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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	<ul style="list-style-type: none"> ▪ 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	<ul style="list-style-type: none"> ▪ 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	<ul style="list-style-type: none"> ▪ 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 Kaspersen 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. Jasanoff 2004, Lemos and Morehouse 2005, Armitage *et al* 2015), among a variety of other topics. ‘Critical’ scholars have examined the discursive nature of science, illuminating when and how knowledge becomes a political tool (see e.g. Budds 2009, Wesselink *et al* 2013).

While a growing body of literature has examined the science-policy-practice interface as it relates to water (see e.g. Brugnach 2007, Dunn *et al* 2017, 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, Lictévout and Faysse 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 useable, 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 future 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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References

- Armitage D *et al* 2015 Science–policy processes for transboundary water governance *Ambio* **44** 353–66
- Brugnach M 2007 Uncertainty matters: computer models at the science-policy interface *Water Resour. Manag.* **21** 1075–90
- Budds J 2009 Contested H₂O: science, policy and politics in water resources management in Chile *Geoforum* **40** 418–30
- Bukowski J J 2017 The science-policy interface: perceptions and strategies of the Iberian ‘new water culture’ expert community *Water Alternatives* **10** 1–21
- Cash D, Clark W, Alcock F, Dickson N, Eckley N and Jager J 2002 *Saliency, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making* (Cambridge, MA: Research Programs, John F. Kennedy School of Government, Harvard University)
- Closas A and Villholth K G 2020 Groundwater governance: addressing core concepts and challenges *WIREs Water* **7** e1392
- Dahlhaus P, Murphy A, Macleod A, Thompson H, Mckenna K and Ollerenshaw A 2015 Making the invisible visible: the impact of federating groundwater data in Victoria, Australia *J. Hydroinform.* **18** 238–55
- Dellapenna J W 2013 Thinking about the future of global water governance *Confronting Ecological and Economic Collapse: Ecological Integrity for Law, Policy and Human Rights* (London: Routledge) pp 120–31
- Dunn G, Brown R R, Bos J J and Bakker K 2017 The role of science-policy interface in sustainable urban water transitions: lessons from Rotterdam *Environ. Sci. Policy* **73** 71–79
- Elshall A S, Arik A D, El-Kadi A I, Pierce S, Burnett K, Wada C and Chun G 2020 Groundwater sustainability: a review of the interactions between science and policy *Environ. Res. Lett.* accepted <https://doi.org/10.1088/1748-9326/ab8e8c>
- Famiglietti J S 2014 The global groundwater crisis *Nat. Clim. Chang.* **4** 945–8
- Foster S, Bath A, Farr J and Lewis W 1982 The likelihood of active groundwater recharge in the Botswana Kalahari *J. Hydrol.* **55** 113–36
- Foster S, Chilton J, Nijsten G-J and Richts A 2013 Groundwater—a global focus on the ‘local resource’ *Current Opinion Environ. Sustain.* **5** 685–95
- Foster S, Evans R and Escolero O 2015 The groundwater management plan: in praise of a neglected ‘tool of our trade’ *Hydrogeol. J.* **23** 847–50
- Foster S and Garduño H 2012 Groundwater-resource governance: are governments and stakeholders responding to the challenge? *Hydrogeol. J.* **21** 317–20
- Green Nylen N, Kiparsky M, Archer K, Schneir K and Doremus H 2017 *Trading Sustainably: Critical Considerations for Local Groundwater Markets under the Sustainable Groundwater Management Act* (UC Berkeley: Berkeley California) (https://www.law.berkeley.edu/wp-content/uploads/2017/06/CLEE_Trading-Sustainably_2017-06-21.pdf)
- Guston D H 2001 Boundary organizations in environmental policy and science: an introduction *Sci. Technol. Human Values* **26** 399–408
- Healy A, Upton K, Capstick S, Bristow G, Tijani M, MacDonald A M, Goni I, Bukar Y, Whitmarsh L E and Theis S 2020 Domestic groundwater abstraction in Lagos, Nigeria: a disjuncture in the Science-Policy-Practice Interface? *Environ. Res. Lett.* **15** 045006
- Huitema D and Turnhout E 2009 Working at the science–policy interface: a discursive analysis of boundary work at the Netherlands Environmental Assessment Agency *Env. Polit.* **18** 576–94
- Jasanoff S 2004 *States of Knowledge: The Co-production of Science and the Social Order* (London: Routledge)
- Kirchhoff C J, Lemos M C and Dessai S 2013 Actionable knowledge for environmental decision making: broadening the usability of climate science *Annu. Rev. Environ. Resour.* **38** 393–414
- Konikow L F and Kendy E 2005 Groundwater depletion: A global problem *Hydrogeol. J.* **13** 317–20
- Koontz T M and Thomas C W 2018 Use of science in collaborative environmental management: evidence from local watershed partnerships in the Puget Sound *Environ. Sci. Policy* **88** 17–23
- Lapworth D J, Lopez B, Laabs V, Kozel R, Wolter R, Ward R, Vargas-Amelin E, Besien T, Claessens J and Delloye F 2018 Developing a groundwater watch list for substances of emerging concern: a European perspective *Environ. Res. Lett.* **14** 035004
- Lemos M C 2008 What influences innovation adoption by water Managers? Climate information use in Brazil and the United States *J. Am. Water Resour. Assoc.* **44** 1388–96
- Lemos M C and Morehouse B J 2005 The co-production of science and policy in integrated climate assessments *Global Environ. Change* **15** 57–68
- Lictevout E and Faysse N 2018 A doubly invisible aquifer: hydrogeological studies and actors’ strategies in the Pampa del Tamarugal aquifer, northern Chile *Water Alternatives* **11** 592–606
- MacDonald A, Bonsor H, Ahmed K, Burgess W, Basharat M, Calow R, Dixit A, Foster S, Gopal K and Lapworth D 2016 Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations *Nat. Geosci.* **9** 762–6

- Mcnie E 2007 Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature *Environ Sci. Policy* **10** 17–38
- Megdal S B and Scott C A 2011 The importance of institutional asymmetries to the development of binational aquifer assessment programs: the Arizona-Sonora experience *Water* **3** 949–63
- Milman A and Ray I 2011 Interpreting the unknown: uncertainty and the management of transboundary groundwater *Water Int.* **36** 631–45
- Moench M 2004 Ground water: the challenge of monitoring and management *The World's Water 2004–2005: The Biennial Report on Freshwater Resources*, ed P Gleick (London: Island Press) pp 79–100
- Molle F, Elena L-G and Frank van S 2018 The local and national politics of groundwater overexploitation *Water Alternatives* **11** 445–57
- Mukherji A and Shah T 2005 Groundwater socio-ecology and governance: a review of institutions and policies in selected countries *Hydrogeol J.* **13** 328–45
- Myriam S-S, Asaad A H, Omar S, Zwahlen F and Jaubert R 2018 Groundwater balance politics: aquifer overexploitation in the Orontes River Basin *Water Alternatives* **11** 663–83
- Nickson R, Mcarthur J, Ravenscroft P, Burgess W and Ahmed K 2000 Mechanism of arsenic release to groundwater, Bangladesh and West Bengal *Appl. Geochem.* **15** 403–13
- Owen D, Cantor A, Nylen N G, Harter T and Kiparsky M 2019 California groundwater management, science-policy interfaces, and the legacies of artificial legal distinctions *Environ. Res. Lett.* **14** 045016
- Rayner S, Lach D and Ingram H 2005 Weather forecasts are for wimps: why water resource managers do not use climate forecasts *Clim. Change* **69** 197–227
- Rodell M, Famiglietti J, Wiese D, Reager J, Beaudoin H, Landerer F W and Lo M-H 2018 Emerging trends in global freshwater availability *Nature* **557** 651–9
- Saarela S-R, Söderman T and Lyytimäki J 2015 Knowledge brokerage context factors – what matters in knowledge exchange in impact assessment? *Environ Sci. Policy* **51** 325–37
- Sarewitz D and Pielke R Jr. 2007 The neglected heart of science policy: reconciling supply of and demand for science *Environ Sci. Policy* **10** 5–16
- Sarkki S, Niemelä J, Tinch R, van den Hove S, Watt A and Young J 2014 Balancing credibility, relevance and legitimacy: a critical assessment of trade-offs in science-policy interfaces *Sci. Public. Policy* **41** 194–206
- Scanlon B R, Faunt C C, Longuevergne L, Reedy R C, Alley W M, Mcguire V L and McMahon P B 2012 Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley *Proc. Nat. Acad. Sci.* **109** 9320–5
- Shah T, Rajan A, Rai G P, Verma S and Durga N 2018 Solar pumps and South Asia's energy-groundwater nexus: exploring implications and reimagining its future *Environ. Res. Lett.* **13** 115003
- Siebert S, Burke J, Faures J-M, Frenken K, Hoogeveen J, Döll P and Portmann F T 2010 Groundwater use for irrigation—a global inventory *Hydrology Earth Syst. Sci.* **14** 1863–80
- Singh D 2007 Who gains and who loses in the game of groundwater markets in water-scarce regions *Agric. Econ. Res. Rev.* **20** 345–60
- Steinman A D, Nicholas J R, Seelbach P W, Allan J W and Ruswick F 2011 Science as a fundamental framework for shaping policy discussions regarding the use of groundwater in the State of Michigan: a case study *Water Policy* **13** 69–86
- Taylor R G, Scanlon B, Döll P, Rodell M, Van Beek R, Wada Y, Longuevergne L, Leblanc M, Famiglietti J S and Edmunds M 2013 Ground water and climate change *Nat. Clim. Chang.* **3** 322–9
- Theesfeld I 2010 Institutional challenges for national groundwater governance: policies and issues *Ground Water* **48** 131–42
- UNESCO 2003 *Water for People, Water for Life: A Joint Report by the Twenty-three UN Agencies Concerned with Freshwater. World Water Assessment Programme* (Paris, France: UNESCO)
- van den Hove S 2007 A rationale for science-policy interfaces *Futures* **39** 807–26
- van Enst W, Driessen P and Runhaar H 2017 Working at the boundary: an empirical study into the goals and strategies of knowledge brokers in the field of environmental governance in the Netherlands *Sustainability* **9** 1962–76
- van Kerkhoff L and Lebel L 2006 Linking knowledge and action for sustainable development *Annu. Rev. Environ. Resour.* **31** 445–77
- Varady R G, Scott C A, Wilder M, Morehouse B, Pablos N P and Garfin G M 2013a Transboundary adaptive management to reduce climate-change vulnerability in the western U.S.–Mexico border region *Environ Sci. Policy* **26** 102–12
- Varady R G, van Weert F, Megdal S B, Gerlak A K, Iskandar C A and House-Peters L 2013b *Thematic Paper No. 5 Groundwater Policy and Governance* (<http://www.groundwatergovernance.org/resources/thematic-papers/en/>)
- Wada Y, Van Beek L P H, Van Kempen C M, Reckman J W T M, Vasak S and Bierkens M F P 2010 A worldwide view of groundwater depletion *Geophys Res. Lett.* **37** L20402
- Weichselgartner J and Kasperson R 2010 Barriers in the science-policy-practice interface: toward a knowledge-action-system in global environmental change research *Global Environ. Change* **20** 266–77
- Wessselink A, Buchanan K S, Georgiadou Y and Turnhout E 2013 Technical knowledge, discursive spaces and politics at the science-policy interface *Environ Sci. Policy* **30** 1–9
- Whaley L, Macallister D J, Bonsor H, Mwathunga E, Banda S, Katusiime F, Tadesse Y, Cleaver F and MacDonald A 2019 Evidence, ideology, and the policy of community management in Africa *Environ. Res. Lett.* **14** 085013