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RESEARCH ARTICLE



## Unraveling transboundary water security in the arid Americas

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### ABSTRACT

Transboundary waters are characterized by diverse and complex socio-political-economic obstacles to effective water management. We examine five distinct cases in the arid Americas – in locations from the US–Mexico border to the Andes mountains – employing water security as a conceptual prism to unravel the multiple and varied attributes of transboundary water challenges. We describe how borders complicate water security in arid regions and explore how institutional arrangements and practices – within and across jurisdictions – respond to these challenges. We find that institutional capacity is needed on multiple levels for effective water management, and institutions must be responsive and flexible to change.

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Arid regions; climate; institutions; transboundary; water security; the Americas

## Introduction

Physiographic regions – defined by unique geography, climate and ecosystems – often span human-drawn borders of nation-states or other political jurisdictions across which governance structures and processes may diverge (e.g., state, municipal, tribal). While such transboundary regions are divided politically and administratively, their ecosystems and natural resources – and water resources in particular – remain connected.

Until the 1980s, discussion of issues peculiar to these cross-border regions usually focused on surface water in the context of large international catchments, with

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disagreements over allocation of their waters spawning river-basin commissions and sometimes treaties. But other than in regions of potential conflict, the literature on natural-resources management infrequently evoked transboundary issues.<sup>1</sup> Instead, management at a country or jurisdiction level was emphasized. As scholars and water professionals began to appreciate the prevalence and significance of such basins (Udall & Varady, 1994; Varady & Morehouse, 2003; Wolf, Natharius, Danielson, Ward, & Pender, 1999), they also recognized that transboundary situations are characterized by socio-politico-economic obstacles – e.g., asymmetrical infrastructure, disparate national values and interests, contrasting institutional arrangements, and the conflicting needs of upstream versus downstream riparian states – that challenge effective management (Kliot, Shmueli, & Shamir, 2001; Marty, 2001; Morehouse, 1995).

Over the past three decades, approaches to transboundary water management have emphasized nation-to-nation cooperation, international treaties and agreements, and multinational organizations. All these instruments have been proposed to address challenges of hegemonic control, equitable use, conflict resolution, and coordination – with transboundary rivers the most common objects of these efforts. Early studies include Wolf (1998), Hamner and Wolf (1998), Falkenmark and Lundqvist (1999), Milich and Varady (1999), Marty (2001), Sadoff and Grey (2002), and Uitto and Duda (2002).<sup>2</sup> In the case of water, these approaches promote local-level participation and individualized treaties to address the site-specific nature of transboundary challenges (Blatter & Ingram, 2001; Conca, 2005; Feitelson & Haddad, 2001; Gerlak, 2004; Ingram, Laney, & Gilliland, 1995; Schmeier, 2013; Van der Zaag & Savenije, 2000; Zeitoun & Mirumachi, 2008; Zeitoun & Warner, 2006). Since the early 2000s, other types of transboundary contexts for water have been increasingly recognized that do not necessarily follow basin boundaries, such as international river-water transfers, effluent exchanges, and import/export of ‘virtual water’ via water-intensive goods and produce (Allan, 2002, 2011). In short, cross-border water contexts are richly varied and complex.

In this paper, we employ water security as a conceptual prism to unravel the multiple and varied attributes of transboundary water challenges and distinguish the most pertinent water-security attributes for five cases in the arid Americas. Water security is a broad, integrative concept, incorporating many attributes, including aspects of water supply, such as water quantity and quality; water access, affordability and equity; water use for the environment and safeguarding ecosystems; and protection from water-related hazards, such as floods and droughts (e.g., Bakker, 2012; FAO, 1996; GWP, 2000; Grey & Sadoff, 2007; Norman, Bakker, Cook, Dunn, & Allen, 2010; OECD, 2013; Scott et al., 2013; UNESCO, 2013; UN-Water, 2013). A water-security framing facilitates examination of water challenges at multiple spatial scales, and invokes a range of types of institutional capacity to address water challenges at multiple governance levels (Bakker & Morinville, 2013).

Our five cases – in locations from the US–Mexico border to the Andes mountains – feature different geophysical and socio-political transboundary contexts that are thematically distinct. Yet, all are in arid-to-semiarid regions, where local surface water scarcity is a common challenge. Given the complexity introduced when political borders transect resource systems, in addition to the highly place-specific nature of water management, we expect to find a range of multidimensional water-security challenges and an equally broad array of institutional responses.

We begin by describing our case-study approach and the water-security framing technique we employ for analysis. Then we present five distinctive case studies. In addition to some brief background and historical context, we outline the water-security attributes and highlight the key institutional and policy dimensions. Further detail for each case study appears in the online supplementary material (<https://doi.org/10.1080/02508060.2018.1541583>). In the discussion, we synthesize across the cases with an eye to the commonalities of our case-study research. We conclude with lessons for water-security research in water-scarce transboundary regions of the American continent, while suggesting that those lessons also may be relevant for other arid-to-semiarid regions.

## Our approach

### *Seeing transboundary water issues through a water-security prism*

In recent literature, water security has been defined in various ways that incorporate multiple attributes. Conceptual and empirical research emphasize aspects of adequate quantity, sufficient quality, access, ecosystem health, and protection from risk or hazards (Gerlak et al., 2018). Table 1 shows the range of water-security attributes identified in frequently cited definitions appearing in academic literature and policy documents. We adopt a broad approach to water security, emphasizing in-depth, qualitative analysis as opposed to a reductionist, quantitative approach (Zeitoun et al., 2016).

Because of the overriding importance of place, we can expect certain attributes of water security to be more, or less, predominant in different locations, scales and

**Table 1.** Water security attributes and source definitions (adapted and revised from Gerlak et al. 2018). In each category, attributes are listed in order of frequency. Each source definition included at least six attributes.

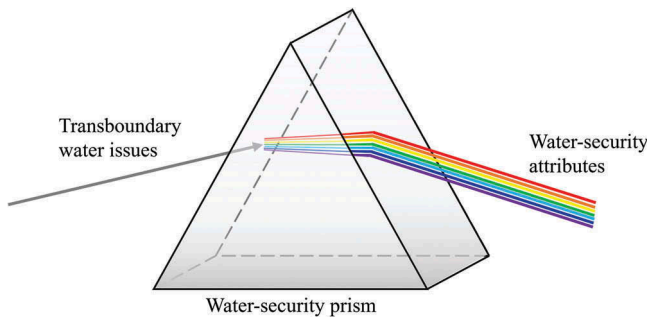
Water Security Attributes	Physical	Quantity Quality Ecosystems Watersheds Global change	<i>Sources: FAO 1996; GWP 2000; Grey &amp; Sadoff 2007; UNEP 2009; Norman et al. 2010; Zeitoun 2011; Lautze &amp; Manthrilake 2012; Bakker 2012; OECD 2013; UNESCO 2013; UN-Water 2013; Scott et al. 2013; Jepson 2014; Wheeler &amp; Gober 2015; Gain et al. 2016</i>
	Human	Access Health/Well-being Economic growth Political stability* Policy Livelihoods Sanitation Time/Reliability Preference Transport Industrial resources	
	Cross-cutting	Sustainability Risk/Hazards Resilience Uncertainty Food and energy resources	

\*Includes peaceful international relationships, intra-national political stability, and national security.

contexts (Cook & Bakker, 2012; Gerlak et al., 2018; Jepson, 2014). Attributes of water security in Table 1 can be argued to be more fundamental (e.g., quantity, quality) or more influential – meaning they have a strong effect on fundamental aspects – for example, resilience to global change (Scott et al., 2013), political stability (UN-Water, 2013), or food and energy policies (Varis, Keskinen, & Kummu, 2017). Many factors can influence water security – and its obverse, insecurity – including culture, politics, power relationships, level of cooperation, infrastructure, and management regimes (Gerlak et al., 2018). In international contexts, peaceful inter-state relations and intra-state stability are particularly relevant to water-security frames (Jepson, 2014). However, transboundary water security involves more than formalized international cooperation, treaties and agreements – it encompasses many aspects of how societies use water resources (Mirumachi, 2013).

To portray the varied attributes of water security demonstrated in Table 1, we conceptualize water security as a prism through which transboundary water issues can be examined. When viewed through the prism of water security, multiple attributes are revealed for each case study – much in the way a dispersion prism separates white light into its constituent colours (Figure 1). We use the water-security prism as an analytical tool, combined with in-depth case study analysis, to distinguish the most pertinent aspects of transboundary water issues for each case from among the many that can characterize water security. The resultant key water-security attributes for each case reflect the highly contextualized and multidimensional nature of water-resource challenges. For example, in some transboundary contexts, the pressures of economic development and political contention may be most critical to understanding water security; in other places, ensuring equitable water access and sanitation may be paramount.

Guided by the attributes of water security, we scrutinize the transboundary character of each case – that is, how a water source (stream, aquifer, glacier) or activity (water transfer) interacts with boundaries to influence water security. Recognizing that the transboundary character of shared water sources is profoundly influenced by how political entities govern and use these resources (Sanchez & Eckstein, 2017), we pay special attention to the geopolitical, institutional and economic aspects of transboundary water utilization – particularly how these conditions can deteriorate and change in response to water-security challenges.



**Figure 1.** Conceptual diagram of the water-security prism used to separate transboundary water issues into various water-security attributes.

## Case-study approach

Following Yin (2003, 2017), we use a qualitative, descriptive case-study approach to determine how water-security challenges are manifested in five illustrative border regions of the arid Americas. We ask, how do borders influence water-security challenges in the arid Americas? And what institutional responses to such challenges can we observe? To address these questions, we identify key water-security attributes that are evident in: (a) water-security challenges, (b) the influence of the transboundary context, and (c) institutional capacity and transboundary cooperation. Knowledge and information on the cases is derived from multiple sources, including local expertise, fieldwork, and attendance at stakeholder workshops, formal meetings, and science-policy dialogues – buttressed by document analysis and literature reviews.<sup>3</sup>

In a north-to-south continuum across the Americas our cases feature an assortment of physical and socio-economic landscapes (Figure 2). Table 2 describes each case's defining features, which include various types of water supplies shared across borders – surface water, groundwater, desalinated water, and glacial sources. They also represent a host of water-security concerns intersecting with instances of cross-border political friction, many of which underscore long-standing geopolitical conflict or disparate ecopolitical power among water users. The cases are all located in semiarid-to-arid environments,<sup>4</sup> where water-resource challenges are pronounced due to surface water scarcity – a condition that is expected to worsen given climate-change projections (IPCC 2007, 2014; Maestre, Salguero-Gomez, & Quero, 2012). In the discussion that follows the case studies, we synthesize lessons learned across the arid-Americas studies.

## Five transboundary cases, five water-security challenges

In this section, we discuss each case study, guided by our framing of water security as a spectrum of various attributes (Table 1; Figure 1). For each case, we link our observations to water security by identifying each case's relevant attributes, which are emphasized in italics.

### **Case study 1. Water security and groundwater in the binational Santa Cruz River basin: cooperation in the contentious US–Mexico border region**

Spanning the US–Mexico border, the Santa Cruz River basin encompasses the cross-border Ambos Nogales urban corridor – the neighbouring cities of Nogales, Sonora, and Nogales, Arizona (Figure 3). Here, and throughout the border region, rapid industrialization, urbanization, and population growth have occurred over the past few decades on the Mexican side, fueled by US consumer demands and a comparatively weak Mexican economy – causing uneven development patterns and stressing the natural environment (Varady & Ward, 2009). Economic asymmetries also contributed to periods of high migration rates and a resultant long-standing US security presence at the border (Varady & White, 1992). Despite periodic disagreements between the two countries on certain border issues<sup>5</sup> and stark differences in legal-political systems, when it comes to water, they have historically found ways to cooperate. Viewed through the water-security prism, this case highlights the key attributes of water *quality*, particularly

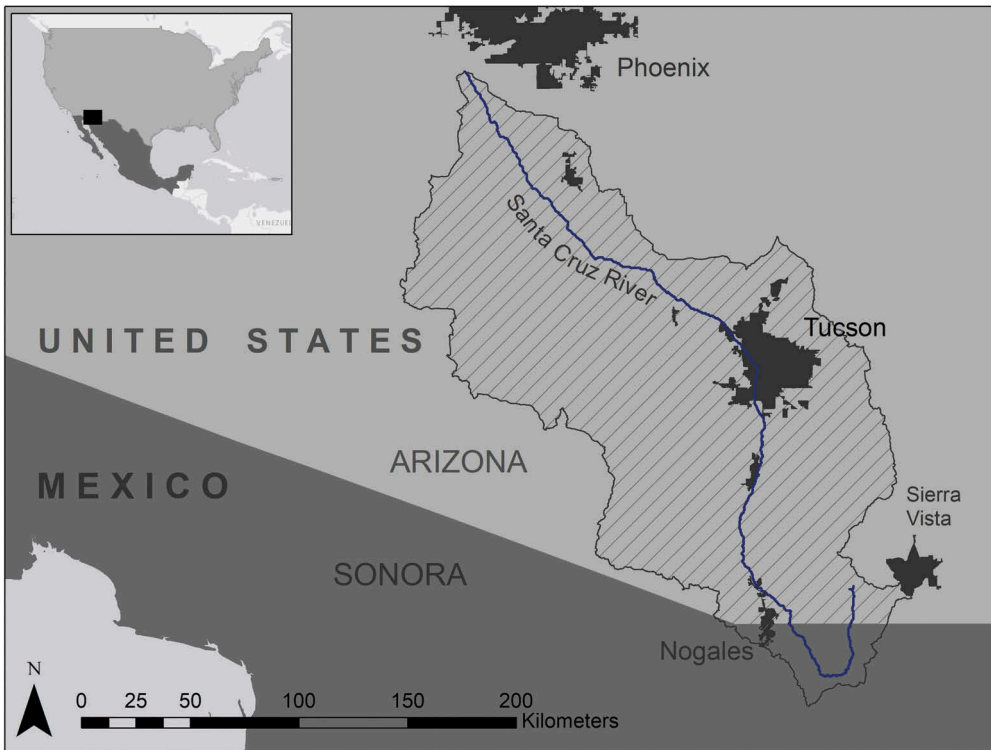


**Figure 2.** The American continent, showing the five case studies. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

as it relates to *sanitation*, as well as water resource *uncertainty* in the face of *global change*. It also brings to the fore how asymmetric *economic growth* and *political* contention complicate transboundary water security.

### **Water-security challenges**

As a semiarid basin with limited surface water, the region relies heavily on groundwater supplies for the cross-border urban corridor, as well as for agricultural water uses on the US side and industrial uses on the Mexican side (Scott, Megdal, Oroz, Callegary, & Vandervoet, 2012a). Easily accessible, shallow groundwater is vulnerable to drought (Shamir et al., 2015), and while deeper stores are sheltered from climatic fluctuations, they are costlier to tap, and their long-term sustainability is largely unknown (Nelson, 2007). On the Mexican side of the border, local groundwater is insufficient to meet



**Figure 3.** Location of Santa Cruz River basin, crossing the border between Arizona (US) and Sonora (Mexico). The aquifer lies within the basin. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

demands – up to 40% of the water used in Nogales, Sonora, is transferred from the Los Alisos basin to the south (Wilder et al., 2012).

On both sides of the border, pollution threatens water security. Nogales, Sonora, has undergone rapid economic and population growth over the past two decades due to expansion of the *maquiladora* industry (foreign-owned plants) that boomed in northern Mexico following the passage of NAFTA<sup>6</sup> (EPA & SEMARNAT, 2013). The population in Nogales, Sonora, has grown to over 200,000 (INEGI, 2010) – nearly 10 times the population of its Arizona sister city (US Census, 2015). This rapid growth stresses the natural environment, particularly because wastewater infrastructure development has not kept pace with increases in industrial and domestic wastewater production. Statewide, wastewater-treatment coverage in Sonora is less than 40% (CONAGUA, 2016). In Nogales, large populations live in off-grid residential areas (*colonias*), which typically lack municipal services (Kelly-Richards & Banister, 2017). Leaks from old or overworked pipes, open wastewater discharges in areas where wastewater infrastructure is unavailable, and system overflows that occur during storm events contaminate shallow groundwater and surface water (Kapoor, 2017). Because the growing urban areas of Nogales, Sonora, are upstream of Arizona, wastewater treatment is a transboundary concern.



**Table 2.** The five case studies at a glance.

Site	Location	Defining issue	Climate	Authors
Upper Santa Cruz Basin	Arizona–Sonora (US–Mexico) border region	Transboundary groundwater	Semiarid Sonoran/Chihuahuan Desert; 35–90 cm annual precip.; most occurs during monsoon (July–September)	Albrecht, Megdal, Varady, Lutz-Ley
Northwest Mexico Desalination	Coastal areas of Sonora and Baja California	Supply enhancement via binational desalination	Semiarid Sonoran Desert and Upper Gulf of Mexico; less than 30 cm annual precip.	Zuniga-Teran, Lutz-Ley, Pineda
Catamayo–Chira River Basin	Western transboundary Ecuador–Peru area	Transboundary river basin spanning a historically contentious international border	High variability in precip. across basin (sea level to 3700 m elevation)	Taboada, Willems
Ica River Basin	South-central Peru	Trans-jurisdictional hydro-hegemony within a single nation	Varies throughout basin from cold and humid in headwaters (4600 m elevation) to dry, desert along Pacific coast; and from 1 cm (lower basin) to 77 cm (upper basin) annual precip.	De Grenade, Taboada
Maipo River Basin (Chile) and Mendoza River Basin (Argentina)	Interglacier river basins in central Chile and Argentina	Montane glacier-fed basins from a shared source–region	Maipo: 29 cm annual precip.; Mendoza: 23 cm annual precip. Both: low-lying areas influenced by strong intra-annual and interannual variability (e.g., ENSO) <sup>a</sup>	Ocampo Melgar, Meza, Martin, Rojas

<sup>a</sup>ENSO: The El Niño Southern Oscillation produces wet El Niño years, in contrast to dry La Niña years (Aceituno, 1989).

### *Influence of the transboundary context*

Groundwater supplies are vulnerable to pollution and overuse on both sides of the border. While researchers suggest that groundwater extraction and pollution in Mexico will affect groundwater availability and quality downstream in Arizona, the extent of such impacts is uncertain (Milman & Scott, 2010). Limited scientific data and an incomplete understanding of the hydrogeology of the Santa Cruz Aquifer, particularly its degree of interconnection across the international border, complicate the task of addressing water security in this transboundary region.

Asymmetries in water governance between the US and Mexico also complicate international water cooperation (Table 3). Mexican water management is highly centralized at the federal level (Scott & Banister, 2008). Water-rights allocation is managed by the Mexico City-based National Water Commission (CONAGUA), which is far removed from transboundary water issues in the northern state of Sonora.

In the US, in contrast, water is mostly governed at the state level, with management tasks often split among multiple agencies (Table 3; Milman & Scott, 2010). For example, in Arizona water quality is in the domain of the Arizona Department of Environmental Quality, while water rights and allocations are administered by the Arizona Department of Water Resources. Management of surface water and groundwater resources is also conducted separately (Megdal & Scott, 2011). Arizona regulates groundwater use via comprehensive legislation designed to maintain ‘safe yield’<sup>7</sup> and prevent long-term groundwater-level declines (1980 Groundwater Management Act, Arizona Revised Statutes §45–561). The area of the Santa Cruz basin in Arizona was designated a separate Active Management Area in 1994.

**Table 3.** Organizations involved in Arizona and Sonora water governance (adapted from Milman & Scott, 2010).

Organization	Role
<b>Arizona</b>	
City of Nogales	Local water utility
Santa Cruz Active Management Area	Regional groundwater planning and management
Water Resources Research Center	State, university-based research institute
Arizona Dept. of Water Resources	Administers and enforces Groundwater Management Act
Arizona Dept. of Environmental Quality	Establishes and enforces water-quality standards
US Geological Survey	National-level scientific research agency
<b>Sonora</b>	
OOMAPAS	Municipal water utility and sanitation provider
Sonora State Water Commission (CEA)	Coordinates water-supply programmes and planning
Organismo de Cuenca Región II Noroeste	Develops regional water plans with public and private users
National Water Commission (CONAGUA)	Governs water rights, allocation and regulation
<b>International</b>	
Transboundary Aquifer Assessment Program	Binational scientific assessment of priority transboundary aquifers
Border Environmental Cooperation Commission	Approves environmental infrastructure and gives technical assistance in border regions
AZ-Mexico Commission and Commission Sonora-Arizona	Non-profit organizations, facilitate trade and public/private collaborations in border region
International Boundary and Water Commission	Interprets and implements the 1944 Water Treaty; provides avenue for binational cooperation, dispute resolution

### *Institutional capacity and transboundary cooperation*

Despite asymmetries, the US and Mexico have a long history of cooperation on water. In 1906, the Boundary Waters Convention was created to resolve transboundary surface water issues on the Rio Grande River. The 1944 Water Treaty addressed international allocations of the Colorado, Rio Grande and Tijuana Rivers, and transboundary sanitation issues.<sup>8</sup> This agreement also established the International Boundary and Water Commission (IBWC),<sup>9</sup> which provides binational institutional capacity, offering a formal pathway for joint processes, dispute resolution, and a mechanism for binational cooperation (Mumme, 2015).

In the Upper Santa Cruz basin, the two countries have cooperated on a binational solution for insufficient wastewater-treatment capacity in Nogales, Sonora – a problem that threatens groundwater on both sides of the border, along with ecosystems and streams. The Nogales International Wastewater Treatment Plant, constructed in 1951 and enlarged, relocated, and modernized several times since, has treated a significant portion of wastewater effluent from Nogales, Sonora, since its inception (Ingram et al., 1995). However, there is still tension between the two countries regarding payment for wastewater treatment services as a consequence of elevated flows sent by Mexico during storm events, and disagreement among US agencies regarding who is responsible for repairs of the leaking conveyance system (Kapoor, 2017).

While there is a tradition of formal binational cooperation on water, existing binational accords do not specifically address shared groundwater.<sup>10</sup> Without a formal agreement on groundwater, cooperation has progressed in other ways. The most meaningful advance is the Transboundary Aquifer Assessment Program (TAAP), a binational partnership for scientific assessment and data collection on transboundary aquifers.<sup>11</sup> The IBWC played a central role in developing the TAAP by designing a joint process by which the US and Mexico could cooperate at the national level. The joint process limits TAAP activities to those that benefit both countries and requires that they neither infringe on the legal frameworks of individual nations nor contradict existing binational agreements (IBWC, 2009).

The main aim of the TAAP is to improve transboundary-groundwater knowledge through scientific assessment via binational, aquifer-specific technical committees (Megdal & Petersen-Perlman, 2018). Yet, in addition to data-collection and information-sharing advances, the TAAP has also helped build cross-border relationships and promote community outreach (Megdal & Scott, 2011). Organizations on both sides of the border – the Universidad de Sonora, Comisión Nacional del Agua, USGS, and University of Arizona – have engaged in activities including binational hydrogeologic mapping and modelling (via technical meetings), stakeholder workshops, site visits, multi-state meetings and binational summits. A binational, bilingual Santa Cruz assessment report is expected in 2019.<sup>12</sup> In addition to the TAAP, numerous other efforts in the Upper Santa Cruz basin have benefited from collaboration among university researchers and NGOs.

The Upper Santa Cruz case illustrates how US–Mexico asymmetries in economic development, infrastructure, legal-political structures, and implementation of environmental policies, combined with groundwater dependence and climate change uncertainty, complicate water security. Nevertheless, both formal agreements and less formal cooperative scientific efforts have been achieved. Efforts in this basin demonstrate the

value of (1) addressing resource challenges through an existing international commission, and (2) focusing initially on technical aspects that avoid sovereignty concerns while productively addressing information gaps that are key to water-security challenges. This is one approach to enhancing transboundary water security even in the face of political barriers – other approaches may better address other types of water-security challenges, as we see in the next case.

### **Case study 2. Water security and desalination in the US–Mexico border region: binational implications of water transfers**

Binational desalination – that is, desalination that takes place on one side of the border, but benefits both sides either directly or indirectly – is seen by some as a potential solution to water scarcity for the US–Mexico border region (Wilder et al., 2016). This case examines the water-security implications of proposed desalination facilities that would be located on the northern coast of Sonora, Mexico, but provide water supplies for both Mexico and the US. Using the water-security-prism framing (Figure 1), concerns about the region’s fragile *ecosystems* and insufficient water *quantity* come to the fore. It also reveals how *transport* and *energy* requirements for desalination elevate the cost of water, affecting water *access*. And within the existing complex institutional setting and volatile *political* environment, effective environmental *policies* are needed to ensure a balance of benefits for both sides.

#### **Water-security challenges**

The US–Mexico border region is subject to environmental, demographic and economic forces that compromise water security (Leichenko & O’Brien, 2008). In terms of environmental forces, water scarcity is heightened by climate variability and change, and by overexploitation of the Colorado River, a major transboundary river, and aquifers. In the semiarid Sonoran Desert, rivers and creeks are intermittent or ephemeral, and precipitation is scant (Table 2). Climate projections for the western US–Mexico border region in particular – combined with social and political forces – suggest likely rises in water scarcity and water demand (Garfin et al., 2014). Economic growth, including crop agriculture, ranching, mining, manufacturing and urbanization, along with associated population growth in the border region, further increases water demand (Wilder et al., 2012). Specifically, the Upper Gulf of California (or Sea of Cortés) is a semi-enclosed sea that has been heavily impacted for decades by lack of inflow from its main source, the Colorado River (Kennedy, Rodríguez-Burgueño, & Ramírez-Hernández, 2017). In addition, groundwater has been the main water source for decades, and aquifers throughout the Sonoran Desert region are at the brink of depletion or are already depleted (Palma, González, & Cruickshank, 2015).

#### **Influence of the transboundary context**

This transboundary region exhibits an uneven distribution of populated areas and multiple jurisdictions with different water-management approaches. As mentioned in the previous case study, this region – divided by the US–Mexico international border – features different languages, cultures, legal traditions, forms of government and levels of development on either side. The borderline cuts through the Sonoran Desert ecosystem

and the historical territories of indigenous groups, like the Tohono O'odham Nation. As noted above, the neighbouring nations pursue very different water-management and governance approaches. In such a setting, binational issues typically have been handled through nation-to-nation approaches.

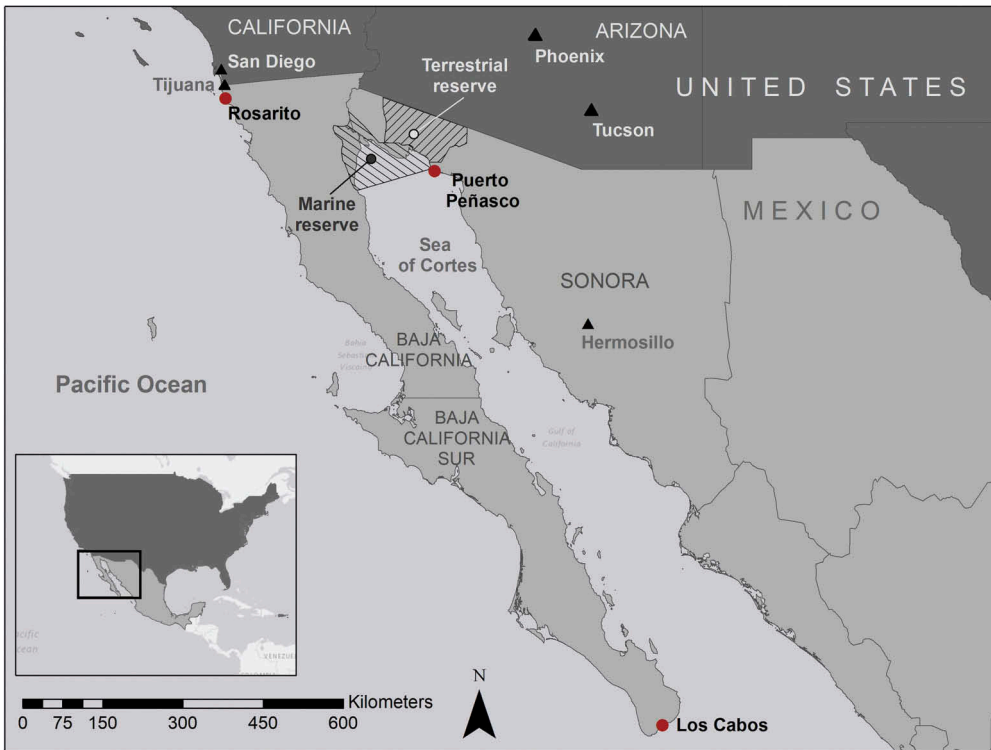
As water managers in both countries search for additional water supplies that can sustain an increasing population under projected water shortages, desalination has emerged (for some) as an attractive, 'drought-proof', water-security-enhancing option (Hirt, Snyder, Hester, & Larson, 2017). Recently some local steps and agreements have been made towards this end. In 2012, for example, IBWC signed an agreement on research exploring two prospective desalination plants (Figure 4). The first would be in Rosarito, Baja California, along Mexico's Pacific coast; and the second in Puerto Peñasco, Sonora, on the Sea of Cortés (IBWC, 2012).

A desalination plant in Rosarito could deliver desalted water to the city of San Diego in California (Dibble, 2014). A plant in Puerto Peñasco could provide desalted water for Arizona and possibly Nevada, depending on the facility's scale (Wilder et al., 2016). An alternative binational desalination scheme relies on the US investing in a desalination plant in Mexico in exchange for water rights from the Colorado River. However, in spite of the benefits offered by these two binational projects, the prospects for their actual construction remain unclear. Mexico's CONAGUA would be the ultimate arbiter for such projects, but it has remained silent on them, the main apparent obstacle to approval (Wilder et al., 2016).

In addition to securing CONAGUA's approval, all such initiatives must navigate a maze of legal and administrative challenges. Several reasons render these efforts politically sensitive, and they are viewed by many officials as a losing proposition, with the US reaping the lion's share of the benefits (more water), and Mexico bearing the brunt of the costs, especially environmental externalities associated with desalination. A desalination plant such as the one proposed for Puerto Peñasco would likely affect commercial fishing and sensitive ecosystems that are currently designated as a marine reserve (Figure 4) (Hirt et al., 2017; Ocasiot, 2015). The primary by-product of desalination – a brine that is deposited into the sea – alters the salinity and temperature of the coastal marine ecosystems (Gleick, 2015; Ocasiot, 2015). The desalination technology also employs chemicals that harm some marine species, and the intake process inevitably catches fish (Gleick, 2015). If desalted water is conveyed to the US, terrestrial ecosystems could also be negatively affected by the conveyance system. Pipes would need to cross a protected area, the Pinacate y Gran Desierto de Altar Biosphere Reserve, which lies between Puerto Peñasco and Arizona, fragmenting the reserve and disturbing the habitat of many terrestrial species (Wilder et al., 2016).

### ***Institutional capacity and transboundary cooperation***

Inadequate environmental regulations for monitoring and handling brine disposal in Mexico exacerbate the consequences of ecological degradation due to desalination. The Ministry of Natural Resources and the Environment (SEMARNAT) does require an environmental impact assessment for the construction of a desalination plant, and CONAGUA would need to issue a discharge permit. But beyond these two requirements, there exists no regulation for brine discharges (McEvoy, 2015). Environmental regulations for desalination are urgently needed in Mexico to protect ecosystems and



**Figure 4.** Location of desalination plants and marine and terrestrial reserves in the Sonoran Desert. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

related livelihoods (Pombo, Breceda, & Valdez Aragón, 2008). Other important factors for binational desalination are the huge energy requirement and the greenhouse-gas emissions associated with the process (Meerganz von Medeazza, 2005). The use of renewable sources is not currently feasible for large-scale energy supply (Wilder et al., 2016), which constrains cost–benefit ratios.

Should binational desalination at these sites or elsewhere become a reality, US cities undoubtedly would be the largest consumers of the desalinated water. But such projects also can be attractive to Mexico, because additional water would allow Mexican cities to grow and develop, while also providing local employment. What remains uncertain, however, is how Mexican enterprises and residents would pay for desalinated water that would cost seven times what they pay now (Wilder et al., 2016). The desalination plant in Los Cabos, Baja California, offers a glimpse of what could happen to make water prices affordable for the local residents: the city highly subsidizes the desalted water, absorbing the high cost of production – but with no sustainable future for business operation (McEvoy, 2014).

Although desalination shows promise for increasing supply, it has a steep price. Binational desalination that creates disproportionate negative externalities for Mexico could enhance disparities and aggravate binational political tensions (Hirt et al., 2017). Elucidating the various water-security attributes of this case reveals that improving water security for the transboundary Sonoran Desert and Upper Gulf of California

region will require multiple conditions: technical and environmental feasibility of the binational desalination project and its conveyance system; new, more favourable economic conditions, including cheaper renewable sources of energy; a more responsive and innovative institutional framework that includes monitoring of the environmental impacts of desalination; and a more integrative, cooperative and mutually beneficial binational political relationship. In the next case, we examine another pair of neighbouring nations, Ecuador and Peru, where political relationships are similarly influential in transboundary water security.

### **Case study 3. Water security in the Ecuador–Peru border region’s Catamayo-Chira basin: limitations of local coordination in a binational river basin**

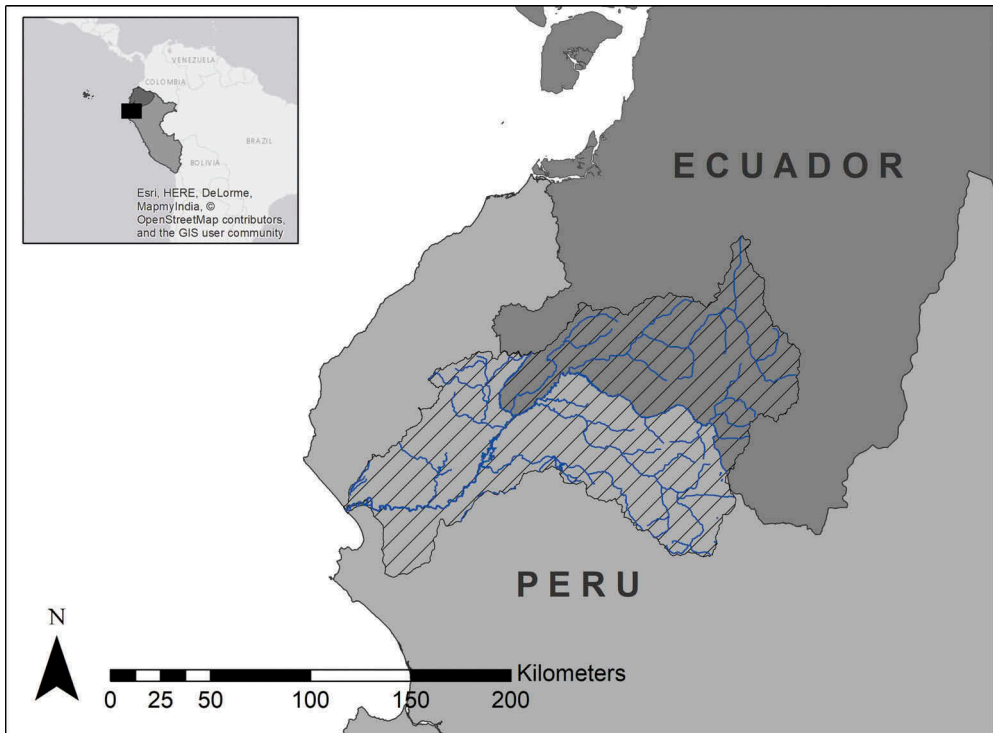
The transboundary Catamayo-Chira basin crosses the mountainous Ecuador–Peru border (Figure 5). In both nations, the basin’s residents struggle to access sufficient water for their daily needs. Cooperation on water management between Ecuador and Peru, which have a long history of conflictual relations, has evolved slowly but consistently (Toledo, 2017). Still, differences in management and institutional structures make it difficult to address binational water challenges. Viewing this case through the water-security prism exposes the need for effective *policies* and international coordination – i.e., promoting peace and assuring *political stability* – between the foreign ministries of Ecuador and Peru to close the gap in transboundary water-security challenges – primarily water *quality, sanitation and access* – that have for years been addressed mostly locally.

#### **Water-security challenges**

Water-security challenges in the Catamayo-Chira basin are driven by high climatic variability (e.g., the El Niño Southern Oscillation) and anthropogenic impacts on water quality, which contribute to insufficient access to drinking water and uncertainty for local livelihoods, which rely on irrigated agriculture. Access to potable water is a perpetual challenge – only 59% of basin inhabitants have potable water service (PNUD, 2015). Dumping of untreated wastewater from domestic, agricultural, industrial and mining activities degrades surface water quality (ANA, 2015). Although considerable aquifer storage is estimated, groundwater use is limited (AECID, 2005). To compound water-supply and quality challenges, service providers are generally unreliable, and potable-water management remains weak. Due to increased rainfall variability, surface water storage reservoirs are becoming less reliable. On the Peruvian side, the Poechos reservoir maintains less than 50% of its original capacity (which was 1000 Mm<sup>3</sup>) due to sedimentation. Traditional practices – such as *tajamares* (protective walls) and *albarradas* (artificial, earthen-dike wetlands) – through which small dams store water, have been abandoned and not yet replaced with functional management regimes (PNUD, 2015).

#### **Influence of the transboundary context**

On the national level, Ecuador and Peru have their own institutional structures to guide water governance (Table 4). However, these arrangements differ between the two countries, and both management systems and regulations have been inconsistent over



**Figure 5.** Location of Loja Province, Ecuador, and Piura Province, Peru, and the Catamayo-Chira River basin. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

time. While in Peru a water law was approved in 2009 that included specifications for water management in transboundary basins (motivated in part by Peru’s goal of rising to the economic level of OECD full-member countries), in Ecuador a new water law was not approved until 2014. During the absence of specific legal and institutional frameworks in both nations – according to some Peruvian technicians involved – dialogues regarding Integrated Water Resources Management (IWRM) in transboundary basins were infrequent.

Ecuador and Peru had a sustained period of border conflict and political crisis, from their early-nineteenth-century beginnings until 1998. However, as in other border regions, political tensions were often transcended by strong cultural kinship and high social mobility between border communities, which increased economic transactions and strengthened cultural connections. In spite of political conflict, the international border did not prevent the circulation of ideas, people and products (Hocquenghem & Durt, 2002).

The 1998 peace agreement and other efforts towards international cooperation – such as the Catamayo-Chira Binational Project, promoted by the Spanish Agency for International Development Cooperation (AECID) – have deeply influenced local communities thanks to direct-intervention strategies in border areas. One of this project’s outcomes was the 2011 Land Use Planning, Management and Development Plan for the Catamayo-Chira transboundary basin, which was recognized by local authorities in Loja (Ecuador) and Piura (Peru) but not endorsed by other government levels. Nevertheless,



**Table 4.** National-level regulatory instruments in the Catamayo-Chira basin.

Instrument	Ecuador	Peru
Environmental management	Decentralized System of Environmental Management (2004)	National System of Environmental Management (2004)
Water management	National Environmental Policy (2011)	Environmental National Policy (2009)
	Strategic National System of Water (2014)	National System of Water Resources Management (2009)
Water-resources policy	Organic Law of Water Resources, Use and Exploitation (2014) and bylaw (2015)	Water Resources Law (2009) and bylaw (2010)
	National Plan of Water (2016)	National Policy and Strategy of Water Resources (2015)
		State Policy of Water Resources (2012)

Source: Water Secretariat (Ecuador) and Water National Authority (Peru).

the local governments of Loja and Piura have spearheaded efforts at cross-border dialogue, sidestepping mediations that are typically regulated by the two foreign-affairs ministries. Such local-level actions typically are less sensitive to sovereignty issues than national-level dialogues.

### *Institutional capacity and transboundary cooperation*

Institutionally, both countries have changed how they manage their water resources. For example, in 2009 Peru adopted an IWRM approach accompanied by a new organizational architecture; comparably, in 2014, Ecuador established new institutional practices for water-resources management. In Peru, the Autoridad Nacional del Agua (ANA, the National Water Authority) is responsible for managing water resources and serves as the highest technical and regulatory authority in the National System of Water Resources Management. As in many countries with important agricultural sectors, this institution is housed within the agricultural ministry. ANA coordinates with the foreign-affairs ministry when signing multinational agreements for integrated water management in transboundary basins. In the structure of Peru's new water-resources law, the Sub-directorate of Transboundary International Waters was created in the foreign-affairs ministry. This agency executes and evaluates foreign policy to safeguard Peru's transboundary-waters interests. Thus, Peruvian law assigns ultimate authority for management of these interests to its foreign-affairs ministry, with technical participation from ANA.

In Ecuador, the National Water Secretariat (SENAGUA) is responsible for guiding water-resources management in an integrated and sustainable way using an ecosystem approach. Created in 2008, SENAGUA operates directly under the Presidency of the Ecuadorian Republic, with its own resources and budget, and with technical, operational, administrative and financial independence. As in Peru, the Ecuadorian Ministry of Foreign Affairs and Mobility shares the authority to establish binational-cooperation guidelines to maintain proper functioning of the Binational Development Plan. This ministry is a member of the binational Ecuador-Peru Neighbourhood Commission, which promotes and coordinates programmes, projects and activities according to the interests of both countries.

In addition to the national ministries, extra-governmental actors (e.g., USAID, European Union, Spanish AECID, German GIZ, and Swiss SDC) often play an important role in moderating bilateral water-resources governance in the Catamayo-Chira

basin via local- and national-scale projects. Examples include providing seed funds to implement basin-level water-resources management, and promoting binational dialogues whenever appropriate.

Some regional institutions – such as organizations, policies, binational strategies, and agreements – exist between Ecuador and Peru that help guide transboundary water-resources management (PNUD, 2015; Binational Development Plan, 2016; Toledo, 2017):

- Presidential Statements between Ecuador and Peru (2007, 2009, 2010, 2012–2017)
- Proposed Binational Commission for IWRM between Ecuador and Peru (2015)
- Quadripartite agreement between ANA (National Water Authority, Peru)–SENAGUA (National Water Secretariat, Ecuador)–Binational Plan–Binational Fund Ecuador Peru (2014)
- Andean Strategy for IWRM in the frame of the Andean Commission of Nations (2011)
- Binational Plan for Border Region’s Development (2007)
- Peru-Ecuador Comprehensive Border Integration, Development and Neighbourhood Agreement (1998).

The presence of institutional frameworks and legal water-management tools offers the potential to encourage and enhance binational dialogues and actions in the Catamayo-Chira basin. Yet, current policies and agreements do not yet provide a clear basis for binational cooperation, and national-sovereignty concerns between Ecuador and Peru often prevail over environmental ones. Nevertheless, according to basin water-management representatives, similarities between the two nations are more common than differences, especially regarding water quality and ecological conservation.

The possibility – even if it remains remote – of achieving consensus on water issues that affect both sides of the border may represent the limit of bottom-up processes. The Catamayo-Chira Binational Project illustrates the challenge of translating local-level capacity into higher-level (e.g., national or binational) understanding. In this basin, water availability, quality and access clearly are difficult to secure in view of physical conditions and anthropogenic impacts – in addition to national-sovereignty sensitivities. But the recent design of tailored, cooperative institutional frameworks, some of them binational, offers hope for overcoming those barriers and solving mutual problems jointly and equitably. Designing legal frameworks and policies to promote equitable water security can be a challenge, even within a single nation, as the next case demonstrates.

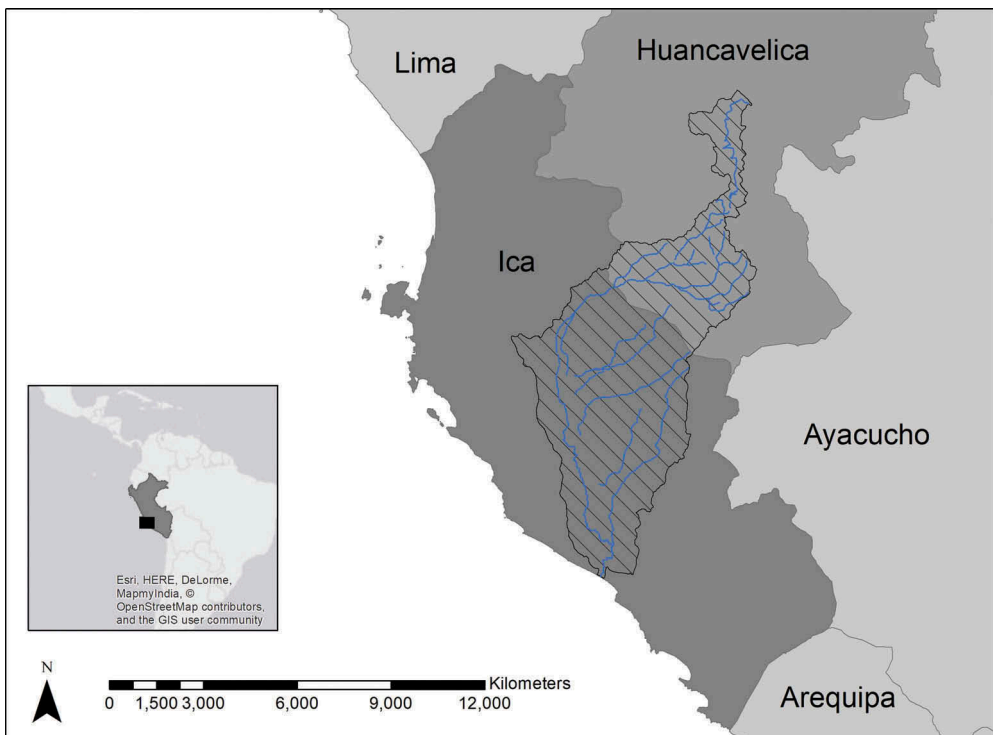
#### ***Case study 4. Water security in Peru’s subnational Ica River basin: transjurisdictional asymmetries between poor upstream and prosperous downstream provinces***

The Ica River basin extends across two departments in Peru,<sup>13</sup> and thus represents a *transjurisdictional*, transboundary context situated entirely within one country (Figure 6). In spite of a single political system and shared language and culture, multiple water security challenges are revealed via the water-security prism. These stem from the Ica River basin’s extreme disparities between the two departments – most notably, in water

quality, economic growth, sanitation, political stability/power, transport, and water-resource access. This basin presents an atypical upstream–downstream relationship, where downstream water users hold more economic and political power than those upstream. The Peruvian government is planning to expand interbasin transfers to further supply the downstream, coastal communities, but these plans have spurred regional conflict.

### **Water-security challenges**

Water-security challenges characterize the entire basin, though they are very different in coastal and highland areas. In the coastal lowlands around the city of Ica, the agricultural (e.g., for export) and industrial sectors rely heavily on groundwater, which has declined rapidly. As new areas of reclaimed desert are converted to agricultural production, thousands of deep wells are being drilled in the valley. Many smallholder wells and urban wells have gone dry, leaving suburban and rural families without access to water. Extreme responses have included corruption among water users and regulators, ‘land grabbing’ for water-rights access, efforts to use surface water to recharge the aquifer, and now pressure to expand the existing interbasin Choclococha transfer project – a system of tunnels, reservoirs, and canals – to draw more Amazon basin water to the dry Pacific Ica basin (Cárdenas Panduro, 2012; Damonte, Pacheco, & Grados, 2014; Urteaga, 2014). Water quality has been degraded by urban and industrial waste from



**Figure 6.** Location of the Ica River basin in central Peru. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

intensive agriculture, expanding urban and peri-urban centres and lack of public facilities, and highly permeable desert soils.

In the intermountain and the high-alpine *puna* regions, water insecurity presents another paradox: plenty of rain falls, but water shortages may remain because precipitation is spatially and temporally uneven, and because surface water may be highly contaminated by livestock, human waste, and mining activity. In a survey of Ica basin residents in the department of Huancavelica, Herz Sáenz and Huamán Arias (2014) found that 74.5% of interviewees experienced consistent water scarcity, and 16.4% said that water was scarce during some times of the year and/or in some locations. Many families struggle to provide water for irrigation and livestock, and most do not have basic water services – either access to potable water nearby or septic facilities (INEI, 2007). Fuel to boil water is scarce, and access to medical facilities to treat water-borne diseases is often unavailable.

### ***Influence of the transboundary context***

Intra-national, transjurisdictional challenges – e.g., between neighbouring states or provinces – are highlighted in the Choclococha interbasin transfer system, completed by the Peruvian government in 1958 to move water from the Andes-Atlantic Pampas basin to the Andes-Pacific Ica basin. In Peru, the Amazon basin receives 90% of the water, but 90% of population is in the arid Pacific basin. By capturing Amazonian-slope water and transporting it via a mountain tunnel into the Ica River to flow for some 320 km to the Pacific coast, the Choclococha project expanded irrigation in the Pacific coastal lowlands of the valley by 10,000 hectares. Along the flow path, in the Tambo intermountain region, Choclococha water has extended available canal water by several months, though farmers in other tributaries still rely heavily on rainfall and springs. Approximately two-fifths of the Choclococha water is lost to infiltration, evaporation and use before it reaches the Ica, accelerating demand for still more water to be diverted from the highlands and increasing political, environmental and social conflicts (PETACC, 2010).

The prospect of a Choclococha expansion has generated tension among residents of both Huancavelica and Ica, as national-government-funded projects draw even more Andean highlands and Amazonian Pampas basin water for the needs of coastal agriculture, industry, and urban expansion. Although both Ica and Huancavelica are geographically involved in this project, thanks to its superior economic power and prominence in federal politics, the Ica regional government downstream determines the legal and political outcomes of water-resource decisions (Damonte Valencia, 2015; Geng, 2016). While Huancavelica's rural and isolated communities upstream have participated actively in the policy process and in integrated-policy dialogues, their influence in water distribution and use has been very limited.

Water demand in Ica has fueled myths, tensions, inequity in representation, and conflicts at all scales, such as altercations between small farmers and agro-exportation companies, domestic and agricultural users, and Ica and Huancavelica for their respective water rights (Boelens & Vos, 2012; Hepworth, Postigo, Güemes Delgado, & Kjell, 2010; Herz Sáenz & Huamán Arias, 2014). A common perception – based on our experience in science-policy dialogues and stakeholder meetings – is that Huancavelica is water-rich, and water is either not needed (because the region is too cold to grow

crops), used inefficiently, or not as necessary as in Ica. Lima-based NGOs and politicians have exacerbated the dichotomy for political reasons, either to integrate this case as a component of environmental/conservation strategies or as part of a larger political agenda, primarily in the context of state elections. Huancavelica residents have received only small advantages from the interbasin transfer (e.g., locals are employed seasonally to clean the canals) while losing a large part of their water resource. At the same time, they maintain that the effects of the diverted water on downstream communities in the Pampas basin, on the eastern Andes slope, remain unexamined.

### ***Institutional capacity and transboundary cooperation***

Currently, Ica and Huancavelica state agents and NGOs are engaging in natural-resources management dialogues to resolve water conflicts. Ica, with its economic advantage and political power, dominates the debate. The Peruvian government has exercised contradictory roles in the process, taking advantage of dialogue progress to push for the extension of the Choclococha system while also supporting other minor regional development projects and environmental agreements. The decision-makers remain largely those with political sway – local water authorities from both states have participated in these discussions, but have not significantly influenced the outcomes (Geng, 2016).

Across the Andean gradient, mountain-based mining and hydroelectric generation and lowland agro-export industry support a thriving national economy and enhance the communities' resource security. Still, resource challenges and competition have contributed to environmental degradation, social deprivation, and conflict. Additional drivers directly and indirectly impact farmers' and consumers' livelihoods.<sup>14</sup> NGO and government initiatives have promoted idea exchanges between Ica and Huancavelica, but the thriving coastal economic engine still holds sway. In such a setting, inadequate water security and insufficient transboundary discourse could worsen environmental, economic and social outcomes in the Ica Valley.

The Peruvian inter-state, transboundary Ica–Huancavelica example illustrates the potential for *intra-national* tensions, even where participants share common nationality, languages, culture, laws, and political frameworks for resolving water conflicts. The degree of mutual animosity and conflict in Peru underscores the even greater difficulty of achieving *international* transboundary agreements, which may not offer the collective domestic benefit needed for water-management solutions. The next case demonstrates the challenges of achieving international coordination for regional collective benefits when water security is complicated by uncertain future conditions and water sources lie far removed from residents' everyday lives.

### ***Case study 5. Water security in the Andes: climate change and transboundary glacial headwaters in the Chile–Argentina border area***

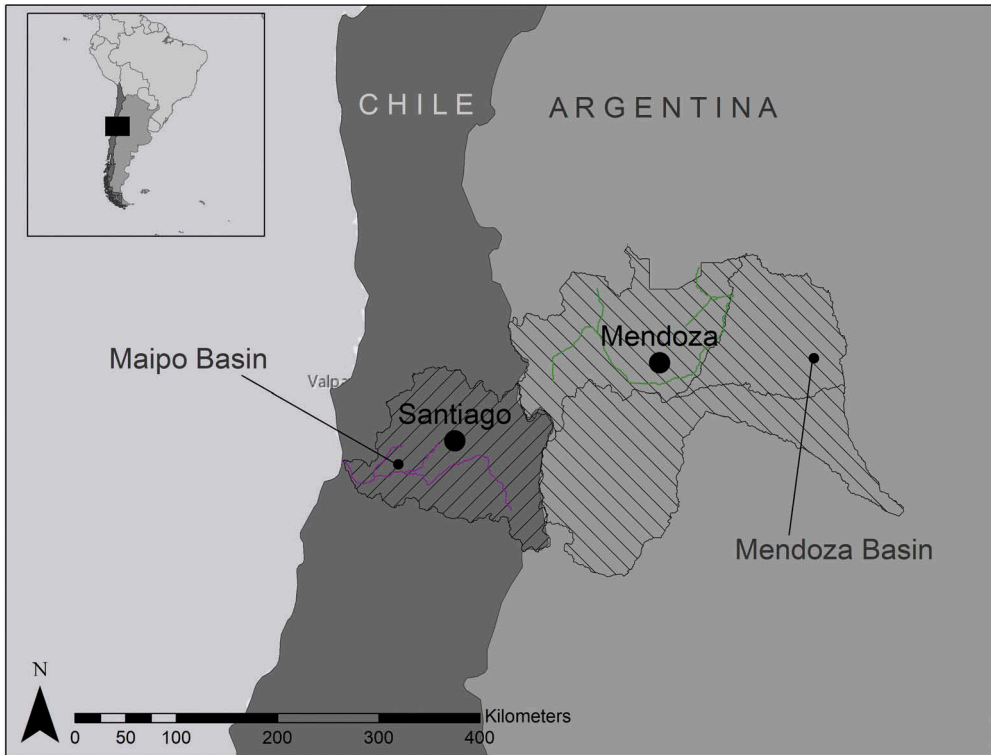
Meeting in the Andes mountains at the international divide, the Maipo and Mendoza River basins share a common origin in the high-elevation mountains (Figure 7). Downstream urban areas – the Chilean capital of Santiago and the Argentinian city of Mendoza – both depend on snowmelt and glaciers that traverse the Chile–Argentina international border as a chief component of their water supplies.

This case highlights an unusual transboundary context, yet one that is sure to become more important in areas where climate change threatens the high-mountain glaciers and seasonal snowpack that supply water for users downstream. Viewed through the prism of water security, this case sheds light on the *uncertainty* involved in water-security challenges driven by *global change* and the potential conflict between preserving glacial water sources – which provide water *quantity* – and advancing the supply of *industrial resources*. In Chile and Argentina, government *policies* and private-sector activities regarding Andean glaciers affect both nations’ water security.

### **Water-security challenges**

Due to its relatively low precipitation, this transboundary region supports agriculture only with irrigation. In Mendoza, agricultural systems, mainly vineyards, olive groves, fruit orchards and vegetable farms, form a growing oasis (Abraham & Villalba, 2008). New agricultural projects, along with residential and touristic developments, have stressed existing surface water distribution systems and increased reliance on groundwater. Current irrigation practices – surface application of large volumes of water – are inefficient and degrade soil and groundwater quality.

Over the last few decades, increasing urban development and commercial expansion (e.g., petroleum exploitation and tourism) in the Mendoza basin have raised water demands on local aquifers (Hurlbert, 2018). The situation in the Maipo basin is similar,



**Figure 7.** Location of the Maipo River (Chile) and Mendoza River (Argentina) basins. Basemap sources: Esri, DeLorme, HERE, MapmyIndia.

but in this basin (which covers twice the area of the Mendoza basin) agriculture and industrial activities (e.g., mining) must coexist with the major urban centre of Santiago. In the upper reaches of both basins, high-elevation open-pit mines pose a risk of pollution, and are often below glaciers – key water supplies for downstream areas (Khadim, 2016).

Both basins experience interannual hydroclimatic variability (alternating wet and dry years) associated with the El Niño Southern Oscillation (Aceituno, 1989). Long-term trends suggest that reductions in snow accumulation and accelerated glacier melting will likely reduce basin-wide water availability (Masiokas, Villalba, Luckman, Le Quesne, & Aravena, 2006). More winter precipitation will fall as rain, versus snow (Surfleet & Tullos, 2013), causing ‘rain-on-snow’ events that can reduce glacier water storage and cause earlier and faster melting periods. These changes could also prompt severe flash flooding in the mountain foothills.

The lower water availability and rising water demands will likely affect the reliability of water-use rights for agriculture differently in each basin (Meza, Wilks, Gurovich, & Bambach, 2012). This is because water rights in Mendoza are tied to the land, whereas in Chile water rights can be obtained via trades, independent of land ownership. In this context, water-management schemes that are adaptive and use alternatives for supply and demand management are becoming critical (Richardson, Steffen, & Liverman, 2011).

### *Influence of the transboundary context*

In this transboundary region, the Maipo and Mendoza basins are linked via trade and economic activities. The route connecting Mendoza to Santiago is an important commercial link that transports five million tonnes of merchandise annually. Both basins largely rely on agricultural and related activities (e.g., vineyard-associated tourism) that depend on Andean snowmelt. In addition to agriculture, a key contributor to the national GDP of both Chile and Argentina is mining, which directly threatens water resources.

While Chile and Argentina have taken individual approaches to glacier conservation, a coordinated, transboundary strategy would help ensure preservation of these high-mountain supplies throughout the region. Glaciers, which provide critical baseflows during drought, are considered priority water-security resources because of their imminent threat of depletion. In contrast, the importance of seasonal snowpack is sometimes overlooked and considered an easily replenished resource.

### *Institutional capacity and transboundary cooperation*

Chile and Argentina have advanced differently with regard to glacier conservation and management. Regional advocacy for glacier-conservation legislation was spurred by large-scale, open-pit Andean mining projects in the early 2000s. The initiative began as local efforts to preserve indigenous peoples’ water and land access in response to the Barrick Gold Corporation’s Pascua-Lama and Veladero projects. These developments, located in high-elevation Andean crests in Chile and Argentina, incited local and national environmental advocacy movements (Talliant, 2013). Social and environmental activist groups organized protests, road blockages and publicity campaigns, and lodged formal complaints with the OECD (Khadim, 2016).

In Argentina, these environmental movements garnered the support of NGOs, researchers and political parties to promote a glacier-protection law in 2008 (Law 26.418; Scott et al., 2012b). While the law was initially vetoed due to mining-sector pressure (Isla Raffaele, 2016), its promoters launched a major national campaign denouncing the sector's complicity with the national executive power and raising awareness of the importance of protecting the sources of watersheds (Isla Raffaele, 2016; Wagner, 2017). Finally, in 2010, the glacier law was sanctioned (Law 26.639, 2010). The Argentinian National Glacier Act (Talliant, 2013) prohibits activities that could alter the natural condition of glaciers, including mining and oil exploration; protects freshwater and biodiversity; and mandates a national glacier inventory (Khadim, 2016), be completed in 2017. Mining is also legally regulated in the province of Mendoza (Law 7722, 2007).

However, while the Argentine national government has a mandate to prevent pollution, provinces have original jurisdiction over natural resources – thus, controversy exists regarding who can approve mining projects (Talliant, 2013). The ongoing power struggles between the Argentinian national government and provinces – which might benefit from permitting economic development – reveal a limitation of federal policy-making on this issue.

Environmental organizations and indigenous groups have staged opposition to mining expansion in high-mountain areas in Chile, as well. While local opposition movements have been supported by national environmental NGOs, Chilean government support for these movements is limited. Local governments typically side with mining companies to support economic development, and the national government has failed to pass comprehensive legislation or to address the petitions of opposition groups (Urkidi, 2010). While limited discussion on this issue continues, a national law for glacier conservation does not appear to be on the horizon.

Although there have been a few formal agreements between the two countries – one example is the Treaty on the Environment and the Additional Protocol on Shared Water Resources (1991) – binational channels established by environmentalists and scientists have been much more prevalent than channels at the state level. Researchers at IANIGLA<sup>15</sup> and other Argentine scientific institutions cooperate regularly with Chilean counterparts, as well as with a variety of environmentalists. IANIGLA is leading an effort to map and catalogue glacier formations.

Recently, due to a series of cyanide-laden spills at the Veladero mine in Argentina's San Juan Province, environmental activists sued IANIGLA scientists for not inventorying glacier formations smaller than one hectare.<sup>16</sup> The scientists argue that it is not methodologically feasible to delineate such minor formations and that their contribution to runoff is insignificant. This approach garnered criticism from environmental groups, who claimed that IANIGLA was not doing enough to implement the full scope of the glacier-protection law. This case has thus become a great 'socio-technical-cum-legal' controversy that adds enormous complexity and foreshadows a difficult resolution. Institutional arrangements are needed that help align scientific approaches with social and environmental concerns.

It appears evident that the Maipo and Mendoza River basins, though they are in different nations, might have to prepare jointly for a water-secure future. Among the steps needed to assure snow and ice protection in the Andes are: adaptive operating



rules for water-distribution systems; increasing investments in low-cost technologies that promote enhanced water-use efficiency and equitable distribution; and development of dedicated, coordinated glacier-protection programmes. These steps would increase resilience to climate change and strengthen water security in this important trans-Andean region.

## **Discussion: water security and institutional responses in transboundary contexts**

Examining transboundary water issues through the water-security prism helps unravel the multiple and varied attributes of transboundary water challenges in the arid Americas. The challenges identified reflect the multidimensional and multi-attribute nature of water security, and how transboundary contexts may further confound already complex challenges. Our study also highlights how institutional responses were employed – or are still needed – in each case. In [Table 5](#), we summarize the key water-security attributes, transboundary nature, water-security challenges, institutional capacities and legal frameworks for our five case studies.

Overall, in terms of water-security challenges, we find that in arid environments, water quantity and quality and the uncertainties of climatic changes are common concerns. The need to protect existing water sources from pollution – whether caused by industrial sources or a lack of adequate wastewater infrastructure – came to the fore in multiple cases (e.g., the Upper Santa Cruz, Catamayo-Chira and Ica basins). Climate-change drivers of water insecurity were particularly relevant for groundwater and glacial-water sources (e.g., Upper Santa Cruz, Andean glaciers). For example, rising water demands coupled with likely reductions in groundwater recharge in the US Southwest (Meixner et al., 2016) may make groundwater dependence in the Upper Santa Cruz basin unsustainable. Climate-change impacts on glaciers are expected to be significant – worldwide, glacier retreat is expected to reach 60% by 2050 (Bates, Kundzewicz, Wu, & Palutikof, 2008) – a concern for shared Andean glacial stores.

Our cases also exhibited distinctive water-security challenges. Some cases focused more on water supplies – either emphasizing conservation of existing sources (e.g., the Andes glaciers) or expanding supplies via technology (e.g., binational desalination) and interbasin transfers (e.g., the Ica basin). The negative impacts on ecosystems and the cost of energy needed to desalinate and transport water supplies is a concern specific in the Northwest Mexico case (e.g., binational desalination). Access to potable water was a salient feature of both the Ica and the Catamayo-Chira River basin cases. Our analysis also identified issues related to the water–energy–food nexus (e.g., Ica basin and Andean glacier cases) and the water–energy nexus (e.g., binational desalination). Still other water-security attributes revealed in the case studies reflect their transboundary nature, as we discuss below.

### ***How are issues of water security affected by transboundary conditions?***

Our case studies demonstrate that almost invariably, the presence of borders compromises water security in arid regions. Although we discover that many factors compound the challenge of addressing water security in transboundary contexts, particularly

**Table 5. Key observations of five case studies.**

Site and location	Key water-security attributes	Transboundary nature	Water-security Challenges	Institutional capacity	Legal frameworks
Upper Santa Cruz basin, Arizona–Sonora, US–Mexico border	<ul style="list-style-type: none"> <li>• quality</li> <li>• sanitation</li> <li>• global change</li> <li>• uncertainty</li> <li>• economic growth</li> <li>• political stability</li> </ul>	Binational aquifer (and basin)	Cooperation on transboundary aquifer assessment amid contentious binational relations	Transboundary Aquifer Assessment Program (science-based); International Boundary and Water Commission; national water commission (Mexico); state water management agencies (US)	1944 Water Treaty and La Paz Agreement limited for groundwater
Northwest Mexico Desalination, Sonora and Baja California, Mexico	<ul style="list-style-type: none"> <li>• quantity</li> <li>• ecosystems</li> <li>• energy</li> <li>• transport</li> <li>• policy</li> <li>• political stability</li> </ul>	Binational desalination and water transfers	Binational implications of water transfers from desalination plants in fragile ecosystem and volatile political environment	International Boundary and Water Commission; national water management and environmental agencies (Mexico)	Limited environmental regulations in Mexico; underdeveloped framework for binational benefit-sharing
Catamayo-Chira River Basin, Ecuador–Peru border	<ul style="list-style-type: none"> <li>• quality</li> <li>• sanitation</li> <li>• access</li> <li>• policy</li> <li>• political stability</li> </ul>	Binational river basin	Institutional arrangements to govern transboundary rivers amid international mistrust and dispute	Andean Commission of Nations; Binational Commission for IWRM; Binational Plan for Border Region Development; Peru-Ecuador Comprehensive Border Integration, Development and Neighbourhood Agreement; national water policies	Peru water law (2009); Ecuador water law (2014); binational peace agreement
Ica River Basin, south-central Peru	<ul style="list-style-type: none"> <li>• quality</li> <li>• sanitation</li> <li>• access</li> <li>• economic growth</li> <li>• transport</li> <li>• political stability</li> </ul>	Subnational, transjurisdictional river basin	Transjurisdictional asymmetries between poor upstream and prosperous downstream provinces	Ica regional government; state agents and NGOs	Peru national water law (2009)
Maipo River Basin (Chile) and Mendoza River Basin (Argentina) – Andean glaciers	<ul style="list-style-type: none"> <li>• quantity</li> <li>• global change</li> <li>• industrial resources</li> <li>• policy</li> <li>• uncertainty</li> </ul>	Binational glacial headwaters	Changing water availability from transboundary sources of ice and snowmelt	National water agencies; civil society groups; scientific institutions (IANIGLA)	Argentina’s National Glacier Act; Treaty on the Environment and Additional Protocol on Shared Water Resources (limited inclusion of glaciers)

problematic conditions are traditions of political contention and cross-border asymmetries that inhibit coordinated institutional responses.

The Catamayo-Chira River basin in Ecuador and Peru offers the starkest contrast between neighbouring countries. Fueled by a history of contentious international relations, Ecuador and Peru developed strategies for water management by different methods on vastly different timelines. As a result, their respective institutional arrangements for managing water do not align well. The tense political history between these nations has heightened concern about each nation's individual sovereignty, challenging attempts towards faster international negotiation. As noted by long-time water-conflict scholar Aaron Wolf (2007), such imbalances in growth and institutional capacity, accompanied by a tradition of contentious relations, confound international cooperation over shared water.

National-sovereignty concerns and incongruous institutional arrangements for water governance also confound water security between the US and Mexico. Cross-border coordination is more difficult due to differences between the centralized Mexican system and the decentralized, often fragmented, US system of water governance.

Information asymmetries also persist across borders, particularly when dealing with hard-to-measure groundwater resources. Sufficient information is not always available to both sides because nations and agencies may be unwilling to share it, or the appropriate channels for sharing it do not exist, or the extent, type and quality of the collected data differ (Linton & Brooks, 2011; Milman & Ray, 2011). Accordingly, binational efforts on transboundary groundwater in the Upper Santa Cruz basin (e.g., the TAAP) have focused on addressing information asymmetries through scientific assessment, while simultaneously avoiding national-sovereignty concerns.

Moreover, economic, social and cultural asymmetries – and their effect on binational power dynamics – emerge as complicating attributes for transboundary water security. Along the US–Mexico border, Mexico has experienced faster industrial and urban growth in the past few decades than the US. In the Upper Santa Cruz basin, this trend has resulted in asymmetric water needs, infrastructure development, pollution risks and overall water insecurity across the border. We observe that desalination – while seemingly attractive as a technical solution for increasing water supplies – fails to address water-security concerns in the region sustainably, or equitably. Instead, transnational disparities are emphasized, and manifest themselves in an uneven distribution of environmental externalities, such as degraded ecosystems and a steep rise in water prices. These would be shouldered by Mexican communities, as desalinated water is shipped across the border to the US. Such mismatches between who benefits from such water projects and who pays (via environmental impacts) may impede cooperation (Fischhendler & Feitelson, 2003).

As our Peruvian case illustrates, economic asymmetries and uneven political power, even within a single nation, can make equitable water security difficult to achieve. In the Ica River basin, while upstream communities might typically have greater control over water resources (Zeitoun & Warner, 2006), economic disparities are so dramatic they trump hydrologic position. Upstream communities, while closer to reliable water sources, are disadvantaged and experience water insecurity due to their low economic means. Downstream communities exert control via structural and financial means, building infrastructure to capture water from upstream basins. Amidst economic

disparities, institutions that promote equitable allocation and benefit-sharing are critical. In multiple cases (e.g., the binational desalination, Catamayo-Chira and Andean glacier cases), the need for effective water-management institutions and policies – at subnational, national, and binational levels – was a key theme.

### ***What have we learned about institutional responses to transboundary water-security challenges?***

Overall, in our cases, we discern a broad range of institutional responses to transboundary water-security challenges, from informal cross-border cooperative scientific research, to social movements that inspire national legal frameworks, to binational frameworks being developed between historically contentious neighbours. Across all cases, the need for robust and well-coordinated institutions for water management was consistent. Addressing water-security challenges in particular calls for context-specific governance approaches (Gerlak et al., 2018) that are adaptive, multilevel and attentive to social power (Bakker & Morinville, 2013). Our case studies suggest that in transboundary contexts, institutional capacity is needed on multiple levels, and institutional arrangements and practices need to be flexible and responsive to changing or emerging conditions.

Effective institutional arrangements are often invoked to address transboundary water issues, such as conflict resolution, risk management and trade-off negotiation (Pahl-Wostl, Palmer, & Richards, 2013). Yet, institutional approaches are implemented at multiple levels. While transboundary water security can be addressed via collective action at the international level (Tarlock & Wouters, 2009), it can also be promoted by coordinating domestic laws and policies to address regional concerns (Mirumachi, 2013).

In the case of international neighbours, political relationships between national governments can evolve over time, but may be slow to transition from conflict to cooperation. Where international relationships remain strained, international organizations may play a crucial role to help facilitate cooperation as third parties. In the Upper Santa Cruz basin, in the absence of a legal framework for binational groundwater management, efforts to address transboundary groundwater have leveraged existing institutional capacity. The IBWC helped devise a framework for cooperation on binational aquifer assessment. The resultant TAAP engages binational academic institutions, government agencies and NGOs in cooperative scientific assessment. While imposing binational groundwater management is explicitly forbidden by the agreed framework (IBWC (International Boundary and Water Commission), 2009), scientific cooperation has other benefits: it can contribute to trust-building, participation, cross-border dialogue and relationship-building (Blomquist & Ingram, 2003; Gerlak & Mukhtarov, 2016).

In other instances, solutions to shared problems may exist at the local level. Locally based cooperation may be easier to implement and better reflect local needs (Eckstein, 2013). In the Ica River basin, we saw that subnational basins had better access to tools and mechanisms for addressing water security than transnational ones. However, local capacity has limitations. In the transboundary Catamayo-Chira basin, although land-use planning was conducted locally, its influence on transboundary water-management outcomes was limited without support from higher government levels. The design of binational cooperative frameworks has been a slow process, underlining the importance

of institutional capacity on multiple levels. If shared interests of riparian nations, particularly those identified via local participation, can be leveraged into formal international cooperative processes, agreements and treaties may be more effective and resilient over time (Wolf, 2007).

Finally, in other cases still, local and regional social movements can influence national legislation, as demonstrated when Argentina passed a national glacier-conservation law, the first national glacier legislation of its kind. However, in this case, transboundary coordination is still lacking: thus far, Argentina and Chile have progressed differentially on glacier-conservation legislation. To fully address this transboundary challenge, coordinated binational efforts are needed.

Because our case studies all involve arid-to-semiarid environments, limited water supply is an important driver of water insecurity. While water scarcity can make it more difficult for nations to agree over shared resources (Hensel & Brochmann, 2007), it may also be a catalyst for cooperative efforts (Yoffe, Wolf, & Giordano, 2003) and new technological approaches. However, new technologies must be accompanied by appropriate institutional arrangements. In considering binational desalination in north-western Mexico, for example, we observe the need for institutions designed to address binational water allocation, payments, compensation, environmental impacts and trade to be in place at the start of such a project, accompanied by national-level policies for allocation and use of desalinated water. This illustrates how the viability of technological solutions depends on adequate institutional capacity at multiple levels – which may not exist initially – and stable binational political relations (Wilder et al., 2016).

Another key feature of institutional capacity is the ability of institutions to be resilient to change (Yoffe et al., 2003). In the transboundary context, investments in new capacity can create a feedback mechanism that helps reduce uncertainty and fosters further institutional adaptation (Heikkila, Gerlak, Bell, & Schmeier, 2013). Transboundary institutions that fail to adapt may ultimately fail to be effective (Berardo & Gerlak, 2012). Flexibility and adaptability by design can help address challenges effectively despite dynamic or changing conditions, such as those that result from climatic change.

Climate change is a key driver of water insecurity particularly in arid regions, creating new and evolving challenges that demand flexible, adaptive and responsive institutional arrangements (Eckstein, 2009). While surface water agreements, such as the 1944 Water Treaty, are designed with the flexibility to add incremental items (as with the ‘minutes’), a binational agreement on shared groundwater management is unlikely to be similarly codified. In the absence of an adaptable legal mechanism for groundwater, binational institutions and networks, such as the TAAP and transboundary NGOs, can help guide groundwater management to be adaptable and responsive to climate-change impacts in the short term.

For high-elevation mountain water sources, climate-driven changes in the rate and timing of snow accumulation and glacier melt have had unpredictable effects, which may even result in redirection of flow among neighbouring basins (Shugar et al., 2017), possibly with transboundary impacts. In the Andean mountains, because glaciers span the border between Chile and Argentina, a coordinated policy response is needed at the international level. Until now, cross-border cooperation on glacier conservation has not been a priority, and national policies have developed slowly in this region. Sharing of scientific information and knowledge, which Argentina and Chile have already begun, is

essential to fully understand the transboundary nature of glacier-stored water supplies and thereby address water security.

Adaptable institutional arrangements are also needed to redress inequity in water access (Pahl-Wostl et al., 2004). In the Ica River basin, water allocation practices are driven by economic and political power asymmetries. Infrastructure and water management policies are designed by and for powerful downstream communities. In the Catamayo-Chira River basin, access to potable water supplies is hindered by weak water provisioning and management. To improve water security, water-management policies must provide equitable benefits both upstream and downstream. Overall, while strategies involving enhanced institutional capacity and adaptive management involve high transaction costs associated with cooperation, dialogue and information-gathering, these may still be warranted when dealing with the complex issues characteristic of transboundary water (Raadgever, Mostert, Kranz, Interwies, & Timmerman, 2008).

## Conclusions

Our close examination of five cross-border cases across the arid Americas reveals that each case features a distinct set of water-security attributes and corresponding context-specific challenges. Our analysis shows how the transboundary context, in a variety of configurations, can challenge planning, governance and implementation, while also permitting constructive, cooperative action across political barriers in some cases.

Many factors, individually and collectively, make addressing water security a complex endeavour in cross-border, or trans-jurisdictional, settings. The chief compounding factors related to the transboundary context are national-sovereignty concerns and uneven power dynamics; political, economic and physiographic asymmetries; and insufficient institutional capacity. We observe a broad range of institutional responses to these challenges – from informal cross-border scientific research, to social movements, to binational frameworks between historically contentious neighbours. Yet, we also see where institutional capacity is lacking, resulting in failures to promote international collective action, uneven benefit-sharing exacerbated by binational arrangements, and persistent inequity in water access.

Robust and well-coordinated institutional arrangements are needed to deal with the challenges of political contention, cross-border asymmetries and changing physical, social or institutional contexts, yet effective institutional arrangements will differ by location. Governance capacity at multiple levels can be relevant for transboundary water issues – from local cooperation to coordination of domestic policies and international collective action. In some cases, local, domestic or regional efforts can be effectively leveraged into cooperative agreements at the international level. In others, certain roles or functions (e.g., regulatory enforcement, data collection or participation) may be better suited for national to subnational levels and can address challenges when barriers inhibit collective action at the international level. Furthermore, institutions can be more effective and have greater longevity if they are flexible and adaptable to change.

However, building institutional capacity requires both resources and time. Other challenges may be that existing political frameworks and path-dependency may limit the options of institutional responses or that power asymmetries derived from

differential economic development, financing, technology or resources may be difficult, if not impossible, to redress at the international level. Thus, it is imperative that the historical, cultural, political, economic and social aspects of the transboundary context are considered in determining feasible institutional responses in each context.

Our analysis is not without limitations. The water-security framing we employed enhanced our analysis, yet the water-security attributes listed in [Table 1](#) are not comprehensive, nor do they represent a standardized list. Not all of the relevant attributes revealed by our case studies were represented – namely, cultural, social, institutional and information asymmetries, as well as power dynamics. We also recognize the limitations of our results due to our consideration of only five cases and our qualitative approach. Further research should examine other transboundary contexts in arid regions, and combine quantitative data with qualitative analysis. A useful next step in research would go beyond identifying the breadth and diversity of water-security attributes to examine the nature of their interactions and feedbacks via a system-dynamics approach (e.g., Kotir, Smith, Brown, Marshall, & Johnstone, 2016).

Nevertheless, our results can inform strategies for addressing transboundary water security in arid regions via robust, coordinated and adaptable institutional capacity at multiple levels, while demonstrating the distinctly context-specific nature of both water-security challenges. Distinguishing the many and varied components of complex transboundary water-security challenges is helpful to shed light on an equally broad range of context-appropriate – and ultimately effective – strategies for enhancing transboundary water security.

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## Notes

1. See Conca (2005), Young (1989), and Hayton and Utton (1989), whose seminal model groundwater treaty recognized what they called 'critical transboundary resource management areas'.
2. Among the earliest examples of such arrangements are the Colorado and Rio Grande (1944), Danube (1948), Indus (1960), Rhine (1963) and Senegal (1963) river basins, all of which created basin commissions or authorities, and some of which enacted treaties.
3. The case-study analysis relies on knowledge and experience developed through years of fieldwork and research projects conducted by the co-authors in these locations. Authors are active participants (or close affiliates) in two water-security networks operating in the Americas: the International Water Security Network, which is headquartered in Bristol, UK, and AQUASEC, the Inter-American Institute for Global Change Research centre of

excellence for water security in the Americas. Both were established in the early 2010s to study place-based water-security conditions and foster enhancements through science-policy dialogues.

4. Throughout this essay, we use the term ‘arid’ to refer generally to water-scarce areas. This includes regions that are semiarid (200–500 mm precipitation per year), to arid (25–200 mm), to hyperarid (less than 25 mm), according to the classic definition by Grove (1977).
5. These include the heated discussion over a border wall, immigration, narcotrafficking, and free trade – all of which have become more prominent since 2016.
6. The North American Free Trade Agreement went into effect in 1994.
7. Safe yield is defined in Arizona as ‘a groundwater management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial recharge in the active management area’ (A.R.S. §45–561).
8. The 1944 Water Treaty (Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande) allocated 1850 million cubic metres of the Colorado River’s flow to Mexico, addressed allocations on the Rio Grande and Tijuana Rivers, and emphasized the need to prioritize transboundary sanitation issues. ‘Minutes’ are added to the treaty for incremental adjustments.
9. IBWC’s Mexican analogue is CILA, the Comisión Internacional de Límites y Agua; thus, both countries have representatives in this binational institution.
10. The only formal agreement that addresses groundwater is IBWC’s Minute 242, of 1973, which limits groundwater extraction in a small area near San Luis, AZ.
11. In 2006, the US Congress passed the Transboundary Aquifer Assessment Act (Public Law 109–448), authorizing the US Geological Survey, in partnership with federally recognized, public-university-based water-resources research centres in US border states, to cooperate with Mexico on this effort.
12. The first TAAP report, conducted on the San Pedro aquifer, the Binational Study of the Transboundary San Pedro Aquifer (Callegary et al., 2016), includes a binational database, technical analysis and binational maps, printed in both English and Spanish. The San Pedro aquifer is also shared between Arizona and Sonora, and is directly east of the Santa Cruz.
13. In the US and in Mexico, the largest subnational administrative units are called states; in Ecuador and Argentina, they are provinces; in Peru, they are departments. Chile has 15 large regions, which are divided into 54 provinces.
14. These may include urban expansion, changing climate and hydrologic regimes, invasive species, and shifting socio-political-economic processes.
15. Argentinean Institute of Nivology, Glaciology and Environmental Sciences.
16. The suit is highly ironic since it plays into the hands of the environmentalists’ adversaries, the mining companies.

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