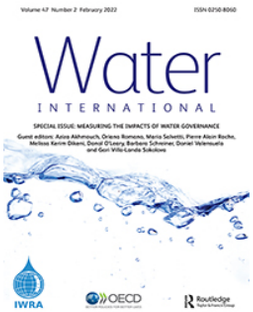

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Patterns in transboundary aquifer governance: comparative analysis of eight case studies from the perspective of efficacy

Maya Velis [a], Kirstin I. Conti [b] and Frank Biermann [c]

[a]Houston Advanced Research Center, The Woodlands, TX, USA; [b]International Bank for Reconstruction and Development, Washington, DC, USA; [c]Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, the Netherlands

ABSTRACT

We performed a comparative analysis of eight case studies worldwide from the perspective of transboundary aquifer governance efficacy. First, we mapped variation in institutional design, applying institutional design criteria in four dimensions linked to The OECD Principles on Water Governance. We then identified explanatory factors: (1) physical variables, including aquifer size and hydrogeological characteristics; (2) watershed variables, including groundwater exploitation capacity and water transfer infrastructure; and (3) political factors, including international donor support. We found that transboundary aquifer governance efficacy is closely linked to problem structure and less attributable to institutional design in the presence of specific contextual variables.

KEYWORDS

Groundwater; institutional design; empirical analysis; international; regional environmental governance; water security; sustainable development; The OECD Principles on Water Governance

Introduction

Groundwater sustains lives, livelihoods, and ecosystems worldwide, yet groundwater resources are often overused and undervalued. Over the twentieth century, economic development has rapidly intensified groundwater exploitation. In recent years, there has been a growing appreciation of groundwater's role in climate change adaptation due to its capacity to buffer against water variability (Velis et al., 2017).

A growing share of aquifers – groundwater-bearing geological formations – is subject to stress. Groundwater overuse has been linked to the decline of water tables worldwide. Groundwater depletion has already affected 15–20% of environmentally critical streamflows and poses risks to approximately 1.7 billion people living above these aquifers and others who depend on the ecosystem services they provide (De Graaf et al., 2019). As of 2021, over 1300 experts from over 100 countries signed the Global Groundwater Sustainability Statement (2019), raising the alarm on the far-reaching consequences of groundwater depletion and pollution.

Groundwater governance is inherently complex, owing partly to the challenges of resource monitoring (Akhmouch & Clavreul, 2018). Despite advances in satellite data applications, groundwater monitoring is typically complex and intensive. Compared with surface water, groundwater has long residence times and wide-ranging renewability. As

CONTACT Maya Velis mvelis@harcresearch.org Houston Advanced Research Center, The Woodlands, TX, USA

a result, there is often a lag from onset to observation of negative impacts (e.g., reduction in yield or increased salinity). Groundwater flow further depends on resource-specific properties of the water-bearing formation, any overlying layers and connections to the water cycle. Depending on such characteristics, intensive groundwater use and unsustainable land management may have far-reaching impacts beyond the area where such activities occur, with potential transboundary implications (Eckstein & Eckstein, 2005).

Transboundary aquifers are particularly prone to gradual depletion or pollution as typical groundwater governance challenges are exacerbated. Transboundary aquifers run across international borders, where the land overlying the aquifers falls under the jurisdiction of different countries (henceforth, aquifer states). At least 468 aquifers are transnational, as delineated by the International Groundwater Research Assessment Center (IGRAC) (2021).

Transboundary river basin agreements increasingly touch on groundwater. For example, Lautze et al. (2018) mapped the increasing prevalence of provisions related to 'conjunctive use' of groundwater and surface water. Nevertheless, merely 1–2% of all transboundary aquifers are the subject of dedicated formal (codified) agreements, compared with 42% of international river basins (Puri & Villholth, 2017). Further, half of the world's countries have domestic legislation in place to preserve groundwater resources, including groundwater allocations via permits or licences to drill granted by the government or the courts (Conti & Gupta, 2016). In addition, informal participatory institutions and other pragmatic mechanisms have emerged at the subnational and transboundary levels. Although local governments and public service providers may participate, these mechanisms are typically community led.

This study aims to identify explanatory factors for transboundary aquifer governance design based on a comparative analysis of eight case studies from the perspective of efficacy. So far, the empirical analysis of transboundary aquifer governance emergence and efficacy has mostly consisted of self-contained case studies or multiple transboundary aquifers in the same region (e.g., the European Union). The comparative framework deployed in this research pivots a quantitative analysis approach of transboundary aquifer cooperation, similar to empirical analysis of river basin agreements (e.g., Mitchell & Zawahri, 2015; Zawahri et al., 2016).

Methods

We deploy a comparative approach to the analysis of transboundary aquifer governance, which allows for structured analysis of patterns in institutional design, contextual factors and level of efficacy. Our approach comprises four steps: (1) developing a framework for characterizing institutional design; (2) analysing the contextual factors that impact transboundary aquifer governance; (3) identifying and comparing transboundary aquifer governance institutions' design features and relevant contextual factors; and (4) using available data about the aquifer to assess the efficacy of the governance arrangements qualitatively.

Framework for comparing institutional design

Our framework is underpinned by normative frameworks that link to The OECD Principles on Water Governance (henceforth, OECD Principles; OECD, 2015) and the governance principles for common-pool resources first articulated by Ostrom (1990).

We characterize our case studies on the spectrum of institutional integration in transboundary aquifer governance, where an integrated institution is on one side and unilateral decision-making on the other (with coordination mechanisms somewhere in between). Effective (ground)water governance is underpinned by a strong alignment between institutional mandates and the governance objective (Mahon et al., 2017). In our framework, we consider the number of (legal) powers entrusted to the governing institution included in the work of Zawahri et al. (2016).[1] This reflects the importance of clear roles and responsibilities (OECD Principle 1) and managing water at the appropriate scales within basin systems (OECD Principle 2).

To capture the institutional design parameters in transboundary aquifer governance, we draw on models developed by Velis (2016) and Mahon et al. (2017). Our framework's components are based on literature focusing on the theoretical underpinnings and empirical consequences of effective groundwater governance. The literature review matched the provisions of institutional arrangements to 25 coding elements (Table 1), identified based on criteria induced from governance literature and deduced from formal documents that codified the institutions. The coding elements are grouped under four overarching dimensions. For each case study, we calculate the fraction of coding elements represented for each respective design dimension as well as an aggregate index across the four dimensions:

- *Normative foundation*. Principles of international environment and water law guide water allocation between functions and user groups and reflect overlapping values, viewpoints and interests (Conca et al., 2006; Rijswick et al., 2014). The coding elements build upon the work of Conti and Gupta (2016), including the International Watercourses Convention and the Draft Articles of Transboundary Aquifers. While not explicitly legal in focus, several OECD Principles align with international legal norms. For example, cross-sectoral coordination (OECD Principle 3) is a key attribute of integrated water resource management.
- *Clarity on shared objectives, baselines and indicators*. A shared understanding of the physical attributes of the aquifer is critical to establishing clear objectives, baselines and indicators. This includes resource boundaries and the aquifer's role in the water system. Consideration of spatio-temporal distribution of sustainability issues accounts for costs, benefits and distributional effects (Hearns et al., 2014; Rijswick et al., 2014). This dimension elaborates the need to address trade-offs across users, rural and urban areas, and generations (OECD Principle 11) and promote stakeholder engagement (OECD Principle 10).
- *Monitoring and adaptive capacity*. Data sharing (infrastructure) facilitates continuous monitoring of resource sustainability and the direct impacts of environmental institutions. Flexible mechanisms account for emerging priorities and developments likely to impact groundwater availability and use (Armitage et al., 2015; Elshall et al., 2020; Hearns et al., 2014; Tujchneider et al., 2013). This dimension is closely linked to the need for timely and consistent data (OECD Principle 5), regular monitoring and evaluation (OECD Principle 12), and innovative water governance practices (OECD Principle 8).

- *Authority and legality*. This dimension relates to institutional credibility and aligns all stakeholders towards shared objectives, discouraging actions based solely on self-interest (Brooks & Linton, 2011; Hearns et al., 2014; Spilker & Koubi, 2016; Zawahri et al., 2016). This dimension elaborates the importance of effectively implementing and enforcing sound regulatory frameworks (OECD Principle 7) and mainstreaming integrity and transparency for greater accountability and trust in decision-making (OECD Principle 9).

Table 1. Framework for the comparative analysis of institutional design in transboundary aquifer governance based on four dimensions.

Dimension	Codes and statements
Normative foundations	Governance reflects principles of International Environment, Water, and Groundwater Law. Codes cover 13 principles recognized in scholarship: • Exchange of information[a] • Precautionary principle • Environmental conservation • No significant harm[b] • Notification of transboundary impacts[a,b] • Notification of accidents[b] • Social inclusion[a] • Reasonable and equitable use • Polluter pays[b] • User pays[b] • Access to water and sanitation • Integrated water resource management[a,b] • Conjunctive use of water resources
Objectives and baselines	Governance objective:[a] governance reflects a well-defined objective in terms of the problem that it aims to address (e.g., groundwater depletion, pollution or knowledge gaps) Basic geospatial understanding:[a,b] governance reflects a mutual understanding of aquifer dimensions and geography. Maps may be indicative of this Dynamic understanding of groundwater flow:[a] governance reflects groundwater flow dynamics, including natural discharge/recharge and any links to other water bodies Pressures on groundwater sustainability: governance reflects a shared understanding of pressures (and socio-economic drivers) such as land-use conversion and technological advancement
Monitoring and adaptive capacity	Platforms and mechanisms for data sharing and integration:[a] at the minimum, governance contains provisions to ensure the continuity and consistency of data records Governance innovation:[a] governance embodies mechanisms for normative refinement and course correction. Pilots and demonstration projects are indicative of such a learning-by-doing approach Infrastructure for groundwater monitoring:[ab] governance provides for (or is informed by) resource monitoring infrastructure such as well networks, possibly complemented with remotely sensed data Hydrological models:[a] governance provides for (or is informed by) a hydrological model. Numerical models facilitate calculations and projections. At least a shared conceptual model is in place Flexibility and contingency mechanisms:[a] governance entails provisions to account for shifting priorities, emerging (climate) risks or crises, and technological development
Authority and legality	Strong normative provisions:[a] governance includes strong normative provisions for prevention (or abatement) of groundwater sustainability issues such as depletion and pollution, as relevant Legally binding status:[a] governance institution is based on legally binding provisions in an international treaty ratified by all aquifer states Enforcement mechanisms:[ab] governance outlines mechanisms for enforcement and/or adjudication and clearly assigns responsibilities to that effect

Notes: [a]Codes that reflect one or more of the OECD Principles. The content of the principles touches upon nearly all of the coding elements presented. Several of the principles cut across two or more dimensions. Marked here are those with the closest overlap.

[b]Codes that reflect one or more of Ostrom's eight design principles for managing the commons. The relevance of these principles may vary based on contextual issues.

Framework for the analysis of contextual variables

We examine the influence of contextual variables on institutional design for the governance of transboundary aquifers, distinguishing variables at three levels: physical, watershed and political. This framework integrates some of the factors in the emergence of transboundary institutions identified by previous research. These include the involvement of third parties (e.g., international organizations and non-governmental entities) and the rate and distribution of environmental change, population growth and economic development (Brooks & Linton, 2011; Puri & Villholth, 2017). Additionally, we consider capacity differentials between aquifer states, reflecting the significance of technical, institutional and financial capacity to deliver upon institutional mandates (aligned with OECD Principles 4 and 6).

Case study selection and data sources

Eight transboundary aquifers were selected as case studies, based on four selection criteria, namely: (1) their inclusion in the IGRAC database as aquifers that are crossed by international borders; (2) active water governance or groundwater management problems flagged by multiple studies or scientifically documented by the riparian actors; and (3) a codified mechanism for governance put in place with a primary focus on the aquifer (such as an international treaty or a memorandum of understanding). For these case studies, we compiled treaties, agreements, strategies, plans and Memoranda of Understanding from various databases (including Burchi & Mechlem, 2005), along with official project documentation and joint models and databases on government websites.

Figure 1 shows the resulting eight cases that we studied:

- The Abbotsford-Sumas aquifer crossing the states of British Columbia (Canada) and Washington State (United States), studied by Zebarth et al. (2015), Rivera (2015) and Norman & Melious (2004).
- The Genevese aquifer crossing the Canton of Geneva (Switzerland) and the Prefect of Haute-Savoie (France), studied by Cobos (2018).
- The Guaraní aquifer crossing Argentina, Brazil, Paraguay and Uruguay, studied by Sindico et al. (2018), Sugg et al. (2015), and Walter (2015).
- The Hueco-Bolsón aquifer crossing Chihuahua (Mexico), Texas and New Mexico (both United States), studied by Tapia-Villaseñor & Megdal (2021) and Keller et al. (2007).
- The Iullemeden Aquifer System crossing Algeria, Mali, Niger and Nigeria, studied by Nlend et al. (2018) and Hearns (2009).
- The North-Western Sahara Aquifer System crossing Algeria, Libya and Tunisia (henceforth, North-Western Sahara), studied by Schmidt (2008).
- The Nubian Sandstone Aquifer System crossing Egypt, Libya, Sudan and Chad (henceforth, Nubian), studied by Quadri (2019) and Sefelnasr et al. (2015).
- The Saq-Ram Aquifer System crossing Saudi Arabia and Jordan, studied by Van den Berg (2017) and Charalambous (2016).

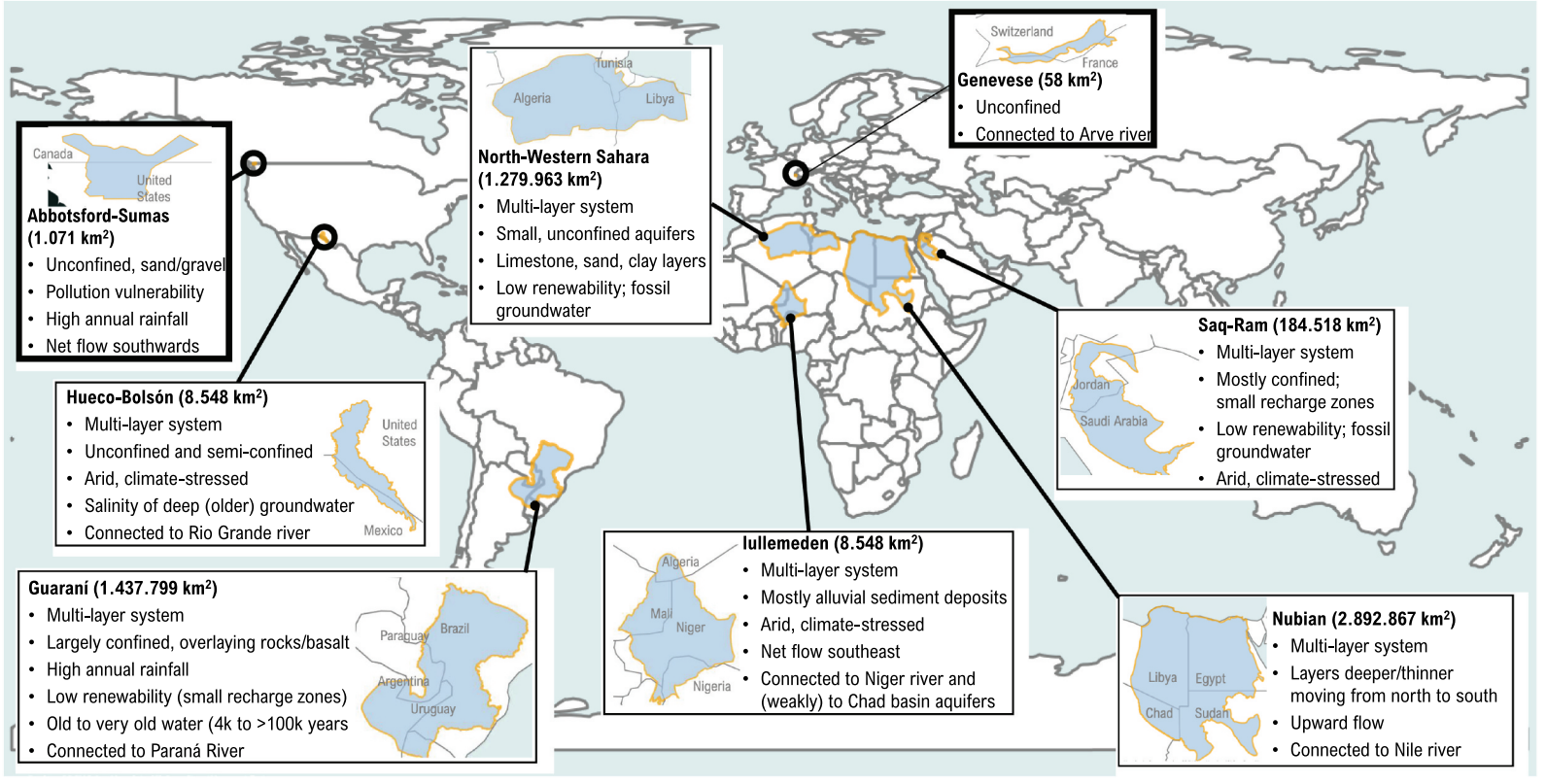

Figure 1. Geographical location and key attributes of the case studies based on the Transboundary Aquifers of the World Map (IGRAC, 2021)

Qualitative analysis of efficacy

Based on a literature review of the case studies, we evaluate governance efficacy in terms of the objectives detailed by the aquifer states themselves. These objectives include (1) conservation of groundwater resources, especially for institutions that have anticipatory mandates; (2) development of a shared knowledge base related to hydrogeology and groundwater sustainability; (3) addressing depletion[2] and pollution issues that are observed or expected to arise in the future; and (4) addressing the needs of groundwater-dependent ecosystems and communities for sustained access to groundwater resources. Efficacy is captured as low, moderate or high (as applicable).

Institutional design and contextual factors in groundwater governance

This section describes our findings related to institutional structure and mandate, followed by a structured description of institutional variables and contextual variables.

A treaty or other intergovernmental arrangement formalized the institution in most cases, except for one led by local water utilities (Hueco-Bolsón). The Hueco-Bolsón and Genevese cases rely on permanent technical committees that focus on joint knowledge dissemination or monitoring. Other cases have committees headed by ministerial representatives (Saq-Ram) or reporting to a governing board (Nubian Sandstone Aquifer System). Intergovernmental mechanisms have complex organizational structures with internal checks and balances (Guaraní, Iullemeden and North-Western Sahara). The Abbotsford-Sumas Aquifer International Task Force is uniquely participatory with representation from various stakeholders, including (sub-)national governmental agencies, the agricultural sector and indigenous communities.

Most institutions emerged in response to a specific governance issue such as impending depletion or pollution. This reflects in transboundary aquifer governance that is specific in scope to address quality or quantity concerns (e.g., Abbotsford-Sumas, Hueco-Bolsón and Genevese). Others have broader mandates aimed at the aquifer's sustainable and equitable development and use (e.g., Iullemeden and Guaraní). The most common power across institutions relates to resource monitoring and information gathering, including the appointment of experts and the establishment of data infrastructure. Monitoring of compliance with specific provisions of the agreement is less widespread. For example, the Genevese and Saq-Ram institutions have an advisory mandate for the construction of waterworks, and the Iullemeden institution could advise on 'any issue submitted to it'. Narrow mandates reflect a need for problem-oriented governance, following the observation of pressing sustainability issues.

Our case studies vary in institutional mandate, membership and relative importance of science and politics. Our findings suggest that while technical committees operate in relative independence from political leadership, these are also specific in scope; intergovernmental mechanisms are broader in scope yet more politicized.

Table 2. Indexed scores of case aquifers use of coded institutional design elements (0.0 being no applicability of design elements and 1.0 being applicability of all design elements).

	Normative foundation	Objectives and baselines	Monitoring and adaptive capacity	Authority and legality
Abbotsford-Sumas	0.19	0.50	0.40	0.00
Genevese	0.15	0.25	0.60	1.00
Guaraní	0.38	0.50	0.80	0.75
Hueco-Bolsón	0.04	0.75	0.60	0.00
Iullemeden	0.69	0.50	0.80	0.25
North-Western Sahara	0.04	0.25	0.60	0.00
Nubian Sandstone	0.35	1.00	0.60	0.38
Saq-Ram	0.12	0.38	0.00	0.63

Note: Colours correspond to the values in the boxes (using heatmap functionality in Excel). Readers of the print version can view the table in colour online at https://doi.org/10.1080/02508060.2022.203892

Institutional design variables

The evaluation of institutional design variables across the four dimensions (Table 2) shows considerable variation across the case studies for each dimension and – to a lesser extent – variation in the average across all 25 coding elements. Since this framework is not designed to be normative, the heterogeneity reflects that institutional design is context specific. The Genevese aquifer, for example, was well researched at the onset of governance, which could explain the perceived need to establish a joint knowledge base. On the other hand, in the Saq-Ram, aquifer states may have perceived less need for joint resource monitoring since they established a no-drilling zone. Thus, the normalized average shows that low and high codes can balance out, suggesting trade-offs across dimensions.

Normative foundation

Institutional design reflects to varying degrees the principles of international environmental and (ground-)water law outlined in our methodology. Nearly all the case studies contain specific principles related to data-sharing and the notification of planned measures likely to have adverse transboundary impacts. The Iullemeden, Nubian Sandstone and Guaraní aquifer systems incorporate many principles of international law (in contrast to, for example, Hueco-Bolsón, North-Western Sahara and Saq-Ram). Few cases reference emerging principles related to critical notions of groundwater sustainability, such as conjunctive use of water resources (i.e., to coordinate groundwater use with policy related to the water cycle or water resources inventories) and integrated water resource management (i.e., to coordinate with land use and other policy domains). Our case studies show that elaborate normative foundations correspond to the broadest institutional mandates.

Objectives and baselines

Most cases reflect a shared understanding of governance objectives and basic knowledge of the aquifer's (geospatial) features and flow dynamics. In half of the cases, the governance objective is explicitly stated as addressing depletion or pollution issues, conservation or knowledge development. Half of the case studies contain hydrogeological cross-

sections or specified recharge zones and rates. Accounts of pressures and drivers on groundwater vary in detail, ranging from virtually non-existent under the umbrella of a pre-existing knowledge base (Genevese) to detailed maps and models of human impacts and land-use change (Nubian and Iullemeden). The Abbotsford-Sumas Aquifer Task Force oversaw numerous scientific forums for knowledge development related to hydrogeology, land-use policies and eutrophication. This dimension is strongly shaped by the rationale of transboundary aquifer governance, whether it be proactive or responsive to a pressing sustainability issue.

Monitoring and adaptive capacity

All case studies have infrastructure for monitoring and data exchange in place, although the modality, metadata and monitoring frequency are rarely specified. A numerical model is known to exist for all cases except for Genevese and Saq-Ram. Wells inventories took place in all case studies except for the Abbotsford-Sumas (aligned with the primary governance objective of pollution reduction) and Saq-Ram. Widespread piezometric networks allow for dynamic water level monitoring. Five case studies feature demonstration studies, including pilot studies in problem-intense regions of the Guaraní; a joint feasibility study on water source diversification (e.g., managed aquifer recharge; desalinization) in the Hueco-Bolsón; and various conservation and wastewater disposal pilots in the Nubian. Few case studies have flexible arrangements or contingency mechanisms to inform management decisions, even though five case studies are situated in climate-stressed regions where groundwater renewability is highly limited.

Authority and legality

Case studies feature agreements ranging from legally binding to declarations of intent. Three cases feature a treaty under international law, signed and ratified when all aquifer states had passed a domestic law to that effect.[3] Other institutions were formalized through 'softer' agreements such as memoranda of understanding (Abbotsford Sumas, Hueco-Bolsón and Iullemeden), ministerial declarations (North-Western Sahara and Nubian), and non-binding strategic action plans developed with governmental support (Guaraní and Nubian). Substantively, we find the most robust normative provisions on depletion or pollution prevention (or abatement) in two treaties. In the Saq-Ram, these include a non-drilling zone and groundwater well design guidelines; in the Genevese, these cover groundwater withdrawal allocations and water quality aspects of managed aquifer recharge. Other case studies include more nebulous groundwater protection provisions, such as pilot protection zones (Nubian[4]) and land-use guidelines (Abbotsford-Sumas and Nubian). Some cases have outlined conflict resolution mechanisms to strengthen substantive provisions (e.g., Iullemeden).

Contextual variables

Physical variables: surface area, select hydrogeological features and homogeneity

The case studies vary widely in size, encompassing some of the world's largest and smallest transboundary aquifers, as mapped by the International Groundwater Resources Assessment Centre (IGRAC) (Figure 2). The case covering the largest surface area (Nubian) is approximately 50,000 times the spatial extent of the smallest aquifer

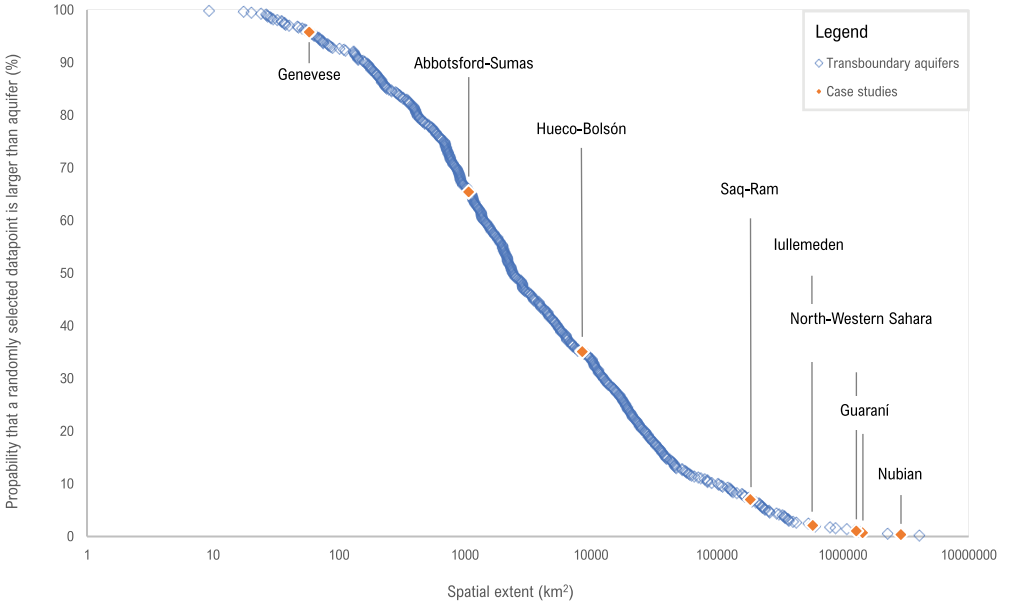

Figure 2. Distribution of transboundary aquifers by spatial extent, reflecting case study heterogeneity. Note: The Genevese belongs to the smallest 5% transboundary aquifers in the world; the Nubian Sandstone, Guaraní and the North-Western Sahara aquifer systems are among the largest 1.0%.

(Genevese). Based on data from the Transboundary Waters Assessment Programme (2015), the vast aquifer systems of the Nubian, Guaraní and North-Western Sahara appear heterogeneous in terms of key hydrological indicators (e.g., lithology, porosity, conductivity and transmissivity). Our case studies further suggest localized sustainability issues in the larger aquifer systems, such as salinization in Hueco-Bolsón and pollution in Guaraní). In contrast, the problem distribution appears more evenly distributed in the smaller aquifers.

Watershed variables: groundwater exploitation capacity differentials and water diversions

Groundwater dependence is either high or rapidly growing in all case studies, but some show significant differentials in groundwater exploitation capacity and the relative viability compared with surface water. For example, in the Nubian case study, wells in Chad and Sudan often fall short of reaching the deep groundwater table due to technical and economic constraints. In contrast, groundwater is used intensively in Egypt and Libya, where the capacity constraints are fewer (and groundwater is closer to the surface). In the Guaraní, 94% of groundwater withdrawals take place in Brazil (even though only 26% of the aquifer area is below Brazilian lands). This is partially attributable to Brazil's economic position enabling well drilling in high concentration. Our case studies suggest groundwater use is not proportionate to the aquifer area that is situated in the respective aquifer states in the Nubian, Guaraní and Iullemeden case studies.

In some cases, sustainability issues can be traced to socio-economic drivers hundreds of kilometres away. Some of the world's fastest-growing megacities are situated in Brazil (including near the border with Uruguay) and along the densely populated Mediterranean coast in Egypt and Libya. In the Hueco-Bolsón, Nubian and Saq-Ram case studies, rapid population growth and urbanization coincided with the expanse of irrigated agriculture. Large-scale groundwater transfer infrastructure exists in the Nubian and Saq-Ram.[5] Further, Egypt, Libya, Jordan and Saudi Arabia have used extensive quantities of non-renewable groundwater for irrigation due to national food security strategies encouraging a shift towards higher value, water-intensive food products, a practice that accelerated in the 1980s. Our case studies show that diverging socio-economic development trajectories, land-use patterns and volumetric groundwater abstraction compound pressures on transboundary groundwaters.

Political variables: history of regional cooperation and the role of third-party actors

Political contexts of the case studies range from stable and collaborative to more tumultuous or conflictual. For example, the Abbotsford-Sumas and Genevese case studies are characterized by high economic integration and long-standing collaborative relationships. In contrast, the Nubian and North-Western Sahara cases have had international tensions in recent history, including border conflicts. In the Guaraní, transboundary aquifer governance emerged in the context of pre-existing international agreements and basin authorities. However, it may have been overshadowed by broader tensions on transboundary waters (i.e., pulp mill dispute between Argentina and Uruguay). Further, political interest appears to have waned over time in the Abbotsford-Sumas, Hueco-Bolsón and North-Western Sahara aquifers.

International project activity with the support of donors was prevalent in four case studies (Guaraní, Iullemeden, North-Western Sahara and Nubian). Along with national governments of the riparian countries, such projects involved international organizations (e.g., International Atomic Energy Association – IAEA); United Nations Environment Programme – UNEP; and United Nations Educational, Scientific and Cultural Organization – UNESCO), regional intergovernmental organizations (e.g., Center for Environment and Development for the Arab Region and Europe – CEDARE; Organization of American States – OAS; and Sahara and Sahel Observatory – OSS); international development funds (Global Environment Facility – GEF; and International Fund for Agricultural Development – IFAD), and companies specializing in remote sensing and geographical information systems, per our mapping of aquifer-specific projects. In some case studies, intensive donor involvement preceded the emergence of formalized governance frameworks.

Efficacy of transboundary groundwater governance institutions

This section discusses the extent to which the institutional design and contextual variables correspond to governance efficacy in the case studies.

Efficacy in terms of objectives of transboundary aquifer governance

Table 3 summarizes each case's efficacy across the criteria set out in the methodology and discussed in the text below.

Table 3. Efficacy in terms of objectives of transboundary aquifer governance.

		Efficacy in terms of (expressly stated) governance objective			
	Institutional design	Conservation	Knowledge development	Depletion	Pollution
Abbotsford-Sumas	Multi-stakeholder mechanism	n.a.	High	n.a.	Moderate
Genevese	Permanent (scientific) committee	n.a.	n.a.	High	n.a.
Guaraní	Intergovernmental mechanism – local committees	High	n.a.	n.a.	n.a.
Hueco-Bolsón	Multi-stakeholder mechanism	n.a.	High	Moderate	n.a.
Iullemeden	Intergovernmental mechanism	n.a.	Moderate	Low	n.a.
North-Western Sahara	Intergovernmental mechanism	n.a.	Moderate	Low	n.a.
Nubian Sandstone	Permanent (scientific) committee	Insufficient data	Moderate	Low	Insufficient data
Saq-Ram	Permanent (scientific) committee	n.a.	n.a.	Insufficient data	n.a.

In terms of groundwater conservation, the Guaraní's institution has been effective considering governance's anticipatory, precautionary nature. Aquifer states developed a joint knowledge base, including a monitoring system and well inventory, and (drilling and land-use) guidelines to address local hotspots of depletion or pollution. However, for the Nubian case study, data gaps leave the evaluation of groundwater conservation objectives inconclusive. Gaps remain despite the long timespan of governance; collaboration with international donors started in the late 2000s to better characterize the system's hydrogeology and to consider a transboundary governance mechanism for safeguarding resource sustainability and (community or ecosystem) needs.

All five case studies geared towards knowledge development objectives reflect moderate or high efficacy for substantively advancing the understanding of (expected) groundwater sustainability issues as well as pressures and drivers. For example, the Hueco-Bolsón case covered a groundwater monitoring information system to support local water utilities in developing a plan for managed aquifer recharge. In the Iullemeden, aquifer states conducted climate change vulnerability assessments and developed a joint hydrological model, supported by well inventories and quality sampling. Geospatial analysis and isotope dating were deployed in the North-Western Sahara case study.

Out of the five case studies that have groundwater depletion mitigation among the governance objectives, two are moderately or highly effective. The institutional and technical design helped stabilize groundwater levels in the Genevese, despite continued high withdrawal rates. The innovative benefit-sharing mechanism may have been vital for the required political will to emerge for the managed aquifer recharge project. In the Hueco-Bolsón, the institutional mechanism sought alternative sources to satisfy an ever-growing water demand and prolonged the projected life span of the aquifer by nearly 20 years, following a temporary dip in pumping rates around the year 2008. Growing demand for groundwater outpaced conservation efforts in the case studies with negligible groundwater renewability (Iullemeden, North-Western Sahara and Nubian).

For the single case study with groundwater pollution mitigation as its primary governance objective (Abbotsford-Sumas), the perceived effectiveness of the transboundary taskforce is implicit in its official incorporation within a decade after its informal emergence. Specifically, a joint knowledge base was developed to cover land use, nitrates, volatile organic compounds

and public health. The taskforce enabled ad-hoc stakeholder consultations but was faced with a lack of structural funding and waning political will. As a result, mean nitrate concentrations remained high, although peak values were lowered.

Implications for institutional design and policy recommendations

Our comparative analysis shows that the case studies differ widely in institutional design, suggesting that contextual factors shape transboundary aquifer governance efficacy. We examined how physical, watershed and political variables shape the incentives for the governance of transboundary aquifers.

The role of institutional design in efficacy

Our findings suggest that the most significant contributors to efficacy in transboundary aquifer governance are in the following dimensions of institutional design: (1) institutional structure and mandate; (2) objectives and baselines; and (3) monitoring and adaptive capacity. However, we find mixed evidence for the contribution of the dimensions of normative foundations and authority and legality.

The institutions that rank most favourably in efficacy have institutional structures and mandates tailored to a specific sustainability issue (e.g., Abbotsford-Sumas, Genevese and Hueco-Bolsón). Problem-based institutionalization reduces the need for a broad range of technical capacities and enables the relevant stakeholders to target resources more efficiently. Moreover, clarity on objectives and baselines is an important prerequisite for the efficacy of transboundary aquifer governance. When the knowledge base was not already substantial at the onset of institutionalization efforts (such as in Genevese), aquifer states embark on joint fact-finding efforts. This serves to identify key pressures and drivers, calibrate the appropriate scale for governance, and identify solutions to any governance issues that prompted the institution's emergence. In a couple of cases, aquifer states initiated this process before any impacts of sustainability issues were observed (Guaraní and Iullemeden). Our cases suggest that data and information availability comprise a necessary condition for effective transboundary aquifer governance. Further, experiences with managed artificial recharge (Hueco-Bolsón and Genevese) and sustainable land-use practices (Abbotsford-Sumas) suggest innovative and adaptive governance approaches have great potential to enhance sustainable development when supported by groundwater sustainability monitoring systems.

Our findings suggest that a robust normative foundation that embodies certain normative principles is not strongly correlated with the efficacy of transboundary aquifer governance. For the highest-scoring aquifers on the normative foundation index, there is only mixed evidence of active implementation efforts supporting these principles. Further, these case studies were assessed as having low efficacy for delivering on their overall mandate. Similarly, the more formal and legalistic mechanisms (except for the Genevese agreement) have not necessarily translated to better governance or groundwater management outcomes with respect to efficacy. However, the two other institutions with similar status to the Genevese (Saq-Ram and Guaraní) are less than 10 years old, necessitating caution in drawing early conclusions on the role of authority and legality in transboundary aquifer governance efficacy.

Contextual variables shaping institutional design

Our analysis suggests the efficacy of transboundary groundwater governance institutions to deliver on their mandates is, up until now, related to aquifer size and hydrological homogeneity. The three case studies ranked as highly effective in terms of at least one governance objective are among the world's smallest aquifers (Abbotsford-Sumas, Genevese and Hueco-Bolsón). Relative homogeneity in hydrological conditions and groundwater dependence translate into shared perceptions of sustainability issues, governance objectives, and solution areas (although this coincides with high socio-economic integration). Larger case studies tend to focus on localized areas of observed depletion or pollution. For example, the Saq-Ram agreement applies to a border strip covering a fraction of the spatial extent of the aquifer system. The Guaraní agreement provides for local committees, presumably for those parts where perceived sustainability risks are most pressing.

Our analysis suggests that governance formality is shaped by groundwater dependence and disparities in exploitation capacity. Particularly, unilateral development of a transboundary aquifer seems to increase the willingness of the other aquifer states to commit to more formal or legalistic governance institutions (Nubian and Saq-Ram). This finding is consistent with the literature on large-scale infrastructure and rural–urban water transfers as a 'catalyst' of negotiations related to transboundary waters. Moreover, our case studies suggest governance efficacy can vary over time, subject to (among other aspects) the emergence of competing domestic or regional priorities. Our analysis echoes political science arguments that governance design reflects underlying power relations and constellations of interests in the broader context of deliberation (e.g., Mitchell & Zawahri, 2015).

Exogenous factors may catalyse the emergence of governance institutions for transboundary aquifers and reflect in institutional design. For example, the conclusion of international treaties and ministerial declarations followed years of intensive and well-financed project activity in four case studies (Guaraní, Iullemeden, Nubian and North-Western Sahara). This suggests international development (finance) institutions gravitate towards larger aquifers where degradation would potentially impact the health and livelihoods of large numbers of people. The involvement of international finance institutions and other international organizations is also reflected in a broad normative foundation. This finding is consistent with notions of policy convergence and 'diffusion' in environmental governance literature (Busch & Jörgens, 2005; Conca et al., 2006).

Our case studies suggest that alignment and complementarity between policies enhance governance efficacy. This includes horizontal alignment with other policy domains for integrated water resource management and vertical embeddedness of groundwater governance across administrative levels. In the case of the Abbotsford-Sumas, parallel emergence of national policies and water quality standards enhanced the effectiveness of the collaborative efforts to curb pollution in the transboundary aquifer. Similarly, in the Saq-Ram case study, national policies to prioritize municipal water needs emerged in parallel to transboundary aquifer governance, overriding long-standing food security prioritization. Finally, in the Hueco-Bolsón case study, the pursuit of water source diversification – including water conservation and reuse, managed aquifer research, and desalinization – may have helped mitigate depletion. This is consistent with the conclusions of Conti and Gupta (2014) on legal pluralism in groundwater governance.

Based on the analysis above, we have drawn two main conclusions on the efficacy of transboundary aquifer governance:

- In the small sample of cases reviewed, efficacy is closely linked to problem structure reflected in the institutional design, which implies that effective transboundary aquifer governance institutions can appear in a range of shapes and forms. When aquifer states agree on the primary groundwater governance problem being exigent and aquifer-wide, governance is more effective concerning its defined objective. Narrowly defined objectives allow resources to be dedicated exclusively to resolving the primary problem. Our smaller case studies with well-defined institutional mandates are well positioned for effective governance (although these also have high-capacity stakeholders). However, if key stakeholders have different perceptions of urgency or the problem definition is primarily precautionary, there is a more pressing need for a broad normative foundation. The combination of the broad normative foundation and misaligned (or loosely aligned) incentives for governance can result in a lower level of efficacy (beyond the areas of data collection, monitoring and information exchange).
- Efficacy is heavily influenced by contextual factors that are rarely explicitly addressed within the institutions' mandates. Our findings suggest that initial gains in groundwater conservation and water-use efficiency may be offset by watershed-level developments, including land-use change and large-scale infrastructure development, resulting in waning efficacy over time. Long-term efficacy of transboundary groundwater governance thus requires sustained commitment from key stakeholders and the political will and financial resources to maintain an ongoing dialogue between aquifer states. In these cases, groundwater governance institutions can be pockets of effectiveness for implementing broad-based principles. However, unless the approach is nested within a (moderately) functional broader institutional context, sound institutional design is unlikely to overcome challenges related to technical and institutional capacity in groundwater governance. Further, the involvement of external actors can be conducive to effectiveness to the extent that it helps bring about the convergence of values (beyond the embodiment of legal principles on paper), develops a shared knowledge base, and builds mutual trust. However, when institutional design is significantly influenced by the presence of external actors, the level of efficacy is less predictable and less attributable to the governance mechanism itself.

These conclusions suggest that normative and policy-driven approaches to institutional design can unlock sustainable groundwater development, including vis-à-vis populations dependent on groundwater for their livelihoods and groundwater-dependent ecosystems. Our findings demonstrate that promoting groundwater governance at the appropriate scale is paramount and that capabilities of responsible entities should be accordingly (aligned with OECD Principles 2 and 4). These also highlight the vital role of innovation and adaptiveness in groundwater governance, backed with monitoring infrastructure (aligned with OECD Principles 5 and 8). Further, our conclusions echo the role of cross-sectoral coordination in pursuing policy coherence (OECD Principle 3) and the need for frameworks that help manage trade-offs across water users, rural and urban areas, and

generations (OECD Principle 11). Nevertheless, the adoption of broad-based principles is not a sufficient condition for groundwater governance efficacy since the governance process appears to be more significant than the resulting mechanisms.

We propose the following recommendations enhancing the efficacy of groundwater governance as related to leveraging the OECD Principles:

- Governments and the international development community should prioritize according to problem intensity. This would consider the *extent of transboundary* effects of groundwater development on either side of the border (based on aquifer characteristics and flow regime), which is not necessarily standing practice.[6] Focusing on those aquifers or aquifer segments that would have severe drawdown or pollution issues, now or in the future, would help to ensure efficient allocation of scarce resources in international development.
- Supporting innovation and adaptiveness in transboundary groundwater governance is critical. The growing reliance on groundwater resources for their buffer capacity in the context of climate change adaptation only increases the need for adaptive and innovative management approaches supported by groundwater sustainability monitoring systems. Adopting a 'learning-by-doing' approach allows stakeholders to pivot collaborative management practices that mitigate negative human impacts, while expanding the hydrogeological knowledge base and building mutual trust. The focus should be on pilots and demonstration projects with the potential for benefit-sharing and scaling up.

Future research could focus on the interplay of physical, watershed and political variables from a comparative perspective. This could include the development of quantitative indicators of aquifer-level heterogeneity in terms of hydrological conditions, groundwater exploitation capacity differentials and land-use change. It could also include political factors such as the number of negotiating parties, the quality of international relations and the structure of national political decision-making models (Zawahri et al., 2016). Our findings suggest an underestimation of transboundary externalities such as groundwater drawdown and salinization in some cases, reflecting politicization of knowledge development processes in the context of socio-economic disparities (Elshall et al., 2020). The concept of hydro-hegemony, which considers power dimensions and (dis-)advantages inherent in the geographical position of up- and downstream countries, does not directly translate to groundwater. Future research may apply this concept to transboundary aquifer governance.

Notes

1. These include information gathering, advisory, regulatory, resource monitoring and compliance monitoring.
2. For aquifers with limited to no renewability (i.e., fossil aquifers), we consider 'addressing depletion' to mean that aquifer states have created and are adhering to some agreement around groundwater pumping that would substantially increase the aquifer's longevity.
3. That is, the *Convention on the Protection, Utilization, Recharge, and Monitoring of the Franco-Swiss Génévois Aquifer* (1978; renewed 2007), the *Guaraní Aquifer Agreement* (2010; entered into force 2019), and the *Agreement for the Management and Utilization of the Ground Waters in the Al-Saq/Al-Disi Layer* (2015).

4. Note the potential disparity between the location of the no-drilling zone between Chad and Sudan and the vulnerability to transboundary impacts.
5. Libya's Great Manmade River Project was designed to supply 6.5 billion m^3 per year from the Sahara region to the densely populated Mediterranean coast at an estimated cost of US $25 billion. While it currently supplies 70% of freshwater consumed in Libya, experts estimate its lifespan at less than 100 years (Sternberg, 2016). The Disi Water Conveyance project, operational since 2013, was designed to carry 100 million m^3 per year (over a lifespan of 25 years) across 325 km from the border zone to Amman (Van den Berg et al., 2017).
6. For instance, in monitoring the implementation of Sustainable Development Goals, progress on indicator 6.5.2 is measured as the 'proportion of transboundary basin area with an operational arrangement for water cooperation'.

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ORCID

Maya Velis http://orcid.org/0000-0001-5685-285X
Kirstin I. Conti http://orcid.org/0000-0002-2599-8626
Frank Biermann http://orcid.org/0000-0002-0292-0703

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