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1. Introduction

As the world’s largest distributed source of fresh water, groundwater plays an increasingly important role in supplying water for human needs (Taylor et al 2013). Globally, groundwater accounts for approximately a third of all water withdrawals and nearly half of water used to grow food (UNESCO 2003, Siebert et al 2010, Famiglietti 2014). In some regions, groundwater abstraction has led to excessive depletion (Konikow and Kendy 2005, Wada et al 2010) and questions have been raised about the environmental cost of ever increasing abstraction. These can include rapidly declining groundwater levels, degraded water quality, salt-water intrusion, land subsidence, and impacts to surface water flows and groundwater dependent ecosystems. Global proliferation of such impacts, combined with the threat that some of this degradation is irreversible, has led to concerns that a global groundwater crisis is emerging (Foster et al 2013, Famiglietti 2014).

To reduce, and even reverse, this trend, policies and practices that guide the use and management of groundwater towards more sustainable outcomes are critical. In many regions of the world, policies and practices guiding sustainable groundwater development lag behind the relatively recent (post 1940s) explosion in groundwater use. Knowledge is one barrier (Mukherji and Shah 2005, Theesfeld 2010), although there is often sufficient knowledge to begin to take appropriate action. The nature of policy formation and social practice in relation to groundwater compounds the challenges of managing groundwater sustainably.

Interactions across science, policy, and practice interfaces are particularly important for groundwater. Knowledge production, policy, and practice are social processes, moderated by the individuals, norms, and structures involved both in transmitting and perceiving information as well as in decision-making (Saarela et al 2015, van Enst et al 2017). Yet the attributes of groundwater, as described in table 1, complicate these interactions. Science-policy-practice pathways are complicated by the invisibility of groundwater, the dispersed nature of its users and use, and its physical complexity (Moench 2004). Uncertainty and fraught social dynamics regarding entitlements and externalities also influence the interplay between science, policy and practice in groundwater systems (Molle et al 2018).

This ERL focus collection seeks to improve understandings of the science-policy-practice interface for groundwater systems. To do so, we bring together several articles examining differing aspects of the science-policy-practice interface. This effort is simply a beginning, and, as described below, additional research is needed to more fully delineate how science, policy, and practice interact in ways that promote more sustainable use of groundwater resources.

2. Groundwater and the science-policy-practice interface

The relationship between science and policy, as well as between knowledge and practice, has been a topic of great scholarly interest. From a strictly rational perspective, science has the potential to influence policy across all stages of the policy cycle, ranging from agenda setting, policy formulation, to implementation and evaluation. Yet the production and use of science is not fully rational or objective. The worldviews, perspectives, and at times, interests of the individuals and organizations producing science feed into the framing, design and implementation of research, as well as the interpretation and presentation of results (van den Hove 2007, Sarkki et al 2014, Saarela et al 2015). Decision-makers also manage the production, reproduction, presentation and use of science, and can use science selectively to support or advance policies or conversely, to delay or avoid action (Saarela et al 2015). Further, science and policy do not always directly translate into practice. Practice may rely on informal, rather than scientific knowledge. Practice may also diverge from policy and...
Table 1. Key attributes of groundwater in relation to science, policy, & practice.

**Science**
- Groundwater flows underground within pore spaces and fractures in rocks—and the resource is therefore hidden.
- Groundwater is widespread, and its total volume is 100 times more than water found in rivers and lakes.
- The natural quality of groundwater is generally high, although arsenic, fluoride, salinity and other contaminants can be concerns some areas.
- Variations in climate and land use affect the quantity and chemistry of recharge to the groundwater systems and groundwater and surface water are closely coupled.
- The subsurface is highly heterogeneous and anisotropic. Groundwater flow patterns are highly complex and not often fully understood or predictable.
- Groundwater flows slowly from recharge areas to discharge in rivers, lakes, or abstraction boreholes and generally responds in times scales of years, decades, centuries and millennia.

**Policy**
- Extensive use of groundwater is a relatively new phenomena (post 1940s), consequently, relative to surface water, fewer laws, regulations and policies exist governing groundwater.
- Jurisdiction over groundwater is often not fully defined. Jurisdiction is also sometimes overlapping. Multiple levels of government (national, state, local, community) have the potential to set or oppose policies.
- Groundwater rights are often not fully defined.
- Groundwater is tightly intertwined with surface water and land use, thus there is a need for integration of policies across all three areas.
- Groundwater use and management affects economics, ecosystems, livelihoods and development. Policy-makers must address tradeoffs across varying uses and users.
- Policy-makers frequently do not have technical training or knowledge of groundwater systems.
- Strong interests intervene to influence groundwater policy-making processes.

**Practice**
- Groundwater is a common-pool resource. Exclusion of users is difficult and the use of it affects all users (subtractable).
- Groundwater users are widely dispersed and have individual access to the resource.
- Groundwater can be developed relatively cheaply and progressively with lower capital investment than many surface water schemes.
- There are frequently strong cultural and epistemological differences across competing users of groundwater.
- Knowledge of groundwater is often based on experience or societal norms, rather than scientific analysis.
- Groundwater may be the only feasible source of water available.
- In many areas, social norms regarding use, ownership, have emerged.

occurs even in the absence of policy. Consequently, science, policy, and practice may or may not work together in concert.

A variety of veins of inquiry and associated theoretical lenses have been applied to examine the intersection between science, policy, and practice. Studies have investigated: what makes science useful and useable (see e.g. Cash et al 2002, Sarewitz and Pielke 2007, Mcnie 2007, Kirchhoff et al 2013); how user perceptions, institutional culture, and the frameworks used for decision-making, influence uptake and use of science (see e.g. Rayner et al 2005, Lemos 2008, Weichselgartner and Kasperson 2010); the role of boundary organizations in the science-policy interface (see e.g. Guston 2001, van Kerkhoff and Lebel 2006, Huitema and Turnhout 2009); and possibilities for, and value of, the co-production of knowledge (see e.g. Jasano, Brugnach 2007, Dunn et al 2007, Bukowski 2017, Koontz and Thomas 2018), to date, the nuances of this interface as it relates to groundwater has received scant attention. The vast majority of research on groundwater is rooted in the physical
sciences, examining flows and chemistry of water through the sub-surface. Research on groundwater science, however, does not occur in a vacuum, and much of it seeks not only to provide new scientific understandings, but also to inform policy and practice. For example, water chemistry studies seek to help inform policy on contamination or use (see e.g. Foster et al 1982, Nickson et al 2000); studies of water storage changes (see e.g. MacDonald et al 2016, Rodell et al 2018) and detailed modeling studies (see e.g. Scanlon et al 2012) seek to influence current and future abstraction and managed recharge. How this research translates into action, remains poorly understood. Clearly, the answer varies by science product, yet overall, there is a dearth of research that investigates the comprehension and use of findings from groundwater research by policy makers or groundwater managers or how those studies have led to changes in practices of water users.

Substantial research has also examined groundwater from the perspective of policy and practice. This work stems from varying disciplines, including economics, political science, geography, sociology and anthropology. Research in this vein investigates and makes recommendations regarding policies and governance structures for managing groundwater (see e.g. Foster and Garduño 2012, Dellapenna 2013, Varady et al 2013b, Foster et al 2015, Closas and Villholth 2020) including consideration of the economics of groundwater use and the use and implementation of groundwater markets (see e.g. Singh 2007, Green Nylen et al 2017). Scholars of policy and practice also directly engage with the power and politics of groundwater (see e.g. Molle et al 2018), among other topics. This research on policy and practice in relation to groundwater provides important insights to guide and explain both, yet this literature generally includes cursory, if any analysis of their interface with science.

Only a smaller, and still emerging, body of research has examined explicitly interactions across science, policy, and practice in groundwater. One focus of this literature is on the politics of knowledge in groundwater systems. For example, three papers, each examining groundwater management in a different setting, describe the ways in which uncertainty about the groundwater system and sustainable limits allows for government agencies and stakeholders to justify or support their desired policies (Milman and Ray 2011, Myriam et al 2018, Lictevout and Faysses 2018). Another focus of this literature is on the potential for benefit of collaborative science-based processes to contribute to groundwater management (see e.g. Megdal and Scott 2011, Varady et al 2013a), although such processes cannot fully overcome differences in societal values regarding groundwater use (Steinman et al 2011). Lastly, we know of one paper that has examined the impact of making groundwater data transparent, and specifically the use, usefulness, and useability of a portal designed to communicate groundwater data to interested stakeholders (Dahlhaus et al 2015).

While this emerging body of knowledge is important, the need for expanding understandings of the science-policy-practice interface for groundwater is considerable. There have been notable examples of where groundwater science has underpinned policy and practice, but little reflection on this process. For example, decades of research into nitrate leaching into groundwater eventually led to the Nitrates and then Water Framework Directive in the European Union. Evidence of falling water tables in the High Plains Aquifer in the US led to changes in water law in Kansas; and research into the interconnectivity of the Western Basin Aquifer across Israel and the West Bank led to policies of tight restriction on groundwater use. There are many more examples, which together could form a rich evidence base for examining how the evolution of scientific evidence has been taken and used to develop policy or inform practice.

3. Contributions of the focus articles

The contributions in this special issue begin to develop new understandings of the science-policy-practice interface for groundwater. Each paper examines groundwater in a different region of the world and focuses on a different interaction between science, policy and practice.

Two papers in this issue examine responses to an absence of both science and policy. Lapworth et al (2018) depict collective action by states, agencies and researchers in the European Union seeking to address potential pollution of groundwater by emerging anthropogenic organic substances. Through a voluntary initiative, stakeholders came together to develop a methodology for developing a groundwater watch list—a list of selected priority compounds for voluntary groundwater monitoring by EU member countries. This research raises two important considerations about the science-policy-practice interface for groundwater. The first is the feedback loop that exists: a lack of monitoring data can inhibit the development of water quality regulations, while concurrently, it is often regulations that motivate the collection of monitoring data. In this case, stakeholders were able to work around the loop through voluntary efforts. Yet this was made possible by existing policies and established practice—namely, the principle of voluntary data collection was embedded in the EU Water Framework and Groundwater Directives and institutional bricolage.

Healy et al (2020) examine the proliferation of boreholes in Lagos. In response to insecure access to water, there has been a rapid rise in drilling of wells by households who can afford to do so. This expansion of groundwater use occurs in the context of limited public understanding of constraints on future...
groundwater availability and assumptions about high groundwater quality. While professional drillers are aware of potential water quality and quantity risks of additional boreholes, their knowledge is not widely heard. Further, competition from unqualified drillers is leading many trained professionals to leave the market for other skilled positions, leaving practice to be shaped by limited knowledge. The insights here are about how, even where some expertise does exist, poor practice dominates in the absence of formal policy or widely available reliable knowledge about the groundwater system. Interventions may come through formal policy, or an improvement in practice through improving and widely sharing the science and knowledge base.

Even where knowledge and policy do exist, they may not always be synergistic. Owen et al (2019) analyze the challenges of correcting California’s historic treatment of surface and groundwater as separate resources. While policy-makers in California have introduced legislation that begins to correct this artificial distinction, the legacy of institutions and agencies built around managing surface and groundwater as distinct resources remain. This paper illustrates the complexities of reconciling law with science. As importantly, it highlights that laws and regulations, and the institutions that implement them, accrue and expand upon one another. The implication being that as science advances, a multitude of interconnected policies and practices must be updated to reflect the new knowledge and understandings generated.

The remaining two papers in this issue focus on the policy-practice interface. Shah et al (2018) examine the future rise in the use of solar irrigation pumps in South Asia to replace diesel and electric pumps. The promotion of these low carbon pumps as a solution to the energy and climate crisis may have the adverse effect of accelerating groundwater use and further depleting groundwater by removing what controls the government has in restricting electricity supply and diesel taxation. Whaley et al (2019) examine the evidence for the effectiveness of community based management (CBM) of wells in Ethiopia, Malawi, and Uganda. CBM has become a widely prescribed paradigm for managing water resources where formal policy via the state is either impracticable or absent. Whaley et al’s analysis of six hundred villages shows there is no strong relationship between CBM capacity and borehole functionality. In essence, the paper demonstrates persistence of a policy without strong evidence of how that policy translates into practice, and discusses other reasons for the persistence the policy. Another key take away is the tendency to view governance as the solution, without sufficient science about governance.

Lastly, in an ERL Reviews paper, Elshall et al (2020) examine the topic of sustainable yield, which is generally conceptualized as the groundwater withdrawal that can be sustained over the long-term while meeting environmental, social and economic needs. This paper explains the complexity of quantifying a concept that intrinsically combines science and societal values and using that concept for management. A central insight from Elshall et al (2020) is that coevolution of the social and the biophysical state of groundwater, science and policy are intimately interconnected. While the science required to capture the dynamics and complexity of hydrogeology and its dependent ecological and human systems is only beginning to be established, the authors also argue that participatory approaches that integrate science with policy when defining the objectives for policy and management decisions are necessary to truly represent the complex relationship between humans and the groundwater systems being governed.

4. Conclusions

The papers in this focus issue make a small contribution towards filling the gap in knowledge about the science-policy-interface for groundwater. While individually, each focuses on a different aspect of the interface, a common theme is that in none of the empirical cases examined in the papers are science, policy and practice fully aligned, and in most, at least one of either science or policy is lacking. Many other examples of the interaction of science, policy and practice exist for groundwater, and could provide a rich vein of material for future research. Issues to examine include:

(a) How new technologies for examining aquifers or monitoring groundwater are being incorporated into policy or changing policy practices;
(b) How advancements in knowledge and/or the production of knowledge in groundwater systems are driven by or arise in response to policy;
(c) How policy adjusts or responds to uncertainty about groundwater systems and the long time frames of response;
(d) How groundwater practice evolves with scientific knowledge in the absence of strong policy or regulation;
(e) The processes and factors that influence how groundwater policy is implemented;
(f) How policy and practice advance given the slow and incremental pace in increasing understanding of groundwater systems.

Use of and reliance on groundwater is increasing worldwide. If we, as a planet, are to avoid the negative, (possibly permanent) impacts of groundwater depletion, policies and practices will have to be shifted to support sustainability. Policies and practices that ensue in the absence of accurate understanding of the groundwater system may have unintended or unanticipated effects. Advances in technology as well as
increased monitoring, can help develop better understandings of groundwater systems, yet for that knowledge to be used in policy, we need to understand the dynamics of science-policy interfacing. This includes learning what makes groundwater science usable, useful, and accepted for guiding policy and practice, as well as what can catalyze the production and the use of that information. It also includes developing better understandings of how policy affects practice—and the role of science that process. Further, we need to understand how practice evolves and in turn affects the development of knowledge as well as policy processes. The papers in this themed issue take initial steps at developing these understandings and point to areas where further research is essential for making progress in ensuring science, policy and practice work together synergistically to support groundwater sustainability.

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Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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