Traditional Owners to ensure that highly valued wetlands and rivers receive environmentally optimal flows (State of Victoria 2016:, Part 3AA Water Act).

Governance in relation to groundwater in the Otways

Pursuant to a take and use license issued in 2004 (groundwater license No: BEE032496), a state-owned water supplier for the large regional city of Geelong, Barwon Water, operated the Barwon Downs borefield primarily as a drought reserve. Evidence collected since 1999 suggested that pumping was dewatering the hydrologically connected Boundary Creek and a groundwater-dependent wetland known as the Yeodene (Big) Swamp (Barwon Water 2020). This caused soils to oxidize and acidify in the Big Swamp, leading to discharges of acidic water ($\text{pH} < 4$) and mobilizing metals during wetter periods downstream into Boundary Creek, which landholders use for stock watering. This, in turn, triggered significant fish kills and impacted a significant river downstream, the Barwon River (Barwon Water 2020). Other activities also contributed to dewatering the wetlands, for example, fire control works that diverted surface flows, a generally drying climate and the apparently inadvertent non-compliance of the owner of an upstream on-stream private dam to re-release flows released by Barwon Water to supplement river flows to counter the potential for groundwater pumping to dewater the catchment (Barwon Water 2020). An active local farmers’ and residents’ group, Land and Water Resources Otway Catchment (‘LAWROC’), has been involved in lobbying to stop the pumping for decades.

The situation came to a head when Victoria’s Water Minister, who has supervisory control over waters in the state, issued an emergency order in September 2018 (under section 78, Water Act) to prevent further pumping, except for emergency and maintenance purposes, and formulate a remediation plan (Southern Rural Water 2018). Remediation will involve the ‘continual wetting of Big Swamp through controlled release of water to Boundary Creek and the installation of hydraulic barriers to maintain surface water flows and groundwater levels within Big Swamp’ (Barwon Water 2020:2). The protective force of the emergency order was supplemented by a rules-based constraint on increased pumping from the aquifer in the form of amendments to the permissible consumptive volume. This capped extractions at current levels, precluding resumption of municipal pumping (Minister for Water 2019). The underlying groundwater take and use license has since expired, and Barwon Water withdrew a license renewal application (Barwon Water 2019), but has not ruled out applying for another in the future, since it is concerned about secure water supplies for Geelong in future droughts.

The existing rule-based legal mechanisms that protect the Big Swamp and its hydrologically connected streams have notable weaknesses. The emergency Ministerial order is temporary, and though it requires remediation of the damaged GDEs, there is no requirement for transparency or public participation, nor quantified requirements for protection: the required remediation is described broadly as ‘controls and actions that could be practicably carried out to achieve improved environmental outcomes’ (Southern Rural Water 2018:[2.3]). The order provides for a secondary management plan that also omits any requirement for public consultation. Though consultation is taking place as a voluntary matter in practice, the community, the Minister’s delegate and Barwon Water disagree about the fundamental matters

of exactly what needs to be protected, and to what extent, and whether environmentally damaging municipal pumping should be allowed in the case of future drought (Barwon Water 2020).

The rules-based permissible consumptive volume caps the aggregate level of extraction, thereby constraining the grant of groundwater licenses. It is not a direct goal for protecting any specific GDEs, does not require review, does not provide for any adaptive approach, and can be altered or revoked by Ministerial order without any community consultation or scientific justification (section 22A Water Act).

What would a groundwater environmental right look like and what benefits would it have?

In the context of this case study, the Victorian Environmental Water Holder could be granted a groundwater license to the remaining volume of water in the aquifer supporting the GDEs of concern, or a right to enforce a certain groundwater level at the relevant locations at risk of forming acid-sulphate soils, as a form of environmental groundwater right. This would offer the potential to coordinate with existing environmental surface water rights, more sustainable resourcing, and better responsiveness to new information. The Victorian Environmental Water Holder, which collaborates with local catchment management authorities to deliver environmental flows, already holds environmental surface water rights to the Barwon River (WSE000032 and WSE0260002: Minister for Water 2013, 2018), which was affected by acid pollution. Holding rights over groundwater that discharges to this river could also provide scope for coordination with surface water rights intended to benefit the same body of water. There may also be potential to grant a license to an Aboriginal entity, responding to calls for greater Aboriginal Traditional Owner involvement in environmental water decision-making and in groundwater in Victoria (O'Donnell et al 2021), though there appears to have been no investigation of this option in the context of the Big Swamp. This approach would help avoid the potential for past problems of insecurity of environmental water held by the Victorian Environmental Water Holder in the form of rights, during drought (O'Donnell 2012).

Protecting the relevant GDEs has so far fallen to LAWROC, a single NGO with few resources and predominantly older members. The involvement of the Victorian Environmental Water Holder as an independent agency could institutionalize and make permanent advocacy for the affected GDEs. This is particularly important in light of multiple claims about contributions to the problem (pumping for municipal purposes, peat fire control works, and non-compliance of the upstream dam owner with passing flow rules), which raises the possibility that disputes over attributing blame obstruct efforts to reach GDE-focused solutions. The potential for conflicting incentives between revenue raising (i.e. permitting new pumping) and environmental protection (i.e. restraining new pumping) in the Minister's delegate also supports the involvement of an independent entity.

Institutionalizing protection for the GDEs would help with data gathering and stewardship in the longer term, noting that significant scientific investment in understanding the groundwater dependence of the GDEs (by the water authority) only happened after environmental damage was catastrophic, and now may require decades to remediate (Barwon Water 2020). Public trust in scientific data about groundwater can be low more generally, since groundwater modelling is often perceived to involve 'black box' models, possibly to an even greater extent than surface water (Voss 2011, Moran 2016, Middlemis et al. 2019). An independent voice could also help to increase public trust in the science underlying actions to protect Big Swamp

and Boundary Creek, particularly with the need for pursuing actions flexibly in light of a climate that is predicted to dry in future due to climate change (Barwon Water 2020).

A legal ecosystem for GDE protection

Introducing an environmental groundwater right for GDEs would not require significant legal change, and could be accompanied by other regulatory tools that provide different benefits, especially where potential links between rights, rules and institutions are clear. While significant discussion of these lies outside the scope of the present work, other tools are available. These include plans for ‘special areas’ that can impose conditions on land use that might be able to encompass groundwater pumping (ss 27, 28, 34 *Catchment and Land Protection Act 1994* (Vic)). These plans are administered by catchment management authorities, which are also involved in environmental watering decisions by the Victorian Environmental Water Holder, paving the way for forging links between groundwater environmental rights held by that statutory entity and management of the special area plan. Other options include a statutory water plan that could impose rules-based constraints on others’ use of groundwater to protect the environmental groundwater right (Pt 3 Div 3, Water Act); declaration of a protected area, such as a national park, over areas important to protect the relevant GDEs (though this would not, of itself, constrain groundwater pumping due to the siloed nature of Australian water law, which separates land and water management); or even special-purpose legislation with the potential to integrate land and water management across the whole catchment, as has been advanced in relation to other urban rivers in Victoria (Nelson 2020).