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KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

PERSPECTIVE

Science–policy processes for transboundary water governance

Derek Armitage, Rob C. de Loë, Michelle Morris, Tom W. D. Edwards, Andrea K. Gerlak, Roland I. Hall, Dave Huitema, Ray Ison, David Livingstone, Glen MacDonald, Naho Mirumachi, Ryan Plummer, Brent B. Wolfe

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Abstract In this policy perspective, we outline several conditions to support effective science–policy interaction, with a particular emphasis on improving water governance in transboundary basins. Key conditions include (1) recognizing that science is a crucial but bounded input into water resource decision-making processes; (2) establishing conditions for collaboration and shared commitment among actors; (3) understanding that social or group-learning processes linked to science–policy interaction are enhanced through greater collaboration; (4) accepting that the collaborative production of knowledge about hydrological issues and associated socioeconomic change and institutional responses is essential to build legitimate decision-making processes; and (5) engaging boundary organizations and informal networks of scientists, policy makers, and civil society. We elaborate on these conditions with a diverse set of international examples drawn from a synthesis of our collective experiences in assessing the opportunities and constraints (including the role of power relations) related to governance for water in transboundary settings.

Keywords Adaptation · Collaboration · Environment · Governance · Sustainability · Transboundary water management

INTRODUCTION

Climate change will exacerbate already severe pressure on freshwater resources from agriculture, industry, and growing urban populations (Vörösmarty et al. 2000; Milly et al. 2008). Globally, significant changes in river flow have already been observed, while projected changes in river flow under different climate and water withdrawal scenarios point to significantly increased water stress in many jurisdictions (Palmer et al. 2008; MacDonald 2010; Grafton et al. 2013).

Many of these changes are occurring in transboundary basins, which add to the complexity of problem analysis and identification of effective responses in these key systems (Pahl-Wostl et al. 2013). About 45 % of the Earth's land surface is covered by 276 river basins shared by more than one country (De Stefano et al. 2012). Transboundary basins at subnational levels number in the thousands. Hundreds of transboundary aquifers present even more challenging settings for governance (UNESCO 2009).

Barriers to effective water governance in transboundary settings are significant, and include power imbalances, inadequate attention to rapidly changing biophysical conditions, and a growing array of social actors with a stake in decision making (Zeitoun et al. 2013). Integrating different forms of knowledge—e.g., scientific, local, indigenous, bureaucratic (Edelenbos et al. 2011)—has emerged as a key determinant of governance success (Karl et al. 2007). Scientific knowledge—which for our purpose refers to knowledge about social and natural phenomena that has been generated by people using scientific methods—has long been considered authoritative. However, this is changing. It is now widely accepted that scientific knowledge alone is not sufficient for dealing with complex environmental issues (Lejano and Ingram 2009). At the same time, the gulf that often exists between "decision makers" and scientists can be wide (Cash et al. 2003). Recognition of this fact accounts for the enormous amount that is being written about strategies to improve science–policy interaction (e.g., Roux et al. 2006; Karl et al. 2007; Pielke 2007; Ascher et al. 2010; Kasperson and Berberian 2011).

Without diminishing the importance of other forms of knowledge, scientific knowledge clearly remains central to addressing current and emerging water challenges. The

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barriers to effective science–policy interaction for transboundary water governance are many and can include military and security issues unrelated to water resources, pressures associated with exploitation of resources of economic value (including water), imbalances of power among and between decision makers and societies (see discussion below), and the self-interest of upstream stakeholders over those downstream (Zeitoun and Warner 2006; Zeitoun et al. 2013). Other political challenges to science–policy interactions for transboundary water governance include allocating the high costs of organizing and sharing data and information, disagreements about the accuracy and acceptability of existing baseline data, and the use of data or information as a 'weapon' in directing blame toward particular actors in a transboundary setting (Turton et al. 2003; Timmerman and Langaas 2004; Grossmann 2006).

In this brief perspective, we identify five important conditions that—on the basis of our combined expertise—can be identified as supportive of effective science–policy interactions. The key conditions we emphasize include (1) recognizing that science is a crucial but bounded aspect in water resource decision-making processes; (2) establishing initial conditions and shared commitment among actors; (3) understanding that social or group learning processes linked to science–policy interaction are enhanced through greater collaboration; (4) accepting that the collaborative production of knowledge about hydrological and associated socioeconomic change and institutional responses is essential to build legitimate decision-making processes; and (5) engaging boundary organizations and supporting informal networks of scientists, policy makers and civil society.

Our arguments emerge from our collective international experience and extensive knowledge with science–policy processes in a wide range of transboundary basin settings. During the past decade, we have worked on a range of natural and social science studies in a variety of river basins, including most of the basins from which examples used in this paper are drawn (see Table 1). To catalyze this synthesis of conditions, we met as a group in 2012 for a symposium and workshop to refine our perspectives on the key conditions presented here. We do not claim this list of conditions to be the final word. However, they resonate with experiences in the literature in a host of environmental contexts. The value they add comes from the way they are grounded in transboundary basin settings where institutional conditions for governance and effective science–policy interactions are highly complex.

CHALLENGES FOR EFFECTIVE SCIENCE–POLICY INTERACTION

How science–policy processes can be enhanced to improve decisions about water (and other resources) is a topic of much debate within the environmental science and policy communities, and broad agreement exists around some key principles. For instance, scientists are often encouraged to better communicate risk and uncertainty to non-scientific audiences, and policy makers are urged to use the best available scientific evidence (Guston 2004; Pielke 2007; Toderi et al. 2007). Overcoming disciplinary isolation is also recognized as a priority (Kasperson and Berberian 2011).

A host of factors makes effective science–policy integration challenging in most water decision-making contexts, and especially in those involving more than one jurisdiction. Institutional fragmentation across jurisdictions, unequal power among basin actors in different jurisdictions, a potential for high levels of political conflict, and differences in a culture of decision making contribute to 'wicked' (or 'super-wicked') problem contexts (see Levin et al. 2012), and can undermine efforts to make the science–policy interface work better. Here, we refer to wicked problems as those types of problems that are very difficult (and perhaps impossible) to resolve because they are characterized by strong interconnections and high degrees of uncertainty, incomplete information or contradictory understandings, and value conflicts (see Rittel and Webber 1973).

Sutherland et al. (2013) recently synthesized twenty suggestions or 'tips' to improve the integration of science in political decision making, with a focus on policy makers' understanding of the imperfect nature of science. The list is helpful but ultimately application of the ideas requires a social context in which scientists, policy makers and others attempting to and engaged in governing can actually interact and deliberate. This social context includes the diverse norms and values among the constellation of actors in a water decision-making process (e.g., industry groups, aboriginal communities) as well as differences in power and authority among those individuals and organizations (see below). These constraints have material consequences, and, as a result, uptake of suggestions to improve integration of science in political decision making in real-world settings will continue to be slow unless the social and institutional context for science–policy interactions in transboundary water governance is accounted for and, where inadequate, improved. The conditions we highlight in this perspective are a key part of these improvements.

Doing and using science differently requires reflecting on what science is being used for; understanding how results will be mobilized and by whom; overcoming fragmentation among organizations and the knowledge used to inform decisions; recognizing the social and political aspects of science–policy practices; and accounting for multiple framings of problems and solutions (Roux et al.

Table 1 Overview of selected transboundary water basin science–policy successes and challenges

Transboundary basin	Key issues, successes, and challenges
Colorado	*Issues*
Drainage area: 640 000 km^2	Over-allocation, anticipated increased duration, and severity of drought, growing population, and demand for water
River length: 2334 km	*Successes*
Average annual natural flow: 641 m^3/s	Emerging *network* of science, government, and non-government actors that has facilitated research coordination for the lower Colorado River
Average annual actual flow, measured at the southern international border: 75.3 m^3/s	Increased deliberation and collaboration focused on critical needs relating to environmental flow and allocation reflecting key concerns and illustrating new opportunities for using different types of *knowledge* and opportunities for *learning* among different actors
Population: 40 million	*Challenges*
Jurisdictions: 10 (international)	Establishing formal, long-term processes for stakeholder engagement that sustain collaboration and knowledge sharing through time
	Balancing competing values about water use among upstream and downstream users with different levels of *power*
Mackenzie	*Issues*
Drainage area: 1.8 million km^2	Anticipated flow reductions, existing and proposed hydroelectric development, and increased human demand for water from industry; anticipated increases of pollution from oil sands mining and processing; Aboriginal populations and competing values about water use
River length: 4241 km	*Successes*
Average annual flow: 9910 m^3/s	Development of multistakeholder monitoring partnerships that proactively link communities, researchers, and governments and that have built upon existing *informal networks*
Population: 397 000	Strong emphasis in basin on incorporating science and traditional *knowledge* in decision making
Jurisdictions: 7 (subnational)	Innovative measures to create *positive conditions early on* for decision-making processes by embedding credible scientists on land and water boards
	Challenges
	Developing and implementing effective, long-term inter-jurisdictional and trans-jurisdictional water management agreements given significant power asymmetries and competing interests among jurisdictions
	Developing science–policy processes that reflect local considerations in the broader water-stewardship context
	Capacity building among traditional knowledge-based actors and under circumstances where there are historical and continued distrust among government agencies, industries, southern-based scientists and local and Aboriginal organizations
Mekong	*Issues*
Drainage area: 760 000 km^2	Existing and proposed hydroelectric facilities, asymmetric cooperation among basin states, and the role of the Mekong River Commission (convened by Laos, Thailand, Cambodia, and Vietnam), poverty and economic development pressures
Average annual flow: 14 500 m^3/s	*Successes*
River length: 4909 km	Emergence of civil society-based *network* using action-based research to inform and open-up decision making vertically and horizontally
Population: 70 million	Potential for alternative track to the official interstate negotiations given role of Mekong River Commission as *boundary organization,* i.e., connecting actors through *shadow* networks
Jurisdictions: 6 (international)	*Challenges*
	Capacity building for the development of different kinds of *knowledge* held by various stakeholders and ways to include them in the decision-making process—*science as one input* to decision-making processes can preclude the views and inputs of more marginalized communities in Mekong context
	Addressing hydropower projects that are not necessarily state-led projects but in the form of public–private partnerships and build–own (–operate)–transfer schemes—these initiatives may emerge in the absence of legitimate and transparent processes and undermine *initial conditions* needed for collaboration among science, policy, and community actors

Table 1 continued

Transboundary basin	Key issues, successes, and challenges
Murray–Darling	*Issues*
Drainage area: 1 064 469 km^2	Water quantity and water quality, flow fragmentation, historical over-allocation, ecological rehabilitation; effective implementation and adaptation of a new whole-of-basin plan in conditions where 'co-operative Federalism' is breaking down once more
Average annual natural flow: 409 m^3/s	*Successes*
Average annual actual flow: 161 m^3/s	Institutionalization of environmental flows and Federal and State offices of an Office of Environmental Water Holder help create *initial conditions for better decisions* over the longer term
River length: Darling 2740 km	Scientific input into the Water Basin Plan and evaluative reviews conducted by the former National Water Commission illustrates effective *learning* given past gaps in linking scientific inputs into formal decision making
Murray 2530 km	Market mechanisms employed for buyback of over-allocated water reflect awareness of need for diverse solutions and perspective (i.e., industry) and also reflect increased awareness that *science is ultimately one input*
Population: 2.1 million	Trading of water rights and/or allocations has expanded economic opportunity for irrigators and increased options for environmental buyback
Jurisdictions: 5 (subnational)	*Challenges*
	Sustaining effective river governance across all sub-catchments in the face of state and regional institutional diversities and lack of security of funding to local organisations reflecting an inability to forge a coherent *network* to support science and policy
	Future national policy setting is uncertain with the demise of the National Water Commission which was charged with oversight of delivery of the National Water Initiative suggesting some important *initial conditions* for collaboration and science–policy interaction are not in place
	Uncertain implementation and adaption of the National Plan in the face of climate change and potential institutional failure indicating science inputs will need enhanced institutional networks and institutionalization of *learning* through change
Orange-Senqu	*Issues*
Drainage area: 896 368 km^2	Flow fragmentation, declining water quality and variability of quantity, ecological health, human and financial capacity constraints; and major challenges related to collection of data needed to make decisions
Average annual flow: 364 m^3/s	*Successes*
River length: 2200 km	Institutionalized body (Orange-Senqu River Commission: ORASECOM) established in 2000, which has the potential to serve as *boundary organization* and encourage opportunities for learning
Population: 19 million	Joint Water Quality Baseline Survey conducted by a joint research team of scientists from each of the member states as well as members from the ORASECOM enhanced efforts to bridge perspective and *knowledge* needed to measure key ecological components and function as a baseline against future 5-year surveys
Jurisdictions: 5 (international)	*Challenges*
	Despite the presence of an important boundary organization (i.e., the Commission), limited success establishing public participation processes that are sustainable and feed into decision-making process has limited opportunities for meaningful *learning* and efforts to build vertical and horizontal *networks*
Danube	*Issues*
Drainage area: 801 463 km^2	Pollution, flood protection/prevention, and ecological rehabilitation (e.g., delta)
Average annual flow: 6550 m^3/s	*Successes*
River length: 2857 km	Long-standing and institutionalized *boundary organization* (International Commission for the Protection of the Danube River) established in 1994 to build capacity to link science and policy across 19 jurisdictions
Population: 82 million	Major reductions in pollution, increased basin-wide monitoring, and regular Joint Danube Surveys to guide management actions reflect ongoing process of *knowledge co-production* and *learning*
Jurisdictions: 19 (international)	*Challenges*
	Demonstrating improvements in ecological conditions remains a challenge reflecting the need to communicate the story of success *beyond the science*
	Coordination among diverse institutions in region because of various capacities and organizational issues undermines network of actors and constrains establishment of *conditions* needed for long-term success

Sources US Department of the Interior (2012); Gerlak et al. (2013); Earle et al. (2005); Huisman et al. (2000); MRBB (2003); MRC (2010); MDBC (2003); ORASECOM (2010); Wolfe et al. (2012); Government of Canada (2010); N.B.: Over the last decade, the authors have worked on a range of natural and social science studies in all of these basins

2006; Lejano and Ingram 2009; Sutherland et al. 2013). Our experiences and the cases we draw upon for this paper demonstrate that ad hoc approaches to science–policy integration are unlikely to succeed in complex settings such as transboundary basins. The likelihood of success increases dramatically when science–policy integration processes are institutionalized, in particular, when they are incorporated into the culture, values, and structures of transboundary water governance. Multi-level networks catalyzed by a shared commitment to resolving transboundary water problems have proven to be one effective way to help scientists, policy makers and members of the communities they serve interact effectively (Sabatier et al. 2005).

The need to take into account the role of power and its manifestations in constraining, facilitating and ultimately shaping science–policy interactions informs our perspective. We suggest that scientists and policy makers must reflect more explicitly on how the social relationships and institutional structures they co-create frame, constrain and enable the agency of individuals and groups, as well as the way in which these relationships and structure have material effects (e.g., influencing the uptake of ideas, how rules and regulations are exercised). Agrawal and Ribot (1999) offer a practical way to consider power, and draw attention to the power to create rules, make decisions, ensure compliance with rules and decisions, and adjudicate resulting disputes. Moreover, within these categories and among the various actors involved (e.g., state, NGOs, industry), power may be visible, invisible and/or hidden (see Cornwall 2002). These various dimensions of power and asymmetries of power they reflect strongly influence the five conditions addressed here (Zeitoun and Warner 2006). Power asymmetries can at times be extreme in transboundary settings (Zeitoun and Mirumachi 2008), as there is always an upstream and a downstream party. Upstream parties usually have their way (see for example Conca 2005) and natural dependencies can be exacerbated by differences in economic and political clout (e.g., China's role in the Mekong region, see the discussion later). Understanding who benefits and who loses is essential in any natural resource management process (Raik et al. 2008), especially in water governance (Ingram 1990).

CONDITIONS THAT SUPPORT EFFECTIVE SCIENCE–POLICY INTERACTION IN TRANSBOUNDARY SETTINGS

In this section, we elaborate on the five conditions identified previously. The discussion is grounded in a diverse group of international transboundary settings where we have collective experience (Table 1). We recognize that there is an underlying normative assumption associated with the conditions we outline (e.g., that engaging with bridging organizations or fostering learning will yield beneficial outcomes). The five conditions we have identified here are not a panacea for what often seem to be intractable problems in transboundary settings, or for problems with roots in state sovereignty concerns or long-term historical conflicts among upstream and downstream water users. Rather, we view these conditions as a starting point to address ongoing challenges when integrating science and policy in a wide range of contexts, and as a basis to highlight the need to better understand how to create a social context for science–policy interactions. This need exists in numerous environmental contexts. Hence, the transboundary frame we use here provides a concrete setting to explore these issues.

Science as one input to policy making

Perceptions of science–policy processes as linear ignore the messy reality in which decisions are actually made (McNie 2007; Vogel et al. 2007). A wide range of actors are now involved in making decisions about water (Pahl-Wostl and Kranz 2010), and the position and the role of scientists in decision processes have changed. This trend is part of a broader shift in society toward greater citizen skepticism about science combined with the democratization of knowledge (Pielke 2007; Lejano and Ingram 2009). For scientists, these trends demand a greater willingness to work in settings where other players are helping to shape the research agenda. Scientists who work in these settings need support from governments and universities (e.g., access to databases and literature behind paywalls, flexibility to take more time to do research that involves communities), and they must be open as well to communicating their science better to a diversity of audiences. Rewards, incentives, and requirements for scientists to participate in more open, collaborative, and learning-centered processes are also needed (Ison et al. 2007; Wolfe et al. 2007). In Canada's Mackenzie Basin, for example, the Aurora Research Institute (which assigns permits to conduct scientific research in the Northwest Territories portion of the basin) has developed templates for scientists (natural and social) to use when communicating their research to communities. Implicit in this shift to share and communicate knowledge more effectively is a concern that scientific knowledge is not 'elevated' above or valued to the detriment of traditional knowledge and traditional knowledge holders which has been (and often continues to be) the case (Nadasdy 1999).

The importance of accepting that science is only one input into policy making is particularly evident in transboundary basins. Governments are—and likely always will remain—critical actors in transboundary settings because of their political authority and jurisdiction. However, it is increasingly recognized that governance in transboundary basins involves diverse government and non-government actors, and that a global shift in views about roles and responsibilities of the state is underway (Bruch et al. 2005; Cosens 2010; Akamani and Wilson 2011). Governments are being expected to transition from being primarily the holders of expertise and the main decision-making power to be also facilitators and knowledge brokers (Pielke 2007; Kasperson and Berberian 2011). However, there can be significant differences between participatory transboundary water governance and actually crafting inclusive and effective science–policy interactions that value a range of knowledge sources and types (see below).

Although not without its challenges, the increased participation by a greater array of non-government actors in transboundary settings can lead to greater legitimacy, more effective and equitable allocation of resources, a better ratio of costs to benefits, and an improved access to a diversity of knowledge and expertise (Raadgever et al. 2008), as well as broader acceptance and implementation success. For example, several ecological monitoring programs linking scientific and traditional knowledge have been developed for the Mackenzie River Basin, an enormous internal basin shared by five subnational jurisdictions within Canada. These programs create space for local and traditional knowledge holders, along with scientists, to identify monitoring priorities and to conduct monitoring that provides information about local ecosystem conditions considered as important to local communities. A recent example from this setting is the multifactor Slave River and Delta Partnership. This partnership was created to facilitate community-based monitoring in response to the concerns of aboriginal people and local residents regarding ecosystem health and to provide a mechanisms to increase the 'voice' of communities in decision making (see Box 1).

Greater participation does not always lead to acceptance and improved implementation if other conditions for success are not in place. For example, Mirumachi and Van Wyk (2010) have pointed to the risks associated with an emphasis on cooperation for inclusive, participatory water governance in South Africa and the Orange-Senqu River Basin. They suggest that processes of devolving decision-making authority and including non-state actors may simply reproduce power asymmetries, preventing meaningful empowerment and inclusion and ultimately, more equitable water governance. In such cases, participatory processes may not adequately address the underlying conflicts that constrain implementation, despite institutional frameworks set up to promote better water governance. Experiences in managing the transboundary waters of the Orange-Senqu River in particular highlight the complex political and economic contexts in which water supply and demand become contested. For example, the Orange-Senqu Water Information System has been established to collate, share, and disseminate reports and data for public use. However, the interstate political negotiations over water allocation are bound by considerations of the existing water use, highlighting that data sharing in and of itself does not address the perceived inequity (Keller 2012). Consequently, science needs to be understood as just one input in decisions about transboundary water governance and the ways in which unequal power can shape and constrain access to decision making.

Establish conditions for collaboration and shared commitment early on

Governance of complex environmental problems (such as those experienced in many transboundary basins) requires joint activities, including joint-fact-finding, from which trust-building emerges at the onset of science–policy collaborations. Building relationships to overcome perceptions about the different logics of science (e.g., primarily facts, neutrality) and policy (e.g., primarily values, interests) takes time (Huitema and Turnhout 2009), with few tangible outcomes in the initial stages (Collins and Ison 2010). However, investing time upfront in joint problem-framing and engaging policy makers and other actors (civil society groups, industry, etc.) in the knowledge production process rather than treating them as passive end users help us ensure that high initial transaction costs will yield dividends over the longer term. Early investments of time and resources are needed to create common understanding of key questions and the broader political and sociocultural contexts that frame decisions about water. Also important are regular cycles of carefully designed workshops and stakeholder meetings, getting key people engaged for the duration of the process, and ensuring that any collective achievements are institutionalized through practices, agreements, or legislation (Karl et al. 2007).

Recent experiences in Australia's Murray–Darling Basin (MDB) starkly reveal the importance of both the initial conditions and the shared commitment. The basin jurisdictions, including the Commonwealth government, demonstrated a strong commitment to jointly address the basin's water allocation problems including a significant financial investment of $A10 billion. Since 2007, a new MDB plan has emerged from an often fractious process. New institutions have been conceived and implemented such as 'environmental flows,' 'environmental water,' and the 'office of environmental water holder.' However, Wallis and Ison (2011) have argued that the structural constraints imposed on the MDB Authority by the federal *Water Act 2007*, along with the deeply rooted competing

Box 1 Science, policy, and transboundary water governance in the Mackenzie Basin, Canada

The Mackenzie River Basin (MRB) drains approximately 20% of Canada's landmass within the provinces of British Columbia, Alberta, Saskatchewan, as well as Yukon Territory, the Northwest Territories (NWT), and Nunavut. Despite being located within one country, this enormous basin is truly transboundary because of the controls these political jurisdictions have over water in Canada's federation. The MRB's headwaters begin in the Peace and Athabasca sub-basins in British Columbia and Alberta, respectively, which converge at the Peace–Athabasca Delta in Alberta. The system flows north as the Slave River into the Northwest Territories, which eventually becomes the Mackenzie River and drains into the Arctic Ocean. Upstream jurisdictions (notably Alberta) are conventionally thought of as having significantly more power than downstream jurisdictions (notably the Northwest Territories). The MRB hosts internationally—and culturally—significant deltas and wetlands that are staging and breeding grounds for a variety of migratory birds and are important to local aboriginal communities. Freshwater discharge from the Mackenzie River has a globally significant role in regulating ocean and climate systems (MRBB 2003)

Climate variability is emerging as a key driver of uncertainty in water levels and flood frequency in the deltas, and the weight of evidence points to long-term water availability decline in the upper MRB (Wolfe et al. 2012) with long-term consequences for aquatic ecosystems of global significance. The basin also figures prominently in plans for resource development in Canada, which include hydroelectric and mining projects in the Peace and Athabasca sub-basins and the potential expansion of mining and oil and gas development (including fracking) in downstream Northwest Territories. In the face of climate and development drivers, better science–policy processes to preserve environmental flows is a vital component of transboundary water governance in this basin

Foundations for better science–policy processes have emerged in several crucial ways. For example, a number of ecological monitoring programs that seek to link scientific and traditional knowledge have been developed for important parts of the MRB. The Peace–Athabasca Delta Ecological Monitoring Program (PADEMP) is an effort in knowledge co-production between federal, provincial, territorial, indigenous governments, and environmental non-governmental organizations. Participants are jointly identifying vulnerabilities and key ecological monitoring priorities in the Peace–Athabasca Delta that will be cooperatively evaluated. More recently, the Slave River and Delta Partnership (SRDP) was created to facilitate community-based monitoring in response to local concerns regarding ecosystem health. Actors involved include the federal, territorial and aboriginal governments, academic institutions, and local residents. Key outputs thus far have included improved partnerships and understanding, state of knowledge, and vulnerability-assessment reports, and a greater voice for communities in water-related decisions

The SRDP is an outcome of efforts to establish conditions for future success, including the development (and associated implementation plan) of the Northwest Territories Water Stewardship Strategy (2010), and initiatives to build science capacity into land and water management boards. For example, the Mackenzie Valley Land and Water Board has developed science-based policies and procedures that have directly resulted in wiser decisions that most observers conclude have protected ecological integrity while preserving the profitability of industrial operations. Credible decisions have also strengthened the Board's relations with government agencies and industry, and have fostered trust-building with aboriginal governments and peoples—thus contributing to its role as a bridging organization

Monitoring partnerships and other science–policy initiatives are relatively recent ventures, and their long-term success is uncertain. However, they do display some of the key characteristics of successful science–policy integration including building greater integration among scientists, policy makers, and nonstate actors (aboriginal interests in particular); emphasizing social- or group-learning processes; fostering the collaborative production of knowledge about hydrological change and the range of possible governance responses; and recognizing how science is a crucial but bounded part of the sustainability dilemma in transboundary water-governance settings. The challenge remains to institutionalize gains made in an adaptive manner and to scale-up science–policy processes for the longer term

interests among and within states, effectively guarantee that ongoing governance of the basin will be contested, and during implementation may be prone to systemic failure.

In the Danube and Orange-Senqu river basins, organizations, such as the International Commission for the Protection of the Danube River and Orange-Senqu River Commission, respectively, encourage data sharing and coordination among multiple parties (but not without its problems, as explained later on the latter basin). In the Mackenzie River Basin, the Mackenzie River Basin Board's Traditional Knowledge and Strengthening Partnership Steering Committee is identifying the best practices to incorporate local, indigenous knowledge in water management practices based on reflection and ongoing initiatives. Although capacity challenges persist, efforts to share data, develop common objectives, and institutionalize processes of knowledge exchange can contribute to improved water governance in these contexts.

High political stakes, including a potential for conflict and often unequal power relations, are common in transboundary settings such as the ones considered in Table 1. This makes the challenge to establish inclusive initial conditions for science–policy interactions all the more crucial (Paisley and Henshaw 2013). Actors on different sides of political boundaries may have competing interests, and strong reasons to avoid scientific input; they may only seek scientific input to support particular bargaining positions. In the absence of a supportive institutional framework, legitimate decision-making processes and shared framing of science can be particularly hard to achieve in transboundary basins (Pahl-Wostl and Kranz 2010).

Political commitment to cooperation, demonstrated tangibly through, for example, transfers of decision authority and resources and non-state actors involved in knowledge production processes, is also vital. This level of commitment is difficult to achieve in transboundary basins because national economic development objectives can trump the precaution required to address the scientifically and socially complex issues (Lebel et al. 2005). For example, in the case of rapid hydropower development in the Mekong River basin, national interests of basin states have undermined the ability of the Mekong River Commission (convened by Laos, Thailand, Cambodia, and Vietnam) to facilitate joint problem framing (Hirsch et al. 2006). China is not part of the Commission, but rather an observer, raising questions about the extent to which the river basin organisation can address the issue of hydropower development, some of which are going on in upstream Chinese territory. Moreover, hydropower development is operationalized by both the private sector and government in the form of public–private partnerships and build–operate–transfer schemes (Middleton et al. 2014). Understanding how national economic development objectives are forged by certain stakeholders is important. Power asymmetries and obstacles to commitment to cooperation exist not just at the international transboundary level but also within the individual basin states themselves.

Space for alternative development scenarios is reduced when national governments prioritize large hydroelectric projects to the exclusion of other possible avenues of economic development. This process is supported by macro-economic studies and cost–benefit analysis that suggest significant economic benefits from hydropower (see Flyvbjerg 2005). Alternative considerations of non-market values and the lived experiences of hydropower development do not inform such studies and approaches (Mirumachi and Torriti 2012). As a result, reports by civil society groups pointing to less desirable impacts of dams based on alternative metrics commonly count less in the decision-making process.

Learning to learn through collaboration

Shared understanding of problems and solutions is essential for dealing with complex environmental problems. Social learning is one way this can be achieved, and refers to changes in understanding that go "beyond the individual to become situated within wider social units or communities of practice through social interactions between actors within social networks" (Reed et al. 2010). Social learning processes may seem outside the remit of scientists, especially when science–policy linkages are viewed as linear. However, social learning processes can help one link policy makers, scientists, and other key actors (members of the public, non-governmental organizations, aboriginal groups) through their emphasis on communication, deliberation, and group interaction (e.g., meetings, workshops, study tours, and visits) (Scott et al. 2012). This can help stakeholders to deal with significant uncertainty and complexity, and if social learning processes are well designed (see Bos et al. 2013), they can help surface the relationships of power that must be accounted for if meaningful actions are to be taken (Armitage et al. 2009). In the MDB, salinity management programs at the regional level in New South Wales incorporated context-specific learning, community participation, and multiple types of knowledge. These programs resulted in community and government acceptance of salinity-control measures and greater awareness of salinity hazards. Unfortunately, however, governance has shifted from a community-based to state-dominated model predicated on centralization that has made institutionalizing social learning and transformative change difficult (Wallis et al. 2013) and introduced social inequities due to top-down innovation approaches for irrigation renewal (Wallis et al. 2015).

Learning to learn together ultimately requires that scientists, policy makers, and a wide range of non-state actors are open to hybrid roles and a new 'social contract' (Lubchenco 1998; Palmer 2012). In transboundary water-governance settings, barriers to social learning can exist that go beyond simply the presence of political boundaries. A desire on the part of actors in different jurisdictions to learn together may be insufficient in the face of institutional rigidity often created by less-flexible treaties and compacts. The Colorado River offers an instructive case in the long-term challenge of moving toward a more learning-oriented and collaborative approach.

The history of river management in the Colorado basin is one of fragmentation with competition among a broad array of water interests (agriculture, ranching, municipal), including conflict between the United States federal government and various states (Getches 1997). However, an incremental approach to more inclusive governance of the Colorado River basin has emerged over several decades with greater attention to bi-national cooperation between the United States and Mexico (Getches 2003; Gerlak et al. 2013). Most recently, the Colorado Basin Study—a multiagency and multigovernment effort—offers an example of how a broad array of non-state and state actors, along with diverse scientific expertise, can be brought together to redefine management problems, and to incorporate science into decision making about current and projected challenges (United States Department of the Interior 2012). Issues in the Colorado River Basin have not been resolved, and climatic changes in the region will exacerbate challenges requiring ongoing attention to building knowledge collaboratively. Still, in comparison with the prior history of science–policy interactions and governance in the basin, significant steps forward are evident especially in the Colorado River Delta, and in the lower part of the Basin. For example, in recent years, a diverse set of government officials, scientists, and NGOs have been engaged in experimental management practices, as exemplified by the 2014 pulse flow event which brought water to the parched Colorado River Delta, to collaboratively learn about river restoration (Howard 2014; Gerlak 2015).

Produce and use knowledge of all types

As noted in the introduction, contemporary water governance must draw on knowledge in its many different forms (scientific, local, indigenous, bureaucratic). This knowledge is held, formulated, and communicated by a variety of actors inside and outside government, at all scales (Lejano and Ingram 2009). Integrating different kinds of knowledge in water decision making can be extremely challenging because of differing, potentially contradictory, and sometimes incompatible ways of knowing (e.g., between scientific and traditional knowledge systems). Openness to the use of multiple types of knowledge is important for legitimate decision-making processes (Taylor and de Loë 2012), as is a commitment to processes of 'knowledge co-production' in which a plurality of knowledge sources and types is brought together to define and resolve problems (Armitage et al. 2011). Processes of knowledge co-production are not intended to resolve situations where knowledge and understanding about water conditions are incommensurate. For example, there may be instances where fundamental disagreements remain on sources of water contamination, as is happening in Mackenzie Basin with regard to oil sands contamination in downstream deltas (Timoney and Lee 2009; Hall et al. 2012). However, knowledge co-production processes do help participants to view knowledge not simply as a product, but instead as an outcome of relationships in which different information and values are recognized as being tightly connected (Edelenbos et al. 2011). In transboundary water-governance settings, these forms of interaction have important implications for how science and scientists are engaged with a broader range of actors and in ways that challenge notions of certainty about system conditions.

In the Mackenzie Basin, for example, scientists and traditional knowledge holders (those individuals with a long-term engagement on the land as harvesters and trappers) are working together in new ways through the Peace-Athabasca Delta Ecological Monitoring Program, and specifically, by collaborating on wildlife and environmental surveys. Initially, there was some apprehension among scientists and traditional knowledge holders about working together, but over time, they have come to value collaborating to share knowledge, as has been our experience in similar contexts (Wolfe et al. 2007). It is often difficult for people who are more comfortable with technical information and 'hard facts' to engage someone whose knowledge emerges from ongoing interactions with the land, and who might communicate that knowledge through stories, perceptions of change, and a tendency to situate their knowledge in a broader discourse about values (Wolfe et al. 2007; Armitage et al. 2011; Taylor and de Loë 2012). Ultimately, these changes in relationships and focus on knowledge require a tacit recognition of differences in power, willingness on the part of the individuals involved to relinquish in some cases the positions of power they do hold, and a commitment to trust building (Armitage et al. 2009).

The co-production of knowledge can be especially important in transboundary water-governance settings where objectives, targets, and goals often must be negotiated among actors who lack the power to enforce their views on each other. Monitoring in a transboundary water-governance context is one vehicle for knowledge co-production because it also situates assessment, reflection, and learning in specific empirical contexts. Along the Danube River, information sharing, exchange, and harmonization have been the primary objectives of the International Commission for the Protection of the Danube River (ICPDR) from its inception in the early-1990s (ICPDR 2007). Such efforts feed into the Danube River Basin Management Plan, which outlines concrete measures to be implemented by the year 2015 to improve environmental conditions (Weller and Popovici 2011). Demonstrating improvements in ecological conditions and coordinating among the diverse institutions involved in managing the Danube prove challenging (Gerlak 2004). However, the information collected provides (i) a solid foundation of agreed-upon data which simplifies the process of developing management plans, and (ii) consistent reporting on achievements and remaining challenges in restoring water quality throughout the basin to better guide the decision makers on policy measures (Schmeier 2013).

Engage boundary organizations and informal networks

Boundary organizations work at the interface of governmental and non-governmental spheres, and typically are the formal bodies that mediate interactions (e.g., about values, purposes, strategies) among social actors (Guston 2004; Crona and Parker 2012). Evidence from different environmental policy and governance settings indicates that these organizations can serve as clearing houses for information, foster conflict resolution, and, where supported by legislation, build the legitimacy and credibility needed to encourage behavioral change (Cash et al. 2003; Huitema and Turnhout 2009; Crona and Parker 2012). To achieve these potential benefits, however, boundary organizations require cultivation, experience, and involvement from stakeholders at higher and lower levels of governance.

Where boundary organizations do not exist, or where they are ineffective, informal networks of scientists, policy makers, and community members can sometimes fill gaps (Huitema and Meijerink 2009). In these settings, informal networks may emerge, which can institutionalize science–policy processes over longer term. Informal networks can utilize scientific information and local knowledge to help work around political resistance, entrenched approaches, or attachments to the old ways of doing things. In turn, such networks can catalyze demonstration projects at smaller scales (e.g., demonstration projects or sites within a transboundary context), and subsequently communicate lessons learned to a broader policy context (Roux et al. 2006).

Boundary organizations and informal networks can play especially important roles in linking scientists, policy makers, communities, and other actors across jurisdictions or in transboundary basins (Huitema and Meijerink 2009). This is the case in the Canadian portion of the St. John River, a transboundary river shared by Canada and the United States. Here, an informal network of watershed organizations emerged, despite the failure by the provincial government to implement water-protection recommendations from its own watershed classification strategy (Baird et al. 2014). This network advocated for the implementation of key provisions of the strategy, and had a scope and influence that ultimately had the government re-engage with the issue and with a range of water actors. One of the watershed organizations in the network requested the Provincial Ombudsman to investigate the process around the strategy. The investigation highlighted a long-term and ongoing lack of communication both within government agencies and with watershed stakeholders regarding the status of the strategy and opportunities or alternatives to move forward (Office of the Ombudsman, 2014). Significant pressure is thus being directed on the new government to take corrective actions, while watershed organizations and other actors continue to forge important linkages about freshwater concerns in the basin.

More formal, government-led river basin organizations such as the Mekong River Commission or the Orange-Senqu River Commission also can serve as a type of boundary organization. These organizations can have specific responsibilities to link scientists, donor agencies, policy makers, and communities vertically and horizontally, and as a result, they can function as key nodes in the development of more tightly coupled networks of scientists, policy makers, and civil society actors (e.g., industry, community organizations) seeking to be engaged in decision making. In the Orange-Senqu River Basin, the Orange-Senqu River Commission facilitates information gathering and sharing within the four basin nation states. However, it cannot fully resolve the differences in scientific and technical capacities between basin states which result in challenges providing timely and accurate data. The Mekong River Commission encourages data and information exchange regarding hydrology, biodiversity, and fisheries in the form of State of the Basin Reports. It builds technical capacity (as well as institutional and social capacities), through its Flood Management and Mitigation Program and Initiative on Sustainable Hydropower, which supports adaptation to future stressors (Heikkila et al. 2013). However, like the Orange-Senqu, limited capacity in some states is a challenge for data acquisition. Furthermore, boundary organizations must contend with issues of data sharing with nonmember states, as in the case of the Mekong River Commission and its interaction with upstream China. The Mekong River Commission has its strengths and weaknesses depending on different programmatic areas (Heikkila et al. 2013), and identifying areas with strong or weak organizational capacity will be important.

CONCLUSION

Blueprints for effective science–policy processes in transboundary water-governance settings do not exist because, as in water governance generally, problems and solutions are complex and context specific (Ingram 2013). Nonetheless, it is possible to identify conditions that are likely to increase the chances of success based on international experiences. We have done so here using transboundary water governance examples, but do recognize the value of engaging with a wide range of practitioners and scholars in diverse settings to further reflect upon and build an evidence base of the conditions for effective science–policy processes.

The five conditions considered in this perspective reflect the importance of networks of science and policy actors, as well as a range of non-state actors engaging in new forms of collaboration. Engaging the right people as actors in these processes through experience and interdisciplinary training is necessary. Identifying and publicizing successful cases (in developed and developing countries) of science–policy interactions will help, as will recalibration of traditional measures of scientific success to emphasize processes that are credible, legitimate, and salient.

Recent experiences in the vast transboundary Mackenzie Basin in Canada reflect many of the conditions and lessons outlined in this policy perspective (see Box 1), with the cases in Table 1 offering supporting examples. As previously noted, science–policy interactions often reflect unequal relations of power between nation states (or subnational jurisdictions, such as is the case in the Mackenzie Basin). In some contexts, deliberative approaches in political arenas can create new spaces for actors to engage on difficult issues and build trust (Dore 2014). However, efforts to further science–policy interactions in the Mackenzie Basin are complicated by more than jurisdictional differences in power. There are vested industry interests associated with oil sands production and pressure to engage with new technologies (e.g., fracking) that can subvert local deliberative processes, transboundary governance, and multiscale efforts to institutionalize science–policy interactions. These circumstances do not imply that efforts to foster science–policy interactions will fail, and there are in fact many innovative efforts taking place in the Mackenzie Basin (see Box 1). However, they do make the task all that more challenging.

Given the expanding envelope of variability within which multijurisdictional decisions about water must be made, failure to 'invent' new, conducive, institutions and to institutionalize conditions for better decision making presents significant risks to society and ecosystems. Moving forward, therefore, systematic and comparative assessment is required to identify the full range of conditions for science–policy success (and those conditions that create barriers) across a large sample of transboundary river basins in a diversity of jurisdictional settings (e.g., international, subnational). Even with the application of the five conditions we have identified, some failures in bridging science and policy are inevitable. An ongoing commitment to foster collaborative knowledge networks is required to deal with change in transboundary settings. However, as the examples in this perspective have shown, focusing on strategies and conditions to facilitate science–policy interactions is a pragmatic entrée to resolve water decision challenges in spite of the broader political forces (i.e., imbalances or asymmetries of power, upstream–downstream conflicts) that too often undermine the cooperation and integration crucial for sustainability.

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AUTHOR BIOGRAPHIES

Derek Armitage (✉) is an Associate Professor at the University of Waterloo. His research focuses on the human dimensions of environmental change and adaptive co-management of aquatic systems.
Address: Environmental Change & Governance Group, Department of Environment and Resource Studies, University of Waterloo, Waterloo, Canada.
e-mail: derek.armitage@uwaterloo.ca

Rob C. de Loë is a Professor and University Research Chair in Water Policy and Governance at the University of Waterloo. He currently serves as the Canadian Co-Chair of the Great Lakes Water Quality Board, and has advised the Government of the Northwest Territories in its transboundary negotiations in the Mackenzie River Basin.
Address: Water Policy & Governance Group, Department of Environment and Resource Studies, University of Waterloo, Waterloo, Canada.
e-mail: rdeloe@uwaterloo.ca

Michelle Morris is a PhD candidate at the University of Waterloo. Her research examines the factors that constrain and enable sustainable transboundary water governance.
Address: Water Policy & Governance Group, Department of

Environment and Resource Studies, University of Waterloo, Waterloo, Canada.
e-mail: m24morri@uwaterloo.ca

Tom W. D. Edwards is a Professor in the Department of Earth and Environmental Sciences at the University of Waterloo, Canada, specializing in isotope hydrology and hydroclimatology. His research focuses on the effects of the past and ongoing climate changes on water resources.
Address: Earth & Environmental Sciences, University of Waterloo, Waterloo, Canada.
e-mail: twdedwar@uwaterloo.ca

Andrea K. Gerlak is a Director of Academic Development with the International Studies Association and Senior Policy Scholar with the Udall Center for Studies in Public Policy at the University of Arizona. She is a political scientist with research interests in water policy and governance.
Address: Udall Center for Studies in Public Policy, University of Arizona, Arizona, USA.
e-mail: agerlak@u.arizona.edu

Roland I. Hall is a Professor of Biology at the University of Waterloo. He is an aquatic ecologist and paleolimnologist, who integrates knowledge of hydrological processes to evaluate the past, present, and future environmental changes in water-rich landscapes for improved natural resource protection.
Address: Department of Biology, University of Waterloo, Waterloo, Canada.
e-mail: rihall@uwaterloo.ca

Dave Huitema is a Professor of Environmental Policy at the Netherlands Open University and the VU University, Amsterdam. He is interested in adaptive governance, and specifically in the notions of experimentation, participation, learning, evaluation, and policy innovation.
Address: Institute of Environmental Studies, VU University Amsterdam, Amsterdam, The Netherlands.
Address: Faculty of Management, Science & Technology, Netherlands Open University, Heerlen, The Netherlands.
e-mail: dave.huitema@vu.nl

Ray Ison is a Professor, Systems for Sustainability at the Monash Sustainability Institute (MSI), and a Professor of Systems at the Open University, UK (OU). He leads the Systemic Governance Research Program in MSI, and at the OU is co-responsible for managing a postgraduate program in Systems Thinking in Practice (STiP).
Address: Engineering & Innovation, The Open University, Buckinghamshire, UK.
Address: Monash Sustainability Institute, Monash University, Melbourne, Australia.
e-mail: ray.ison@monash.edu

David Livingstone is a consultant in Yellowknife, Northwest Territories focusing on environmental stewardship issues (including water), facilitation, and conservation planning.
Address: Holarctic Environmental Consulting Ltd., Yellowknife, NWT, Canada.
e-mail: livingstone21@hotmail.com

Glen MacDonald is the John Muir Chair and Distinguished Professor of Geography at UCLA. He works on issues of long-term climate change, water resources, and societal impacts in western North America and other semi-arid regions.
Address: Institute of the Environment & Sustainability, University of California, Los Angeles, Los Angeles, USA.
e-mail: macdonal@geog.ucla.edu

Naho Mirumachi is a lecturer in Geography at the Department of Geography, King's College London. Her research interests focus on the politics of water resources management and she examines issues of water security and water governance, particularly in developing-country contexts.
Address: Department of Geography, King's College London, London, UK.
e-mail: naho.mirumachi@kcl.ac.uk

Ryan Plummer is a Professor and Director of the Environmental Sustainability Research Centre (ESRC) at the Brock University (Canada) and a Senior Research Fellow at the Stockholm Resilience Centre (Sweden). His multifaceted program of research broadly concerns resilience and governance of social–ecological systems. Water resources are the context on which is his research mainly focused.
Address: Environmental Sustainability Research Centre, Brock University, St. Catharines, Canada.
Address: Stockholm Resilience Centre, Stockholm, Sweden.
e-mail: rplummer@brocku.ca

Brent B. Wolfe is a Professor in Geography and Environmental Studies at Wilfrid Laurier University. His research focuses on deciphering the environmental consequences of multiple stressors on northern lake-rich landscapes.
Address: Department of Geography & Environmental Studies, Wilfrid Laurier University, Waterloo, Canada.
e-mail: bwolfe@wlu.ca