Securing a Shared Hidden Resource: Governance Mechanisms for Transboundary Groundwater Security

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Abstract

Globally, groundwater is the largest store of liquid freshwater, making it a key component of a secure water supply. However, over the past few decades, the amount of subsurface water available around the world has been rapidly decreasing. This depletion is caused mostly by mismanagement (e.g., overpumping and under-regulation), but also by reduced natural recharge due to climate change and urbanization. Management of groundwater resources is particularly challenging for the nearly 600 aquifers that are transboundary, meaning that they extend across international political borders. Because groundwater is stored underground, this “hidden” resource is difficult to monitor, assess, and manage. Few international legal frameworks guide the governance of transboundary water resources, and such frameworks as exist are limited by lack of commitment, weak institutional arrangements, insufficient financial resources, and inadequate enforcement. International norms are typically implemented through bilateral and multilateral treaties, a process that reveals the important role of national capacity in managing transboundary resources, but that have mostly ignored groundwater resources. Further, rapid expansion in both the number and scope of global groundwater initiatives points to the growing role of new actors, perspectives, and functions in promoting secure access to and use of shared groundwater resources. Based on these observations, we posit a set of recommendations to enhance transboundary groundwater security.

1.0 Introduction

Accounting for 97% of liquid freshwater, groundwater is a critical component of global water supply (Margat and van der Gun 2013). Household, industrial, and agriculture water users depend heavily on groundwater supplies. Globally, over 2.5 billion people rely on groundwater as a primary domestic water source, particularly in rural areas (UN WWDR 2015), and up to 24% of industrial water use comes from groundwater (Döll et al. 2012). In agriculture, groundwater accounts for 43% of water for crop irrigation worldwide, having major direct implications on food security (Siebert et al. 2010). While most agriculture is still rainfed, irrigated agriculture now provides approximately 40% of human food supply (Aeschbach-Hertig and Gleeson 2012). In addition to increasing population and economic growth, expansion of irrigated agriculture—especially when technologies with sub-optimal water-efficiency are used—further strains groundwater resources (Wada and Heinrich 2013). Human use depletes groundwater globally (IPCC 2013, Wada et al. 2010) -- over the past few decades, extraction rates have been increasing by 3% annually (Conti 2016) Adding to this trend, groundwater is not immune to climate change—recharge rates and groundwater levels are impacted by precipitation variability and extreme events (IPCC 2013 Taylor et al. 2013, Wada 2016). Finally, urbanization not only increases municipal water demand but, as cities grow and expand, the areal extent of impervious surfaces (e.g., concrete and asphalt) increases, preventing the natural recharge of aquifers and thereby decreasing groundwater levels.

The water security discourse has emerged at a time when states and especially global organizations have begun to turn their attention to crises of water supply, effectively "securitizing" discourse over water management (Staddon and James, 2013). Nevertheless, if we consider groundwater within a water security framework, we see how the nature of water supplies is multi-dimensional. A water security framework recognizes the need for an adequate quantity of high-quality water, but it also addresses broader social, economic, and environmental aspects of how water supplies are accessed and used by society and ecosystems. Definitions of water security point to a variety of aspects such as water access (GWP 2000), protection from floods (Grey and Sadoff 2007), water for ecosystem health (GWP 2000, Grey and Sadoff 2007, Bakker 2012, Scott et al. 2013), human health (Grey and Sadoff 2007, Bakker 2012), national security (Bakker 2012), sustainability, uncertainty, and resilience to global change (Scott et al. 2013).[1] Beyond contributing to the volume and availability of water supplies across the globe, groundwater contributes to water security in many ways that are distinct from surface water. For example, in arid areas, groundwater supplies are more locally accessible than surface water, and because aquifers can store large volumes of water, they contribute to drought resilience of the overall water supply.

Despite its manifest and rising importance for global water security, groundwater is often poorly managed (Famiglietti 2014). Groundwater is subject to the full array of management challenges of any common-pool resource, because it is difficult to exclude new users and overuse of the resource can ultimately reduce the amount available for others (Ostrom et al. 1999), particularly in local contexts. Because groundwater systems are difficult to observe (both literally—i.e., by eye—and scientifically, i.e., with reference to its essential properties), they are also difficult to assess, scrutinize, and monitor. Unique physical characteristics of groundwater systems, such as long residence times and delayed responses, make monitoring and detection of impact difficult (Foster and MacDonald 2014). For example, contamination released at the ground surface may take days to weeks or longer to reach the aquifer, and may travel considerable distances underground—and across international boundaries, where such borders are present. Groundwater depletion can have unpredictable impacts on water quality and use, as well as on aquifer sustainability (Aeschbach-Hertig and Gleeson 2012). Moreover, physical characteristics

[1] We use the definition by Scott, et al. 2013: "Water security constitutes the sustainable availability of adequate quantities and qualities of water for resilient societies and ecosystems in the face of uncertain global change." For a full discussion of the various definitions, see Gerlak et al. In review.

governing the direction, rate, and ease of groundwater flow can vary dramatically both within and among aquifers. Because of the hidden nature of groundwater, sustainable management is even more challenging.

Nearly 600 groundwater aquifers are shared by more than one country (see Figure 1; IGRAC 2015; Conti 2016).[2] When aquifers traverse international borders, their management—problematic in any case—is additionally complicated by the involvement of two or more nations that may have different policies, institutional arrangements, cultures, and socioeconomics.[3] Their transboundary nature requires national-level institutions be involved in governance, yet, sub-national groundwater systems are typically managed locally (Aeschbach-Hertig and Gleeson 2012, Conti 2016). In addition, the effects of groundwater depletion can now be seen to extend to the regional scale. Remote sensing technologies have provided new capabilities for observing groundwater depletion at regional scales (e.g., Gravity Recovery and Climate Experiment [GRACE]), yet, complementary local data are often insufficiently available for these shared aquifers (Linton and Brooks 2011, Conti 2016). With rapid population growth, economic development, and increasing dependence on groundwater for irrigation and household use, stress on transboundary groundwater systems has increased rapidly over the past 50 years (Wada and Heinrich 2013). Yet, few international legal mechanisms exist specifically for transboundary water management (Puri and Aureli 2005), and those that address groundwater are still in the initial stages of development (Nanni and Foster 2005, Sugg et al. 2015, Conti 2016). In addition to improving our understanding of groundwater systems, technical approaches are most effective when they are complemented by coordinated and cooperative policy and governance explicitly at the transboundary level.

Improving mechanisms for transboundary groundwater governance will have direct implications for water security. This paper reviews the status of international efforts to govern transboundary groundwater. In the next section, we set the stage for governance and management by describing the distinctive physical characteristics of groundwater. We continue by identifying and discussing the most significant challenges this unseen resource poses for effective management. Then, we consider the status of international legal mechanisms for transboundary groundwater, including a review of existing international groundwater frameworks, international legal principles, and transboundary groundwater treaties. This discussion is followed by a section that takes a more telescopic view by reviewing the major global initiatives that have influenced the trajectory of international governance of shared groundwater resources. Finally, we highlight six selected themes that characterize the state of knowledge on transboundary groundwater governance in academic and policy literature, and offer important recommendations.

2.0 Physical characteristics of groundwater resources

Groundwater aquifers consist of permeable rock units that are saturated and able to yield sufficient quantities of water to be utilized as a water resource (Margat and van der Gun 2013; Lohman et al. 1972). Three general categories of aquifers include unconfined, confined, and fossil aquifers. Unconfined aquifers are well-connected with surface water, and are recharged, often rapidly, by surface infiltration. Unconfined aquifers can either receive water from or supply water to streams. The direction of flow between streams and aquifers can vary among stream reaches based on the topography and aquifer characteristics, and can vary seasonally. For instance, within the same stretch, a stream might lose water to the aquifer in summer months and gain water from the aquifer in winter months. Confined aquifers occur in rock units that are sealed above and below by impermeable layers that prevent interaction with surface water (Schwartz and Zhang 2003). Confined aquifers are recharged by precipitation that infiltrates in limited “recharge zones” where aquifer units are exposed at the ground surface. For confined aquifers, coordinated land management in recharge areas, which may be far removed from the location of

[2] And this number is rising as scientific efforts to identify, map, and characterize aquifers proceeds.
[3] For a discussion of how new international borders complicated natural-resources management at the time of the breakup of the Soviet Union, see Udall and Varady 1994.

groundwater extraction, is needed to protect water quality and quantity in the aquifer, though this can pose problems when the areas of benefit (extraction) is located in a different jurisdiction to the area of cost (recharge) (Nanni and Foster 2005). Groundwater recharge is also affected by the timing, location, and amount of precipitation, evapotranspiration, snowfall and snow melt (Kløve et al. 2014), and the type of surfaces in urban settlements (e.g., pervious vs. impervious). Finally, "fossil" aquifers store water that may have accumulated thousands of years ago. These aquifers receive no recharge, and therefore have finite quantities of water. Once "mined" these resources may be gone forever.

Within these three broad categories, aquifers' properties vary widely, and individual aquifers can be internally heterogeneous (Puri and Aureli 2005). Aquifer characteristics, such as porosity, permeability, and conductivity, affect *in-situ* flow rates of groundwater, the nature and extent of impacts of overextraction, the rate at which water can be extracted, and how much water the aquifer can produce. For example, flow rates within aquifers vary from 0.01 to 10 meters per day and groundwater can remain within an aquifer for anything from a few years to thousands of years (Foster et al. 2013).

Aquifers exhibit physical characteristics that make groundwater a desirable water resource, but they also present some unique challenges for governance. Differences in the physical characteristics of surface water and groundwater aquifers that have implications for water governance are summarized in Table 1. Compared to surface water, groundwater is often of higher quality. During recharge, precipitation infiltrates through overlying materials which serve as natural filtration (and is a key principle of artificial recharge schemes). In arid and semi-arid areas, groundwater aquifers provide a local water source, where surface water may be scarce or need to be transported long distances. Aquifers, particularly confined aquifers, can offer storage capacity that buffers seasonal fluctuations in precipitation and surface water availability. Aquifer storage can also be utilized for long-term storage through water banking practices—where surface water is used to recharge aquifers for future use (Maliva 2014), and as a buffer against the effects of climate variability (Green et al. 2011). Although aquifer storage varies spatially, it is nonetheless a significant contributor to water supply in many areas (Foster and MacDonald 2014). However, estimates of global groundwater storage are approximately three orders of magnitude greater than those of global groundwater recharge, suggesting a looming crisis (van der Gun 2012).

Another important difference between groundwater and surface water is the much slower pace of groundwater flow in aquifers (Giordano 2009). Flow rates within aquifers vary from 0.01 to 10 meters per day and groundwater can remain in the aquifer for years to thousands of years (Foster et al. 2013). Because groundwater transport is slow, impacts of overextraction or pollution can be delayed, spatially dislocated, and difficult to detect. Therefore, the impacts of extraction or pollution may take months to years to be detected and the extent of contamination can be difficult to monitor over time. Remediation of groundwater pollution—which may use biological, chemical, or physical techniques—is nearly always time-consuming and expensive (Nanni and Foster 2005). Groundwater aquifers are also vulnerable to essentially irreversible impacts, such as salinization caused by infiltration of seawater into coastal aquifers, as in the aquifers bordering the Arabian Gulf (Murad et al 2011, Nanni and Foster 2005). Overextraction of groundwater can also mobilize naturally-occurring pollutants from the aquifer host rock, such as fluoride or arsenic (Foster et al. 2013), or draw in water of poor quality from hydraulically-linked areas. Once disrupted, subsurface hydrostatic equilibria that supported large aquifer "lenses", can be virtually impossible to re-establish.

Although aquifers have limited extents, groundwater systems are connected to the broader environment. In unconfined aquifers, where groundwater is directly linked to surface water, overextraction in nearby wells can draw flow away from the stream, and create what are called "cones of depletion", or areas of lowered water levels surrounding wells. Riparian ecosystems, or groundwater-dependent ecosystems in arid areas, can be negatively impacted by lowered water levels (Staddon and Everard 2017). Changes in the timing and location of precipitation and snow melt due to climate change will affect the annual volume and timing of recharge for groundwater aquifers (Konikow and Kendy 2005, Kløve et al. 2014). Further, shifting patterns of groundwater abstraction due to climate change and land use may indirectly alter mechanisms of groundwater recharge (Kløve et al. 2014). Overall, the impacts of climate change on groundwater recharge are uncertain and vary regionally (Döll 2009) and may have compounding effects on groundwater security.

3.0 International groundwater governance mechanisms

We begin our examination of international groundwater governance mechanisms by looking first at specific functional approaches. We consider the current status of international legal frameworks, international legal principles, and transboundary groundwater treaties. The summary provided in Table 2 complements our discussion in the following sections by tracing how groundwater is addressed by these various mechanisms.

Despite being fairly widespread—and notwithstanding the emergence of a global aperture for water governance in the form of global water initiatives (Varady et al. 2009)—the use and effectiveness of legal mechanisms that actually govern transboundary aquifers remain relatively limited (Sugg et al. 2015, Conti 2016). Among these, most mechanisms were originally devised for surface water resources and extended—though not necessarily adapted—to include groundwater. As a result, these instruments are being applied without meaningful consideration of fit and suitability for the special conditions of groundwater systems (Mechlem 2012).

3.1 Existing international legal frameworks

Transboundary groundwater was first addressed in international law by the International Law Association's Helsinki Rules in 1966. The Helsinki Rules include groundwater in transboundary water laws. However confined aquifers—those not connected with surface water—were specifically excluded. In 1986, the International Law Association's Seoul Rules extended coverage of transboundary water law by acknowledging differences between various types of aquifers, particularly between unconfined aquifers and confined aquifers (Jarvis 2007). However, the Helsinki and Seoul Rules, and the related 1989 "Bellagio Model Agreement Concerning the Use of Transboundary Waters," have had little impact on transboundary groundwater governance in practice (Eckstein and Eckstein 2005). Salman (2007) and Jarvis (2005) offer thorough examinations of the subtle differences among international laws with regards to transboundary groundwater.

Perhaps the most influential international law regarding transboundary water is the 1997 Convention on the Non-Navigational Uses of International Watercourses ("Watercourses Convention," hereafter) (UN 1997). The Watercourses Convention laid out several general principles that, in practice, have guided many international treaties and cooperative agreements. These principles include: *equitable and reasonable utilization*, *no significant harm*, *good-faith cooperation*, *prior notification*, and *dispute settlement* (Salman 2007, Eckstein and Eckstein 2005, UN 1997). Intentionally avoiding the term "watershed"[4], the Watercourses Convention defines an "international watercourse" as including "surface waters and ground waters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus." Thus, a "watercourse" is understood to include groundwater *if* that groundwater system "flows to a common terminus" either directly or via interconnection with a surface watercourse. By once again excluding confined aquifers, the Watercourses Convention disregards the contribution made over a decade earlier by the Seoul Rules. Based on this and other significant gaps, the Watercourses Convention fails to provide meaningful inclusion of transboundary groundwater that

[4] A watershed is defined as the land area that contributes surface runoff to a given system of stream channels, and exists the basin at a common downstream location (Schwartz and Zhang 2003).

accounts for its physical, technical, economic, and social characteristics (Salman 2007). Because the Watercourses Convention does not address confined and fossil aquifers explicitly, the applicability of the principles put forth by the Watercourses Convention to various types of aquifers remains unclear (Eckstein and Eckstein 2005).

Other legal regimes have been drafted more recently to address groundwater. The Berlin Rules, developed by the International Law Association in 2004, were more comprehensive and progressive, in terms of regard for consideration of environmental water needs, than the Watercourses Convention. In contrast to the Watercourses Convention, the Berlin Rules: (1) emphasize managing a shared watercourse in an equitable and reasonable *manner* (versus equitable and reasonable *shares* for States), (2) place the principle of no significant harm on equal footing with equitable and reasonable use, and (3) include ample consideration for environmental needs and the human right to water (Salman 2007). However, unlike the 1997 Watercourses Convention, the Berlin Rules do not seek to become legally binding, but rather to operate as a kind of "practitioners" or "best practice" guide (Staddon 2010)

In 2008, the UN International Law Commission (ILC)'s Draft (with the emphasis on "draft") Articles on the Law of Transboundary Aquifers were introduced (ILC 2008). The Law of Transboundary Aquifers addresses the gap in the Watercourses Convention by explicitly including confined aquifers. Although based on many of the principles laid out in the Watercourses Convention, the Law of Transboundary Aquifers differs by including the principle of sovereignty[5]. McCaffrey (2011) argues that, although foundational to international relations, whereas the principle of sovereignty may apply to the rock units that make up the aquifer, when applied to movable groundwater resources, this principle conflicts with existing customary international watercourses law. He argues that the Draft Articles fail to distinguish between the aquifer units and the groundwater itself and thus, pose a challenge for implementation. The UN General Assembly considered the Draft Articles in recurrent sessions from 2008 through 2016, but Articles have not yet been finalized (UN 2016). We note here that it took the United Nations 27 years to adopt the Watercourses Convention after the concept was introduced in draft form in 1970, and then another 17 years to put it into force. Most observers envision a similar timeline for eventual approval of the Law of Transboundary Aquifers.

Although the Berlin Rules and the Draft Articles on the Law of Transboundary Aquifers mark attempts to address problems specific to aquifers in a more cohesive and binding way, international legal regimes remain largely voluntary. In practice, most international basins use the principles of the Watercourses Convention, in some capacity, to guide negotiations, design treaties, and development river basin organizations (Salman 2007, Mirumachi 2013). Although, the Watercourses Convention went into force in 2014 after being ratified by 35 countries (Zhong et al. 2016), enforcement applied only to participating nations. Implementation of other regimes devised to address groundwater discussed herein has been limited.[6]

3.2 International legal principles: equitable and reasonable use and no harm

As noted, international legal frameworks can offer the scaffolding for national groundwater policies regarding international issues. How are such frameworks, where they are deemed suitable, interpreted in regard to working legal principles?

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[5] The sovereignty principle states: "Each aquifer State has sovereignty over the portion of a transboundary aquifer or aquifer system located within its territory. It shall exercise its sovereignty in accordance with international law and the present articles." See http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/68/118

[6] For a good discussion of the evolution of international groundwater law, see Stephan 2011.

Well-established international customary norms, the principles of *equitable and reasonable use* and *no significant harm* form the foundation of the Watercourses Convention. There has been protracted debate regarding the hierarchy of these two principles (Conca 2006). In practice, downstream riparian states tend to favor "no significant harm" because it protects existing uses against impacts from upstream states, whereas upstream states favor "equitable and reasonable use" because that affords current needs the same weight as historic uses (Salman 2007, Wolf 1999). There is a general consensus of opinion that the Watercourses Convention puts equitable and reasonable use first (Salman 2007), possibly because "reasonable use" has a centuries old foundation in Common Law (Staddon 2010).[7] However, many suggest that the principle of "no significant harm" should be prioritized for groundwater, in order to better protect future uses and promote long-term sustainability (Linton and Brooks 2011). Groundwater aquifers are especially vulnerable to pollution and overextraction, due to the difficulty of monitoring and detecting change, time delays of impacts, and the high expense of remediation. Further, active groundwater management, including enhanced and controlled recharge and water banking, may be necessary to preserve aquifers (Schlager 2006).

Applying well-established international customary norms for transboundary water management to groundwater presents challenges related to how groundwater systems are delineated and the different behavior of groundwater compared to surface water. Existing international laws typically exclude recharge and discharge areas from the definition of a groundwater aquifer (Eckstein 2004), despite their important role in the overall groundwater system. Eckstein and Eckstein (2005) evaluate how the Watercourses Convention applies to various groundwater systems. They delineate physical arrangements of a transboundary groundwater system based on: how the aquifer and river system intersect the international boundary, which portion of the aquifer or river system is transected, and whether the aquifer is hydraulically connected to a surface water body. Eckstein and Eckstein (2005) find two types of confined aquifers to which the Watercourses Convention would not apply: (1) a confined aquifer, disconnected from surface water, that crosses an international border and has its recharge area in one state, and (2) completely confined aquifers with no recharge. They also find one case of an unconfined aquifer whose treatment under the Watercourses Convention is unclear: an unconfined aquifer crossing a political boundary, that is hydrologically-connected to a river that does not cross a political boundary but is contained entirely within one State. In this case, to apply the principle of equitable and reasonable use, the entire aquifer and river would need to be managed as a single integrated system.

While established legal principles apply to shared surface waters, when applied to groundwater, we must examine whether these principles produce the desired outcome of sustainable resource management. We see that legal principles that prioritize sustainability may be more appropriate for groundwater due to the high consequence of resource degradation. Further, groundwater systems occur in complex arrangements and involve recharge areas, aquifers, and discharge areas—various groundwater system arrangements require a closer look to determine how to apply existing legal principles most effectively. Treaties devised among two or more individual nations are used to lay out how legal principles will be applied in a given situation and context.

3.3 Transboundary groundwater treaties

It is yet another step to move from general legal principles—which as we have seen can be contentious and difficult to agree on—to practical legal instruments. When considering the governance and management of natural resources that cross international boundaries, the most common accepted

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[7] There is considerable debate in the water law literature about the relative priority of "reasonable" versus "equitable" use, and even whether or not they are legally equivalent – there is much case law to suggest that what is equitable is reasonable and vice versa. Application to surface and groundwater is however complicated in some jurisdictions (e.g., western United States) by the principle of "prior appropriation."

instruments are treaties. These require negotiation, agreement, and adoption. But those conditions, while necessary are usually insufficient. For treaties to be effective, there must be mutual good will and trust, and reciprocal enforcement of agreed-to terms. And with regard to these attributes, groundwater poses uniquely difficult challenges.

In the same way that river basins do not conform to political boundaries, aquifers are often shared by two or more nations (Puri et al. 2008). Therefore, aquifer overexploitation and contamination on one side of a border, directly affects groundwater resources on the other side of that border. As a "hidden" resource, groundwater is not easy to manage, particularly at the transboundary scale. Partly for that reason, it also has been "hidden" in international water law (Giordano et al. 2014, Puri et al. 2008). While management of transboundary water resources has been debated for many years and progress has been made, transboundary groundwater management has been mostly excluded and, therefore, is still in its relative infancy (Puri et al. 2008). Many countries continue to treat groundwater resources similarly to the ways they treat other underground resources including gas and oil, which represents a "backward transition" in international water law (Conti and Gupta 2016), particularly with regard to unconfined aquifers, or renewable groundwater resources. Such a view also tends to exclude consideration of the natural environment and biodiversity (Brels et al. 2011).

The inclusion of groundwater resources in transboundary water treaties happened fairly recently. In a review of transboundary water treaties, Giordano and others (2014) found that treaties that address groundwater were practically non-existent until they emerged in the early 1980s and then increased substantially in frequency in the last decades. But despite this growing interest, groundwater remains ignored in most treaties. Of the treaties reviewed by Giordano et al. (2014), only 14% include a groundwater component. Furthermore, most of the agreements that mention groundwater deal with it as an extension of surface water, while only a small number focus on regulating groundwater quality or quantity directly.

Strong governance capacity in all transboundary nations is needed to support the implementation of treaties. Varady et al. (2016) identified four main governance capacity elements that include (1) institutional setting, (2) availability and access to information and science, (3) robustness of civil society, and (4) economic and regulatory frameworks. The institutional setting comprises the government, non-governmental organizations, private agencies, and common managerial and decision-making practices. Fair, bottom-up, transparent mechanisms that promote information flows can help avoid troublesome disagreement (Milich and Varady 1999), while mitigating potential engagement exhaustion that threatens sustained interest in participation. And finally, economic and regulatory frameworks are important for addressing third-party impacts of pumping that require regulation. As one country pumps groundwater, neighboring countries may require more resources (energy and related cost) to access dropping groundwater levels. Therefore, regulatory frameworks are needed to improve transboundary policies (Varady et al. 2016).

But despite the potential of well-designed, context-relevant, and well-intentioned treaties, as Giordano et al. (2014) have shown, there exist very few such instruments. And those that have been put into place can languish and remain ineffective, as the Guarani Treaty has been (Sugg et al. 2015). New ideas for overcoming these obstacles may arise from concepts and paradigms generated by broad, global-scale discussions among researchers, officials, NGOs, and other stakeholders—including, but not limited to the international legal scholarship community.

4.0 Global initiatives for transboundary groundwater governance

We have seen above that groundwater and the aquifers that contain it have numerous international dimensions—most especially when these span national boundaries. The preceding sections have discussed international governance mechanisms, frameworks, principles, and legal regimes, including treaties. But these aspects of transboundary groundwater management can be seen to exist within a broader, more expansive context: products of a growing emphasis on natural resources policies and governance, with special emphasis on water in general and groundwater in particular. It's worthwhile taking a step back to trace the origins of this globalization of groundwater governance.

With roots in the 1970s' energy crisis that affected the entire planet, the concept of "soft-path" approaches to development emerged with thinkers like Amory Lovins. Lovins (1977) and others posited that "benign" means could be as effective as more traditional, "hard-path," supply-enhancement solutions that relied on engineering solutions, large public-works projects, and fossil fuels. By the early 2000s, this mode of thinking was adapted to water management. Peter Gleick, in an influential 2002 article in *Nature*, stated that "the world is awakening to the need to rethink fundamentally the way freshwater resources are distributed, managed and used. For Gleick, the soft-path, demand-oriented alternative to hard-path management of water resources could be defined as "rational application of technology and economics, and . . . decision-making at the right scale" (Gleick 2002).

This insight of seeing development as dependent on governance, policies, management, and demand—and not just supply and infrastructure—took hold internationally. It was manifested in the nearly universal acknowledgment of the overarching importance of sustainability—the need to plan effectively and efficiently for the development of resources so as to leave sufficient quantities for future generations (WCED 1987, "The Brundtland Report"). At roughly the same time—beginning in the 1990s—the world experienced a palpable flurry in the establishment of awareness-raising institutions that sought to influence affairs—in this case, water management.

These institutions, known as Global Water Initiatives (GWI), were of several types. Most venerable among them were professional societies such as the International Association of Hydrological Sciences and the International Association of Hydrogeologists[8], to name just two relevant ones. These societies were joined by growing ranks of thematically-oriented organizations, most prominently the Global Water Partnership and the World Water Council. Next, to inspire communication, cooperation, and action, large gatherings were organized: specialized conferences such as the 1992 Dublin Water Conference[9], six World Water Forums since 2000, and two Budapest Water Summits (2013 and 2016). And last, mostly via the auspices of the United Nations, countries joined to declare designated periods meant to promote awareness of certain themes such as sanitation and health and international cooperation.[10] By means of education, information-sharing, agenda-setting, and face-to-face meetings, these organized initiatives began constituting a sort of non-hegemonic form of global water governance (Varady et al. 2008, Varady et al. 2009).

One of the notable accomplishments of GWIs has been their collective role in identifying promising management paradigms. On the heels of the adoption of sustainability, taking a page from the existing concept of integrated pest management—which dates to World War II—an analogue was proposed for water: Integrated Water Resources Management (IWRM).[11] IWRM has sometimes been criticized for various reasons (see Mukhtarov and Gerlak 2014)., including not being sufficiently integrated with sectors other than the water sector (e.g., Saravanan et al. 2009, Medema et al. 2008, Jeffrey and Gearey 2006). Nonetheless, the approach has been adopted by most nations and incorporated into their plans.

[8] Whose mission is to "further the understanding, wise use and protection of groundwater resources throughout the world."
[9] Which issued the influential "Dublin Statement on Water and Sustainable Development."
[10] The International Drinking Water Supply and Sanitation Decade (1981-90) and the United Nations International Year of Water Cooperation (2013).
[11] The chief proponent and architect of IWRM has been the Global Water Partnership (GWP 2009, GWP 2000).

Partly in response to the above critique, the Nexus approach has taken hold internationally. It maintains that in view of their inseparability, water, energy, and food must be considered, and therefore managed simultaneously. The notion of water security, which we discuss throughout, also can be seen as an outcome of the actions and deliberations of participants in GWIs.

As part of this internationalization of water, groundwater has benefited from the new attention to soft-path approaches to management. Until recently, aquifers were in place to be exploited. For the large majority of them, their spatial extents, depths, and volumes were largely unknown. The quality of their waters was equally undetermined, as were the portions of their volumes belonging to each nation bordering on transnational aquifers. Similarly, practices, land and water ownership regimes, laws, and regulations were poorly understood.

But in the early 2000s—on the heels of persistent droughts in the Sahel, overexploitation in South Asia, and population-driven increased throughout the developing world—organizations such as UNESCO's International Hydrological Programme (IHP), the Global Environment Facility (GEF), and International Association of Hydrogeologists began addressing the management of groundwater. Most prominently, the Internationally Shared Aquifer Resources Management program (ISARM) began operating in 2002. ISARM's objective has been to rectify the previously-noted inadequate understanding of scientific, socioeconomic, legal, institutional and environmental issues related to the management of transboundary aquifers. Though a concerted mapping effort led by IGRAC, the International Groundwater Resources Assessment Center in The Netherlands, ISARM has produced detailed maps of the world showing the physical extent of 592 identified transboundary aquifers (IGRAC 2015). ISARM has been especially active in providing information on such aquifers in the Balkan region of southeastern Europe, in Saharan and Sub-Saharan Africa, and in the Americas. In 2010, ISARM organized a prominent conference in Paris, featuring 108 papers presentations (ISARM 2010).

ISARM enlisted GEF—an interagency organization that coordinates technical assistance and funding for global environmental programs, and itself a result of a global initiative, the 1992 Rio Earth Summit—to support its Transboundary Waters Assessment Programme (TWAP). Since 2005 TWAP has worked to assess, evaluate, and develop policy regarding transnational aquifers (Puri and Aureli 2005). In 2011, following the ISARM conference, GEF teamed with the Food and Agriculture Organization of the United Nations (FAO) to focus explicitly on groundwater governance. This was achieved via a multiyear project, "GEF-FAO Groundwater Governance Project: A Global Framework for Country Action." The enterprise commissioned 12 thematic papers on "key economic, policy, institutional, environmental and technical aspects of groundwater management," and tackled "emerging issues and innovative approaches" (FAO 2016, Varady et al. 2013). Although it addressed not only *transboundary* groundwater, the GEF-FAO project yielded the most concerted review and analysis to-date of global governance of groundwater resources. In addition to the thematic papers, the project also produced three summary documents: *Shared Global Vision for 2030*, *Global Framework for Action, and Global Diagnostic* (GEF 2016).

These concerted efforts, stemming from a concerted consciousness-raising initiative, have yielded a body of research grounded in field studies and accompanied by concrete prescriptions for transboundary groundwater governance. They complement the parallel endeavors of the individuals and institutions seeking legal instruments for managing transboundary groundwater.

5.0 Recommendations for enhancing transboundary groundwater security

Given the physical characteristics of groundwater, which we couple with an appreciation of international legal mechanisms and trends in global initiatives for transboundary groundwater, we posit six recommendations to enhance transboundary groundwater security.

These include: (1) enhancing international enforcement (e.g., Wouters and Hendry 2009, Mumme 2000); (2) consolidating governance at the transboundary aquifer scale (e.g., Linton and Brooks 2011); (3) prioritizing future water uses (e.g., Gleeson et al. 2012, Linton and Brooks 2011); (4) promoting conjunctive use of groundwater and surface water (e.g., Famiglietti 2014, de Chaisemartin et al. 2017); (5) expanding institutional capacity (Varady et al. 2016), and (6) integrating lessons from other subsurface resources (e.g., Gupta and Bavinck 2014, McCaffrey 2011, Nanni and Foster 2005, Eckstein and Eckstein 2005).

5.1 Enhancing international enforcement mechanisms

Customary international law is limited in its ability to implement new policies, and many researchers have argued that there is a need for enforcement mechanisms at the international level (e.g., Wouters and Hendry 2009, Mumme 2000).[12] However, even prior to devising mechanisms for enforcement, gaining international agreement on a new set of binding regulations is challenging and time-consuming—for example, as seen above, the Draft Articles of the Law of Transboundary Aquifers were finalized in draft form in 2008, but have yet to be adopted by the UN.

Typically, customary international norms become binding through bilateral or multilateral treaties devised among a limited number of riparian states or thought relevant court decisions, as with the 1997 ICJ decision in the Gabcikovo-Nagymaros case. Wolf (1999) reviewed nearly 150 treaties and found that treaty designs typically address the basin's unique characteristics, suggesting the critical nature of location-specific social, political, and environmental factors to the implementation of international norms (Conca 2006). Wide-ranging enforcement of more generalized laws at the international level may undermine this approach. Further, the need for adaptive governance is particularly salient for transboundary groundwater due to physical system complexities, such as delayed impacts and irreversible effects (Dietz et al. 2003, Gleeson et al. 2012). While mechanisms to enforce minimum requirements, particularly with respect to the duty to cooperate—a key principle of water law—at the international level would be helpful, other researchers emphasize the need for flexibility in international legal regimes to accommodate site-specific details and adapt to changing conditions (Varady et al. 2016).

5.2 Consolidating governance at the transboundary aquifer scale

For transboundary surface water, consolidating management at the watershed scale (e.g., IWRM) has had mixed outcomes (see Benson 2015). Although most international treaties and river basin organizations are designed around basin-level integration, these are often critiqued for overemphasizing technical approaches (Gerlak and Mukhtarov 2016), under-representing politics and social diversity, and mistaking hydrologic boundaries for governance mechanisms (Cohen and Davidson 2011). Some argue that consolidating governance at the aquifer scale is less problematic than doping so at the watershed scale—any watershed is a sub-unit of a larger watershed, however aquifers typically have limited extents and are not subsets of larger aquifers (Linton and Brooks 2011). Despite having limited extents, groundwater aquifers can be hydrologically connected to broader physical systems. Unconfined aquifers can directly impact stream flow and confined aquifers depend on precipitation and infiltration from specific recharge areas. To accommodate the larger or more complex physical system, others suggest taking a systems perspective, or "problemshed" approach (Mollinga et al. 2007, Wescoat and Halvorson 2016), that designs governance to accommodate all relevant system components, and is not based on a particular geographic scale.

5.3 Prioritizing future water uses

[12] The Draft Bellagio Treaty leaves actual enforcement to the "internal administrative agencies of each country" (Hayton and Utton 1989).

Governance regimes originally designed for surface water often serve as bases for groundwater governance regimes, or are merely extended to cover groundwater in addition to surface water without significant revision (Mechlem 2012). However, Schlager (2006) points out that surface-water regimes frequently fail to address the problems that arise in groundwater-resource systems. For example, the notion of *prior appropriation* is the cornerstone of surface water policy in the western United States. When applied to groundwater, however, this principle prioritizes existing and historic uses, thus encouraging overextraction and failing to promote sustainable groundwater use and long-term water storage (Schlager 2006). Gleeson et al. (2012) view prioritization of future use for groundwater as a value-driven choice to sustain groundwater supplies for future generations.

In confined aquifers, annual extraction rates may exceed recharge rates. If extraction rates are not managed over time, aquifer water levels may continuously decline. Alternatively, active groundwater management, including enhanced and controlled recharge and water banking, may be necessary to preserve aquifers (Schlager 2006). However, existing policies may not be sufficient to improve aquifer sustainability. Policy timelines (which are in the range of five to ten years) typically do not align with the time scale of groundwater system problems, which require long-term management plans on the order of 50 to 100 years (Gleeson et al. 2012). For example, due to slow groundwater flow rates, groundwater pollution may not be detected immediately. Thus, the principle of *no significant harm* should be prioritized for groundwater aquifers, as these geologic formations can be very expensive and difficult to remediate (Linton and Brooks 2011).

Similarly, at the international level, the principle of *equitable and reasonable use* prioritizes current and historic uses over sustainability. Linton and Brooks (2011) argue further that future uses be prioritized in transboundary aquifers. They relate five considerations to guide the application of international law principles to transboundary aquifers to promote long-term viability: (1) social and political equity, (2) economic efficiency, (3) ecological sustainability, (4) importance of demand management, and (5) implementability.

5.4 Promoting conjunctive surface water-groundwater management

The connection between groundwater and surface water systems is well-known (Famiglietti 2014)—in well-connected systems, groundwater depletion can draw water away from streams, surface water diversions can reduce groundwater recharge, and limited recharge can impact groundwater-dependent ecosystems (Margat and van der Gun 2013, Kløve et al. 2014). Based on the physical connection between groundwater and surface water, the principle of *hydrological unity* suggests holistic management of surface water and groundwater as a single resource (Eckstein and Eckstein 2003).

Existing treaties have addressed this in various ways. The Watercourses Convention intentionally used the term “watercourse” to acknowledge that groundwater and surface water were part of a broader water system (albeit excluding confined aquifers) (UN 1997). Although never ratified, the Bellagio Treaty advocated for the conjunctive use of surface water and groundwater, noting the potential benefits it would have for distributional and use efficiency. However, the Bellagio Treaty also acknowledged how the diverse and complex hydrological arrangements between groundwater and surface water may produce institutional challenges for coordinated management, and thus suggested that conjunctive management be utilized only “where appropriate” (Hayton and Utton 1989). However, conjunctive management, which allows for water needs to be fulfilled from either surface or groundwater sources, often requires adaptive management. But, shifting all water demands onto groundwater sources during drought periods can lead to overuse and depletion, unless maximum extraction rates are also enforced. For example, the city of Hermosillo in Mexico experienced a severe drought in the late 1990s and early 2000s that led farmers and municipalities to rely on groundwater without restriction, resulting in a depleted aquifer and its associated challenges (Scott and Pasqualetti 2010).

5.5 Expanding institutional capacity

Academic and policy literature alike consider institutional capacity critical for effective transboundary water governance. In case studies of transboundary water management, the institutional capacity needed to accommodate social, political, or environmental change is consistently found to be a main determinate of success in shared water governance (Yoffe et al. 2003). At the transboundary aquifer level, institutions must facilitate decision-making among diverse actors who hold a broad range of values and perceptions on both (or all) sides of the border (Linton and Brooks 2011). Feitelson and Haddad (1995) recommend incremental progress as a strategy to mitigate conflict among diverse actors or multiple nations. Similarly, Mumme (2000) suggests step-wise solutions that build upon shared values and prior successes can also help solidify social support. An incremental approach has been successful in negotiations between the U.S. and Mexico where "minutes," or itemized recommendations, are used to adjust and update the original 1944 Water Treaty (United States and Mexico 1944). These minutes provide a mechanism to address new challenges as they arise, without the need to renegotiate a new treaty (IBWC 2002). Furthermore, institutions need to manage adaptively, allowing for flexibility, integration of public input, and incorporation of new information (Wolf 2007). To incorporate adaptation, the U.S.-Mexico 1944 Water Treaty allows for water deliveries between nations to be delayed or adjusted in quantity based on drought conditions (McCaffrey 2003).

In addition to an incremental, flexible approach, building institutional capacity at the transboundary level may require addressing existing institutional asymmetries between nations. Aquifers shared between the U.S. and Mexico provide a stark example. In 2006, the U.S. Congress established the Transboundary Aquifer Assessment Program (TAAP) to create a binational cooperative framework,[13] lay out specific steps for aquifer assessment, and eventually arrange for a joint funding mechanism (Megdal and Scott 2011). The U.S.-Mexico TAAP aims to follow the guidelines set out in the Law of Transboundary Aquifers. Under this program, U.S. institutions, primarily the U.S. Geological Survey along with university research centers, were funded to establish collaborative partnerships with Mexican institutions, such as the Comisión Internacional de Límites y Aguas (CILA), the Mexican branch of the binational International Boundary Waters Commission (IBWC), and CONAGUA, Mexico's national water agency. Key to the success of these binational collaborations was the attention paid to differences in institutional capacity and the flexibility to adjust the structure of these cooperative frameworks in order to overcome asymmetries (Megdal and Scott 2011). By acknowledging institutional asymmetries and adjusting cooperative frameworks accordingly, the program was able to expand data collection activities and increase the exchange of information used to characterize binational aquifers (Megdal and Scott 2011).

Others suggest that building institutional capacity at multiple levels, particularly the local level, can help to promote self-reliant and more equitable resource governance in border regions (Blomquist and Ingram 2003, Dietz et al. 2003). While researchers find that case studies consistently show the important role of local institutional capacity in improved groundwater governance, they also reveal that governance activities are best shared among multiple levels and diverse actors (Varady et al. 2016). Although multi-level, nested, and overlapping institutions are often proposed as an ideal solution, Garrick and Aylward (2012) note the need for specific guidelines that direct the growth of institutions toward effective and efficient solutions that avoid high costs of transactions between institutions.

5.6 Integrating lessons from other subsurface resources

[13] While the framework is binational, thus far, the funding for TAAP has been unilateral, from the U.S. side only.

Although most transboundary aquifers receive recharge from precipitation, some groundwater is non-renewable. For these non-renewable groundwater resources, aquifers may store large volumes of water, but receive such low rates of recharge that they are not renewable on human timescales (Margat, Foster & Droubi 2006). Many researchers have suggested that governance of non-renewable transboundary groundwater might be guided by strategies employed for transboundary oil and gas (Gupta and Bavinck 2014, McCaffrey 2011, Nanni and Foster 2005, Eckstein and Eckstein 2005). Yet there are important physical, political, and economic differences between fossil fuel and water resources to take into account. Oil and gas reservoirs are typically developed by commercial interests, who allocate costs and benefits based on the proportion of the resource that resides within each state (Eckstein and Eckstein 2005). Water resources are not developed as a commercial interest -- instead they are generally considered a basic human right (Gleick 1999). In arid areas, non-renewable groundwater aquifers may be the only water supply, and therefore must be accessible to all society (Nanni and Foster 2005). Further, groundwater is more vulnerable to resource degradation (e.g., pollution) than fossil fuel reservoirs (Nanni and Foster 2005). However, lessons learned from transboundary fossil-fuel development may contribute to groundwater governance based on the similarities of a "hidden" resource that develops and changes over longer timeframes than dynamic systems on the Earth's surface.

6.0 Conclusions

The critical role of groundwater in enhancing water security, globally and locally, remains undervalued. Nevertheless, it is clear that aquifers provide long-term water storage that buffers climate-change impacts, and supply critical support to ecosystems in many, particularly arid and semi-arid, regions. Groundwater resources are often more locally accessible as drinking water and irrigation sources, and are generally of higher quality than surface water thanks to natural filtration by sediment. Improving mechanisms for transboundary groundwater governance will have direct implications for overall societal water security.

In this paper, we reviewed the status of international efforts to govern transboundary groundwater. We examined how groundwater's unique physical characteristics and "hidden nature" pose significant management challenges that warrant an approach different than that used for surface water.

Existing international legal mechanisms for transboundary groundwater remain limited and insufficient. Modern, progressive global initiatives offer new opportunities for revised thinking and more suitable approaches. These offer a growing role for new and more broadly representative actors and institutions, fresh perspectives, innovative paradigms, and effective strategies for promoting secure access to and use of shared groundwater resources. They represent efforts to address governance deficits by improving our understanding of—among other things—the legal, institutional, and governance dimensions of groundwater.

Our recommendations are grounded in this historic and contextual understanding of the evolution of groundwater governance and in parallel, of transboundary resources management. Individually and collectively, these aim to enhance transboundary groundwater security. We have looked through the literature for ways to improve transboundary groundwater governance. While none of our suggestions represents an encompassing solution or panacea, we think that a combination of these approaches will promote progress toward improved governance.

Our proposed actions include: (1) enhancing international enforcement mechanisms that are context-specific and flexible enough to adapt to changing conditions; (2) consolidating governance at the transboundary aquifer scale, adopting a systems perspective that includes all relevant systems components including politics, social diversity, and equity; (3) prioritizing future water uses and "no significant harm" over "prior appropriation" or "equitable and reasonable use"; (4) promoting conjunctive surface water-groundwater management via the principle of hydrological unity to enable a holistic management of water as a single resource; (5) expanding institutional capacity by facilitating decision-making among diverse actors from all sides of an international border, in an incremental and flexible approach, while addressing institutional asymmetries; and (6) exploring what can be learned from governance of other subsurface resources (e.g., oil and gas), particularly for non-renewable groundwater resources (confined and fossil aquifers).

These and related steps are not intended as a how-to manual for effective transboundary aquifer governance *cum* improved security. Rather, they represent an overall attitude that draws on the generalized concepts of flexibility, adaptive capacity, public participation, sustainability, soft-path approaches, integrated management, conjunctive use, diversity, and societal equity.

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