AGU100 ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1002/2018EF000823

Special Section:
Resilient Decision-making for a Riskier World

Key Points:
- Transboundary water institutions influence the propagation of drought risks and vulnerability to them
- Upstream adaptation decisions create spillovers for downstream jurisdictions that can spur conflict resolution and cooperation
- Informal decision-making venues can prevent spillovers from cascading but may be insufficient to resolve conflicts associated with severe droughts

Supporting Information:
- Supporting Information S1

Correspondence to:
D. E. Garrick,
dustin.garrick@ouce.ox.ac.uk

Citation:
Garrick, D. E., Schlager, E., De Stefano, L., & Villamayor-Tomas, S. (2018). Managing the cascading risks of droughts: Institutional adaptation in transboundary river basins. *Earth's Future*, *6*, 809–827. https://doi.org/10.1002/2018EF000823

Received 22 JAN 2018
Accepted 5 APR 2018
Accepted article online 19 APR 2018
Published online 15 JUN 2018

Managing the Cascading Risks of Droughts: Institutional Adaptation in Transboundary River Basins

Dustin E. Garrick[1], Edella Schlager[2], Lucia De Stefano[3,4], and Sergio Villamayor-Tomas[5]

[1]Smith School of Enterprise and the Environment, University of Oxford, Oxford, UK, [2]School of Government and Public Policy, University of Arizona, Tucson, AZ, USA, [3]Geodinamica Department, Universidad Complutense de Madrid, Madrid, Spain, [4]Water Observatory, Botín Foundation, Madrid, Spain, [5]Institut de Ciència i Tecnologia Ambientals, Autonomous University of Barcelona, Barcelona, Spain

Abstract Transboundary river basins experience complex coordination challenges during droughts. The multiscale nature of drought creates potential for spillovers when upstream adaptation decisions have cascading impacts on downstream regions. This paper advances the institutional analysis and development (IAD) framework to examine drought adaptation decision-making in a multijurisdictional context. We integrate concepts of risk management into the IAD framework to characterize drought across its natural and human dimensions. A global analysis identifies regions where severe droughts combine with institutional fragmentation to require coordinated adaptation. We apply the risk-based IAD framework to examine drought adaptation in the Rio Bravo/Grande—an archetypical transboundary river shared by the United States and Mexico and by multiple states within each country. The analysis draws on primary data and a questionnaire with 50 water managers in four distinct, yet interlinked, "institutional catchments," which vary in terms of their drought characteristics, socioeconomic attributes, and governance arrangements. The results highlight the heterogeneity of droughts and uneven distribution of their impacts due to the interplay of drought hazards and institutional fragmentation. Transboundary water sharing agreements influence the types and sequence of interactions between upstream and downstream jurisdictions, which we describe as spillovers that involve both conflict and cooperation. Interdependent jurisdictions often draw on informal decision-making venues (e.g., data sharing, operational decisions) due to the higher transaction costs and uncertainty associated with courts and planning processes, yet existing coordination and conflict resolution venues have proven insufficient for severe, sustained droughts. Observatories will be needed to measure and manage the cascading risks of drought.

1. Introduction

Droughts are a recurring natural hazard with cascading direct and indirect economic impacts (Freire-González et al., 2017). Climate change is projected to bring more frequent and severe droughts, particularly to midlatitude regions (Prudhomme et al., 2014). In this context, there is increasing focus on the human dimensions of drought which shape vulnerability and the distribution of impacts across society and scales (Kallis, 2008). A growing appreciation of the human dimensions of drought has led interdisciplinary researchers to claim that we have reached a "watershed moment" that requires "rethink[ing] the concept of drought to include the human role in mitigating and enhancing drought," including the role of people influencing drought events, not just responding to their consequences (Van Loon et al., 2016, p. 89). Recent research has begun to fill this gap by improving our understanding about the channels through which people influence drought including anthropogenic climate change and patterns of land use, irrigation, dam building, and water abstraction (Van Loon et al., 2016). Despite these strides, limited work has focused on the role of institutional fragmentation in transboundary river basins, where decisions in one jurisdiction can have cascading impacts upstream or downstream. The interactions between people and drought are governed by institutions, including rules and norms about the distribution of drought risks and water shortages, which adds a layer of fragmentation to drought characterization and management in the Anthropocene. Severe droughts can trigger decisions that exacerbate pre-existing vulnerability and lead to disputes between user groups and neighboring jurisdictions, particularly during sustained droughts.

This paper fills this gap by advancing the institutional analysis and development (IAD) framework to characterize and assess adaptation to droughts in a transboundary context. It focuses on droughts and related socioeconomic and environmental disturbances and compares institutional arrangements for coordinating adaptation decision-making across political borders and levels of governance. The framework is applied to the Rio Bravo (Mexico)/Rio Grande (United States), a multijurisdictional river basin shared by two countries and the states within them. Mexico and the United States exhibit different levels of decentralization, which offers an ideal laboratory to illustrate key challenges associated with drought adaptation in transboundary river basins globally.

We utilize a multimethod research strategy to address the following questions:

1. How do transboundary water agreements influence drought vulnerability?
2. How do droughts affect interactions (conflict and cooperation) between upstream and downstream jurisdictions and between the central government and local actors?
3. Which types of decision-making venues coordinate adaptation in transboundary rivers, and how effective are they perceived to be?

The structure of the paper is as follows. The rest of this section introduces the IAD framework and extends it by integrating concepts from the risk management and natural hazards literature. This analysis illustrates the multiscale and multijurisdictional nature of drought. It also provides a typology of informal and formal coordination institutions to facilitate cooperation and conflict resolution in transboundary drought adaptation. The second section provides the research setting and methodology. It introduces a two-level analysis of drought severity and institutional fragmentation in transboundary river basins; this section maps the world's federal rivers and identifies transboundary river basins affected by severe, sustained droughts according to the drought severity index. This analysis highlights the Rio Grande/Bravo as an ideal setting for exploring the design and effectiveness of institutional adaptation to droughts due to its history of severe droughts and its transboundary coordination challenges within and between countries. The third section examines evidence for three propositions based on an observatory of drought adaptation in the Rio Grande/Bravo, drawing from primary data on drought characteristics and a questionnaire (n = 50) for water managers involved in adaptation decision-making at different levels of governance. The final section examines the implications for institutional analysis and development, particularly related to trade-offs between local and transboundary adaptation and concludes with implications for theory and practice.

1.1. Droughts and Decision-Making: An Institutional Analysis

We examine decision-making and risk management from the perspective of institutional analysis and common pool resource governance theory. The institutional analysis and development framework was developed by an interdisciplinary group of scholars over the past 35 years. The framework guides systematic comparisons of institutions and governance arrangements (Ostrom, 2011). Institutions are defined as the shared prescriptions (including rules and norms) that structure human interactions, following Ostrom (2005). The framework focuses on *action situations* (Figure 1), which capture interdependent decisions among actors and how actors respond to risks and incentives in the context of a wider set of rules, community attributes, and biophysical conditions. Action situations occur at nested levels of action: operational, collective choice, and constitutional. The operational level involves daily activities, such as diverting water or harvesting crops. The collective choice level entails coordination, rule-making, and compliance activities for the operational level, such as monitoring of water diversions. Finally, the constitutional choice level governs rule making and compliance activities for the collective choice level, such as developing a river management authority or defining who may participate in rule making (Ostrom, 2005).

The IAD framework has been applied across a diverse range of settings from municipal governance to natural resources and the digital commons to study how different configurations of rules affect patterns of interactions among actors and the outcomes they realize (McGinnis, 2011). The growing complexity, scale, and pace of social and environmental change have prompted efforts to extend and expand the IAD framework to understand the dynamics and sustainability of large-scale human natural systems (Fleischman et al., 2014; Stern, 2011; Villamayor-Tomas et al., 2014).

Over the past 10 years, the IAD framework has been expanded into frameworks for assessing the robustness and resilience of social-ecological systems (SES) and coupled infrastructure systems (Anderies et al., 2016; McGinnis & Ostrom, 2014). Doing so has required accounting for biophysical and social complexity, which were treated as "external variables" in the original formulation of the IAD. In these broadening frameworks, external variables have been described in many different ways, including "contextual factors," "exogenous drivers," and "functional infrastructures" (Anderies et al., 2016).

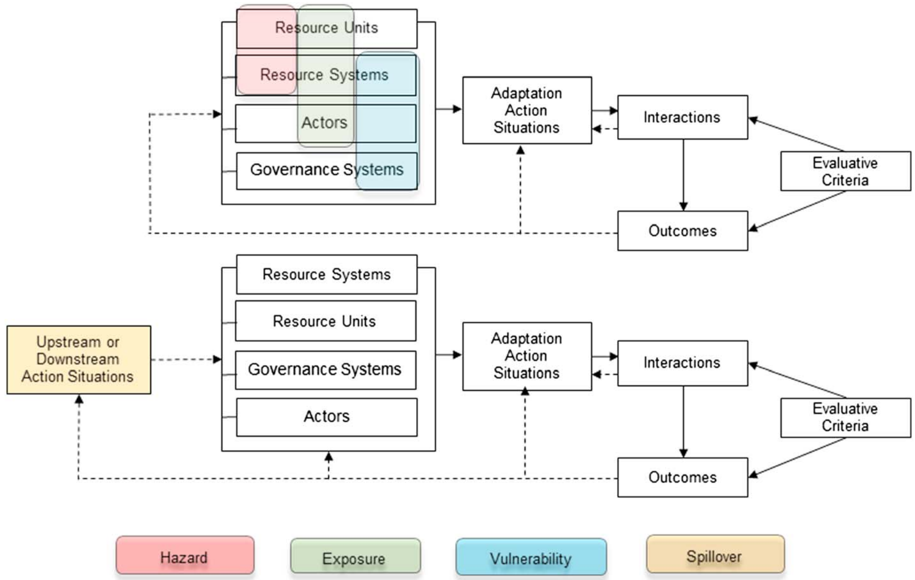

Figure 1. Characterizing drought in a transboundary context: A risk-based IAD-SES framework (Source: own elaboration, building on McCord et al., 2017).

The SES framework sought to enhance our understanding of SES by unpacking their complexity using a consistent set of variables and metrics to support hypothesis testing, theory development, and comparative learning. The framework examines SES in terms of the interactions between natural and human dimensions, including four distinct, yet interrelated, "subsystems": resource systems, resource units, actors, and governance arrangements (Ostrom, 2009; McGinnis & Ostrom, 2014). These analytical distinctions can facilitate finer-grained classification of external variables to examine how well different institutional arrangements respond to disturbances, such as drought (Brown et al., 2016), and to external factors, such as regional and global scale physical social and economic forces (de Loë & Patterson, 2018).

We build on the recent merger of the IAD and SES into a combined (IAD-SES) framework as our point of departure (McCord et al., 2017). The IAD-SES framework combines elements of both frameworks to counteract the weaknesses of each when applied on its own. The IAD captures the dynamics and feedbacks associated with the action situation but lacks capacity to fully represent the complexity of biophysical and socioeconomic attributes. The SES framework offers a more comprehensive accounting of natural and social systems and their constituent attributes, but moving beyond static assessment to dynamic, adaptive systems have proven to be more difficult than envisioned. Hence, their combination (Figure 1) incorporates (a) the subsystems of the SES framework (explanatory factors on the left side of the framework) with (b) the dynamics of action situations (interactions, outcomes, and their feedbacks on the right side of the framework).

Our analysis of drought adaptation in a transboundary context involves two advances. First, we incorporate concepts from risk management into the IAD-SES to characterize drought according to their natural and human dimensions: hazard, exposure, and vulnerability (Carrão et al., 2016; Field et al., 2012). Hazards refer to "the potential occurrence of natural or human-induced physical event that may cause loss…" (Field et al., 2012: p. 560), which has been operationalized for drought to capture the intensity and duration of deficits in rainfall, runoff, and/or soil moisture (Wilhite, 2000); drought hazards are represented in the IAD-SES framework as attributes of the resource system and resource units, including the spatial and temporal distribution of water availability and the predictability of system dynamics (Table 1). Exposure refers to the "presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected" (Field et al., 2012, p. 559) which involves attributes of resource systems, their units and actors, such as the human-constructed facilities, the economic value of water use, and the dependency of actors and their regional economies on water respectively. Finally, vulnerability captures the "propensity or predisposition to be adversely affected" (Field et al., 2012, p. 564) and is shaped by attributes of the actors (e.g., knowledge) and governance arrangements (e.g., property rights and operational rules; Smit & Wandel, 2006). Thus, a risk-based IAD-SES framework involves a diagnosis of

Table 1
Selected Second-Tier and Third-Tier Variables for Characterizing Drought in a Transboundary Context

Second-tier variables	Third-tier variables	Hazard	Exposure	Vulnerability
Resource units (RU)				
RU4: Economic value	Livelihoods			
	Economic value of water and water-related assets			
RU7: Spatial and temporal distribution	Rainfall interannual and intraannual variability			
	Drought severity (intensity and duration)			
Resource system (RS)				
RS1: Sectors	Water			
RS2: Size	Basin area			
RS7: Predictability of system dynamics	Hydroclimatic variability			
RS8: Storage characteristics	Reservoir storage-to-runoff ratio			
	Aquifer storage capacity and recharge properties			
Actors (A)				
A1: Number of actors	Population, sectors and jurisdictions			
A2: Socioeconomic attributes	Income			
	Group heterogeneity			
A4: Location	Upstream/Downstream			
A7: Knowledge	Early warning and other predictive capacity			
A8: Resource dependence	Irrigated agriculture			
	Water-dependence of industry			
	Environmental needs			
A9: Technologies	Irrigation efficiency			
Governance system (GS)[a]				
GS4: Property rights systems	Allocation rules			
	Shortage sharing rules			
GS5: Operational rules	Roles and responsibilities			
GS6: Collective-choice rules	Decision rules			
	Conflict resolution rules			
	Coordination rules			
GS7: Constitutional rules	Intergovernmental agreements			
GS8: Monitoring and sanctioning	Information sharing			

Note. Source = own elaboration, following Meinzen-Dick (2007) and based on Wilhite (2000) for the "hazard" column, Carrão et al. (2016) for the "exposure" column, and Garrick et al. (2013) and Garrick and De Stefano (2016) for the "vulnerability" column.
[a]This table identifies only focal attributes for transboundary river governance, not the wider set of governance attributes associated with local management.

drought characteristics according to the configuration of hazard, exposure, and vulnerability (Figure 1). This enables the specification of second- and third-tier variables which can be used to characterize the risks of droughts and assess the capacity and effectiveness of institutional adaptations (Kallis, 2008). Table 1 illustrates an indicative set of such tiered variables to assess the characteristics of drought hazards, exposure, and vulnerability across the components of the SES. Such variables can offer an initial basis for measuring the risks of drought, tracking their propagation across complex systems, and assessing the influence of transboundary water governance on the distribution of risks and capacity to manage the associated trade-offs.

The second extension to the IAD-SES responds to the transboundary and systemic nature of droughts (Grafton et al., 2016; Wyrwoll et al., 2018), namely: the propensity for drought impacts to propagate across jurisdictional boundaries when upstream adaptation decisions cascade downstream, creating "spillovers" (Figure 1). The concept of spillovers is not new; it has been closely associated with the concept of externalities, which refers to the costs or benefits of decisions that are ignored by decision makers. Although spillovers and externalities are used interchangeably (e.g., Ostrom et al., 1961, p. 832), spillovers offer more precision in the context of transboundary river basins. Spillovers are often associated with the spatial

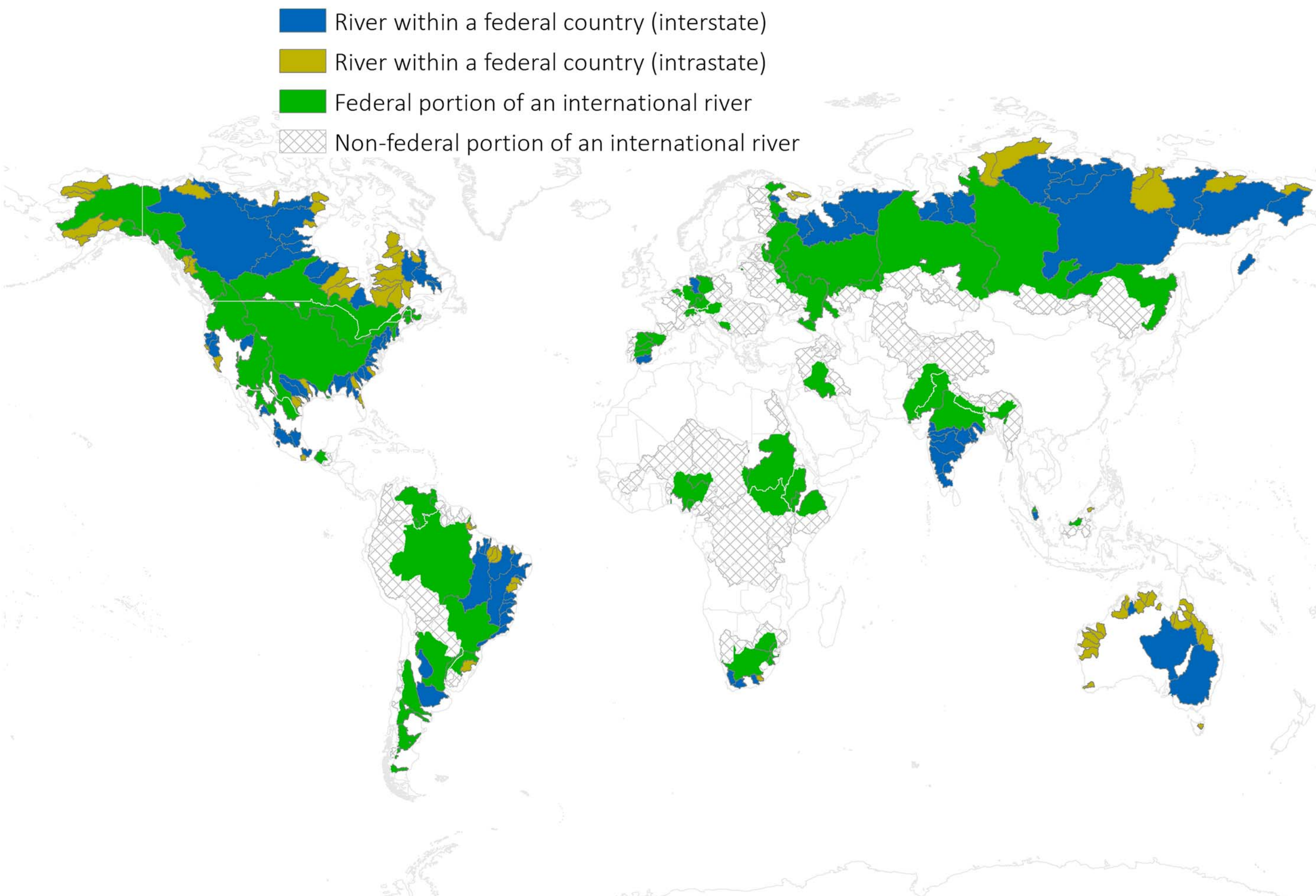

Figure 2. World's federal rivers: Transboundary basins at nested levels, following Garrick and De Stefano (2016).

relationship between adjacent actors or jurisdictions and closely related to issues of scale (Ostrom et al., 1961, p. 833). In principle, spillovers, like externalities, can include both risks and benefits. An example of a spillover risk involves the negative effects of upstream groundwater pumping on downstream surface water reliability. Conversely, an example of a spillover benefit involves management of upstream reservoir storage to create drought buffers for both upstream and downstream jurisdictions. In the terminology of the IAD framework, we conceptualize spillovers as a form of "interaction" between upstream and downstream jurisdictions and expect that adjacent jurisdictions will become more interdependent during droughts (Figure 1).

The need for coordination is particularly pronounced in transboundary river basins due to the spillovers between jurisdictions and levels of governance within a shared basin. Political borders can create transboundary management challenges between and within countries. In federal countries, for example, authority is divided between national and subnational jurisdictions (i.e., states), creating the potential for coordination challenges when multiple, independent states share a river basin. Federal rivers are major river basins within or shared by a federal country, where coordination dilemmas can arise between sectors (e.g., intrastate rivers), states (e.g., interstate rivers), and across international borders (e.g., international rivers); some federal river basins have the dual challenge of coordination across multiple countries and multiple states within them (see Figure 2). Sharing water in transboundary settings is difficult even under average water availability. Drought may bring into sharp relief neglected interdependencies or blur roles and responsibilities, leading to disputes between jurisdictions or across levels of governance (Garrick & De Stefano, 2016; Garrick et al., 2016).

Table 2
Typology of Decision-Making Venues to Address Institutional Collective Action (ICA) Dilemmas (Adapted From Feiock, 2013)

Integration mechanisms	Description	Drought adaptation (indicative venues)
Single issue		
Informal networks	Policy network that emerges from local interactions	Sharing shortages with neighbors
Contracts	Joint ventures and service contracts to address externalities	Dry-year option contract
Special purpose districts	Functionally specialized jurisdiction separate from local government	Irrigation district board decisions
Multilateral		
Working groups	Voluntary association of elected or public officials	Weekly phone calls for reservoir operations working group
Partnerships	Voluntary multilateral agreement among local jurisdictions	Memorandum of understanding on shortage sharing between jurisdictions
Multipurpose districts	Consolidated set of public services within geographic territory	Drought response by watershed or regional organizations
Comprehensive		
Multiplex self-organizing systems	Emergence of regional integration through embedded norms created by overlapping ventures, agreements and contracts	Drought forum by river basin stakeholder groups
Council of governments	Coordination across multiple policy domains governed by statutory framework	Interstate task force on drought
Regional authorities	Regional authorities have a comprehensive scope across a set of functions within a specified geography	Drought planning by river basin authority

Note. The integration mechanisms are listed by scope (single issue, multilateral, or comprehensive) and then by the level authority and formality within each category (e.g., special purpose districts require more formal authority than informal networks).

To unpack drought adaptation in a transboundary context, we draw on institutional collective action theory and its typology of "integration mechanisms" for responding to intergovernmental coordination dilemmas (Feiock, 2013). Integration mechanisms are needed to allow governments to address interdependencies across functions (e.g., fish and wildlife and water resources), jurisdictions (e.g., upstream and downstream states), or levels of government (e.g., local versus state or national). Coordination and cooperation to resolve these dilemmas require effective decision-making venues to bridge across sectors, scales, and jurisdictions.

Institutional collective action (ICA) theory posits that decision-making venues—both formal and informal—are the means by which spillovers are addressed among governments. Coordination venues will vary according to their scope (single issue versus multidimensional) and authority (from informal to formal). The functioning of these venues is governed by rules, that is, collective choice rules, and ultimately also constitutional choice rules (see Table 1, GS6 and GS7). The scope and authority of coordination venues are a function of two variables: the benefits of cooperation (i.e., the consequences of failing to cooperate) and costs of doing so (i.e., the transaction costs of coordinated action). In short, decision-making venues will increase in scope and authority when the benefits of collective action exceed the costs of such collective action. In practical terms this will mean that informal venues focused on a narrow set of issues may be sufficient until severe droughts intensify and lead to spillovers. Severe, sustained droughts may require more significant responses of greater formality and scope, such as creating a conflict resolution venue or a river basin authority to coordinate complex trade-offs. A typology of integration mechanisms can be organized in terms of their formality and scope, as delineated in Table 2 (based on Feiock, 2013).

There are several implications of institutional collective action theory for transboundary drought adaptation. Second-best options are often necessary in a given setting due to transaction costs. Thus, actors are likely to experiment with the least costly integration mechanisms before turning to the more comprehensive and formal mechanisms. Second, the implication of the first point is that the less costly options will often be favored. Finally, experimentation will follow the principle of subsidiarity, as actors directly affected by functional overlaps or spillovers engage in adaptation decisions; higher-level authorities (e.g., courts) serve as a second best option.

1.2. Propositions

We apply the risk-based IAD-SES framework and the theory of institutional collective action to examine evidence for three propositions:

Drought in transboundary context. The institutions for transboundary water management (GS) will influence vulnerability to droughts.

Proposition 1: Transboundary water agreements influence the nature and propagation of drought impacts within the basin by shaping how local decisions spillover through their rules, drought measures, and dispute resolution mechanisms.

Spillovers. In general, drought is likely to lead to tensions and disputes with uncertain consequences among upstream and downstream actors. With the onset of drought, actors may protect their own interests and those of their constituents affecting downstream jurisdictions in the absence of well-functioning integration mechanisms.

Proposition 2: Meeting downstream water delivery obligations during droughts will lead to disputes between jurisdictions and confusion about key roles and responsibilities.

Integration mechanisms. While drought may lead to disputes, actors are likely to access or form various integration mechanisms in response. In general, actors will turn to the least costly mechanisms to support coordination, which are often informal and involve information sharing and are supported by well-functioning monitoring mechanisms. In the most severe, sustained droughts, such informal mechanisms may not be sufficient.

Proposition 3: Actors will cooperate by using relatively low-cost integration mechanisms available to them in responding to drought impacts, but informal arrangements will not be sufficient on their own to address spillovers during severe, sustained droughts.

We first examine the hotspots of severe droughts and institutional fragmentation, highlighting a small set of river basins in federal political systems. We then examine these propositions in the Rio Grande/Bravo river system of the United States and Mexico, which offer a paradigmatic example of a transboundary river system with a history of severe droughts.

2. Settings and Methods

2.1. Setting

A global analysis compared the mean drought severity for the historic period from 1901 to 2008 (Sheffield & Wood, 2008). Overlaying this indicator with the world's federal rivers (Figure 3) highlights the regions where exposure to severe droughts and jurisdictional fragmentation coexist. This analysis highlights three transboundary rivers as prime examples of federal rivers under pressure from severe droughts: the Rio Grande/Bravo, Nile, and Indus. Other regions in Northern Africa and the Middle East, Russia, South America, and northern Australia experience severe droughts. The Rio Grande, Nile, and Indus are unique, however, due to their status as international rivers with one or more federal countries and hence high degrees of institutional fragmentation. The inset maps in Figure 3 illustrate that the Rio Grande/Bravo is also distinct from the Nile and the Indus due to its exposure to severe droughts throughout the full basin—in particular, including its headwaters regions in the Upper Rio Grande (United States) and Rio Conchos (Mexico). As such the Rio Grande/Bravo offers a paradigmatic example of a transboundary river exposed to severe drought that can generate insights about the nature of drought in such settings and the evolution and effectiveness of institutional responses to coordination challenges at multiple scales.

On the basis of this global mapping, we focus on the Rio Grande/Bravo Basin as a laboratory for investigating institutional adaptation to droughts in a transboundary (interstate and international) setting. The basin (approximately 870,000 km^2 including endorheic zones) includes two countries (United States and Mexico) with three U.S. states and five Mexican states (Figure 4). The physical and political geography of the basin has positioned both the United States and Mexico as the "upstream" riparian country on a major tributary before reaching the main stem of the river and forming the border between the countries for approximately 2,000 km. This allows a comparison of local and transboundary adaptation within both countries, controlling for the upstream-downstream position, in addition to the focus on international cooperation and conflict. The United States and Mexico also differ in their levels of centralization and approaches to coordination between upstream and downstream states within each country, which allows a comparison

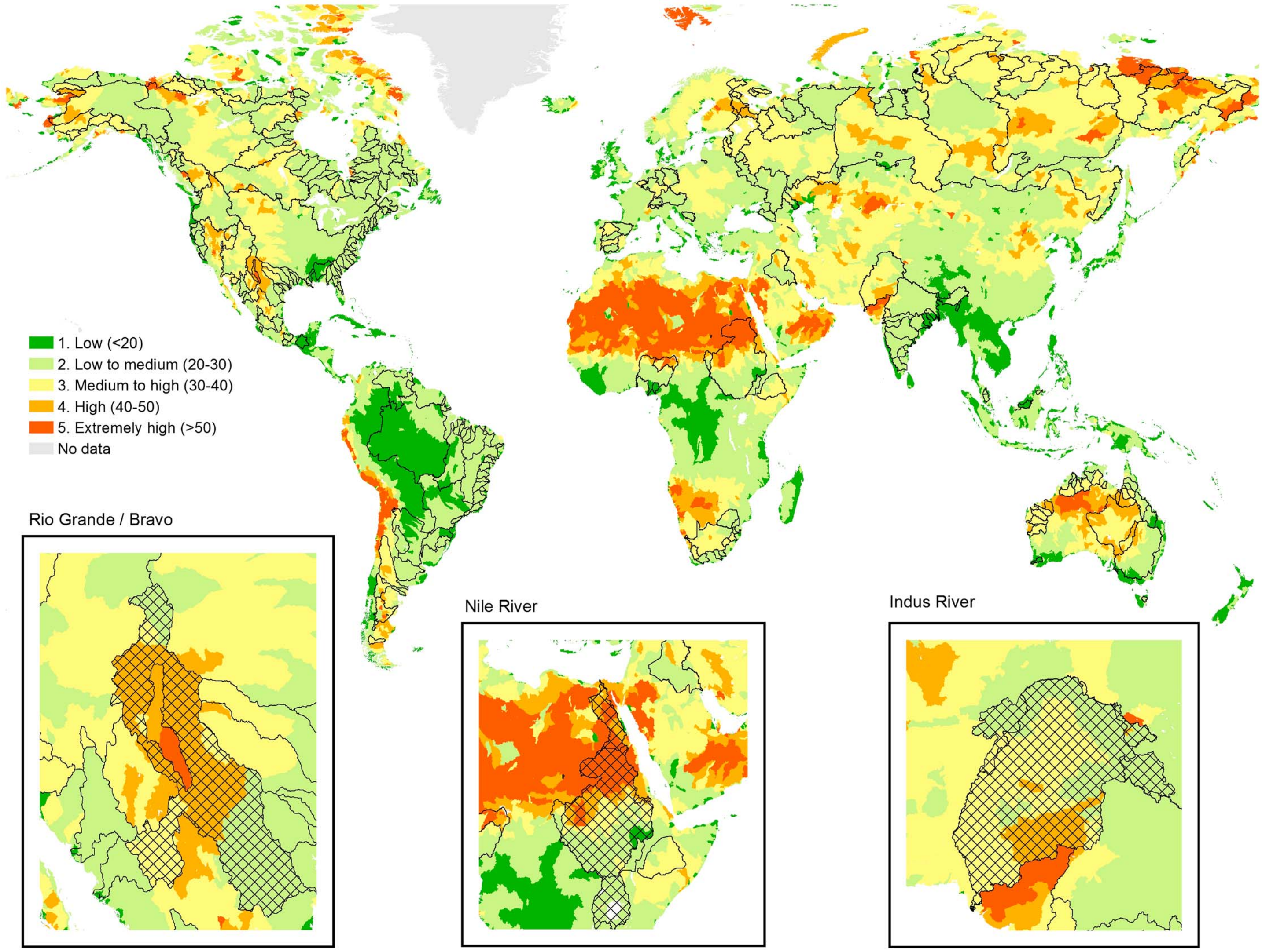

Figure 3. Drought severity in federal rivers, following Sheffield and Wood (2008, drought severity) and Garrick and De Stefano (2016, federal rivers). Polygons (black) refer to interstate federal rivers (within countries) and the federal portion of international rivers with at least one federal country.

of Mexico's relatively centralized governance arrangements with the relatively decentralized approaches in the United States. Finally, as a consequence of the first two elements, the basin has evolved a complex institutional matrix of surface water agreements to share water and shortage risks within and across jurisdictions, which has created distinct and coherent subzones, or institutional "catchments"—the spatial portion of a basin whose administrative boundaries are defined by the compliance points for transboundary water agreements.

2.2. Institutional Catchments

International and interstate water sharing agreements create obligations for upstream jurisdictions to deliver water downstream. Compliance locations for monitoring deliveries form the boundaries between distinct, yet interlinked, institutional catchments. We focus on four institutional catchments: the San Luis Valley, Upper and Middle Rio Grande, Rio Conchos, and Lower Rio Grande Valley. The first two institutional catchments are defined by the Rio Grande Interstate River Compact, a water sharing agreement between the U.S. states of Colorado, New Mexico, and Texas, and the 1906 Convention between the United States and Mexico. The remaining two catchments are defined by the 1944 treaty between the United States and Mexico, which allocates water between the two countries from the Rio Grande/Bravo and the Colorado rivers. The water

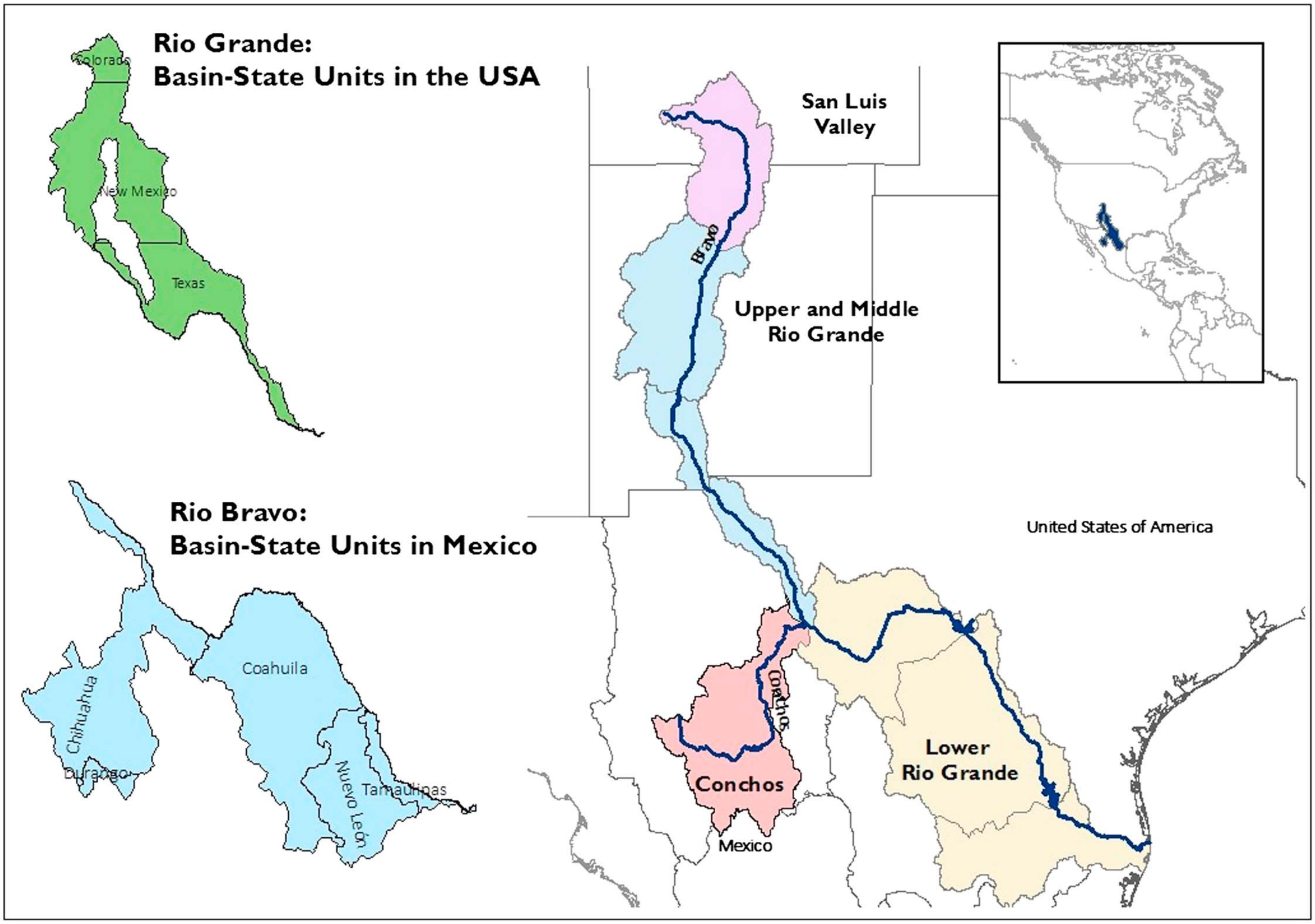

Figure 4. The Rio Bravo / Grande Basin. Basin-state units represent the spatial portion of the basin falling within specific states in Mexico (Bravo) and the United States (Grande). Four institutional catchments have been delineated according to the boundaries established by surface water agreements: The San Luis Valley (Colorado to the Otowi Bridge, New Mexico); the Upper and Middle Rio Grande (from Otowi Bridge to Fort Quitman); the Rio Conchos (to its confluence with the Rio Grande); and the Lower Rio Grande (which encompasses Texas and important tributaries in Mexico).

agreements further subdivide these zones. Specifically, the Upper and Middle Rio Grande is typically subdivided into two parts upstream and downstream of Elephant Butte reservoir in New Mexico, and the Lower Rio Grande is typically divided into the U.S. portion and the Mexican portion, particularly the San Juan Basin.

The San Luis Valley is situated at the headwaters of the Rio Grande cradled by the Rocky Mountains. Snowmelt from 4,000 m mountains feed the surface water hydrology, supporting a high-altitude valley that is 2,345 m above sea level and spans a territory of almost 8,300 km (Cody et al., 2015). The downstream boundary of this institutional catchment stretches into New Mexico at the Otowi Bridge streamflow gauge. The *Upper and Middle Rio Grande* stretches from the Otowi Bridge, near Espanola, New Mexico to the Elephant Butte Reservoir, some 370 km in distance, and then to Fort Quitman, Texas, near the beginning of the international border. For New Mexico, compact compliance is measured by the volume of water shepherded down the river and stored in Elephant Butte Reservoir. Elephant Butte Reservoir is central for the compact's water allocation rules and compliance. Under the requirements of the interstate compact, New Mexico deliveries to the reservoir are proportionate to the volume of water passing the Otowi gauge. The compact also allows Colorado and New Mexico to accrue water debits and credits, which are measured and accounted for at the Elephant Butte Reservoir. The *Conchos River* flows fall entirely within the state of Chihuahua, Mexico. It is the most important tributary of the Lower Rio Grande, providing around 40%–70% of its flow (von der

Meden et al., 2010). La Boquilla reservoir is located upstream in the Conchos River. With a storage capacity of more than 2.9 billion cubic meters, the reservoir serves the irrigation district 5 of Delicias (82,300 ha of irrigable land), a number of traditional irrigation systems, and the city of Delicias (148,045 inhabitants, 2015). The El Granero reservoir (Luis L. Leon dam) is located by the mid-Conchos valley, has a storage capacity of 356 million cubic meters and serves the Irrigation District 90, Bajo Conchos (13,300 ha), a few traditional irrigation systems, and the 1944 Treaty payments to the United States. The *Lower Rio Grande Valley* includes the United States and Mexico and is served by two international reservoirs, the Falcon and Amistad, which allow the United States and Mexico to administer the water allocations provided for in the 1944 treaty. The reservoirs are the compliance point in the lower Rio Grande Valley between the two countries. Within the Lower Rio Grande valley, the U.S. portion and the San Juan tributary within Mexico constitute discrete institutional catchments, which are not included in the analysis.

The water sharing agreements created venues for their administration. The International Boundary and Water Commission (IBWC) administers the 1944 treaty and 1906 convention and operates the two international reservoirs, Falcon and Amistad (Wurbs, 2004). In addition, each country has also established governance arrangements for coordinating interstate water management within their territory. The interstate compact between Colorado, New Mexico, and Texas relies on a proportionate water allocation rule. The amount of water that (i) Colorado must deliver to New Mexico and (ii) New Mexico to the Elephant Butte Reservoir is a function of the volume of river flows. Higher flows require greater volumes of water to be passed downstream. Mexico, in contrast, organizes its water sharing according to the 1992 National Water Law, which vests planning and allocation in a national water agency, Comisión Nacional del Agua (CONAGUA; Hearne, 2004). CONAGUA has delegations at the basin and state levels. Basin-scale delegations are integrated within river basin organizations (RBOs). The RBOs also host river basin councils ("consejos") which aim to provide a platform for engaging major user groups and other stakeholders within the basin (Castelan, 2001). Coordination between CONAGUA's national and state offices occurs through centralized decision-making administered by the state offices, although reforms in the 1992 National Water Law have attempted to decentralize and restructure functions associated with irrigation management and municipal water supplies. Coordination between CONAGUA, state governments, and user groups is expected to happen, at the advisory level, within RBOs.

2.3. Methods

Our analysis involves two steps. First, we examine proposition 1 using primary data on drought, water availability and documentary evidence regarding three focal attributes interacting with droughts: urbanization, groundwater availability and use, and environmental issues. Second, we examine propositions 2 and 3 regarding spillover effects and integration mechanisms using a questionnaire administered as a component of a set of semistructured interviews. The semistructured interviews addressed: the respondent's role in drought adaptation; characteristics, impacts, and responses to drought; roles, responsibilities, and relationships among key actors in drought adaptation; decision-making venues; funding and capacity, and performance (see supporting information for a detailed description of data collection). For the spillover effects and integration mechanisms, we summarize the results of the ordinal Likert scale (ordinal scale with five levels from strongly agree to strongly disagree) for statements posed during the close-ended questions of semistructured interviews. The results are summarized at the basin level and then disaggregated to explore variation across institutional catchments within the basin. The comparisons across the subbasin were assessed using Fischer's exact tests to determine the strength of association, which is suited for contingency tables involving small to medium sized N (see supporting information for results of the tests).

3. Results

3.1. Proposition I

Transboundary water agreements influence the nature and propagation of drought impacts within the basin by shaping how local decisions spillover through their rules, drought measures, and dispute resolution.

The framework indicates that droughts in transboundary rivers need to be understood in terms of the characteristics of the drought (hazard), the population and assets potentially affected (exposure), and the local and transboundary water governance capacity (vulnerability). We examine how drought varies and propagates in a transboundary context in four steps: (i) assessing the history of drought and its spatial–temporal distribution, (ii) characterizing the water management institutions that govern water sharing and drought

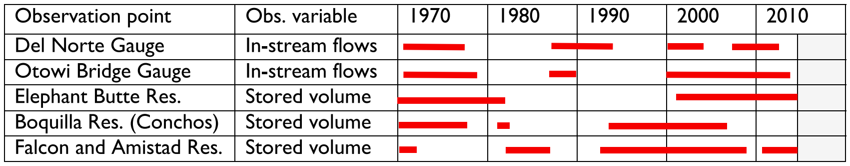

Figure 5. Spatial and temporal variation in water availability indicators, listed from upstream to downstream. Red line indicates periods when the observed variable was below the average of the whole series during more than two consecutive years.

risks across state and international borders, (iii) identifying how drought risks interact with exposure characteristics related to urbanization, irrigation development, and environmental quality, and (iv) documenting the spillovers, both positive and negative, linking different institutional catchments during droughts.

Hazard. Drought is a recurrent, natural phenomenon involving a temporary deficit in runoff, precipitation, and/or soil moisture whose impact and management are highly context specific. This is because drought sets off as a natural event—that is, a period of precipitation below average—but it rapidly evolves into a human-constructed phenomenon where drought impacts are largely determined by the characteristics of the human systems experiencing the meteorological drought.

In the case of Rio Grande/Bravo basin, the characterization of drought and its effects has a double complexity. On one hand, the large size of the basin, its north-south orientation (with a latitude spanning from 37° to 25°), and the geographical configuration of its subbasins mean that drought manifests across the basin unevenly in terms of precipitation and natural runoff deficits. For instance, Woodhouse et al. (2012) analyzed historic data and tree rings to conclude that precipitation and streamflow from the San Juan Mountains (headwater of Rio Grande) and the Sierra Madre Occidental in Mexico (headwater of Conchos) are largely independent from each other and therefore droughts in San Luis Valley and the Conchos are rarely concurrent. Those authors observed that periods of concurrent multiyear drought over the past four centuries were rare, with records of concurrence in the 1770s, 1890s, and 1950s. This trend is also found comparing spatial and temporal variability in water availability indicators during the 1970–2016 period (Figure 5). Differences exist not only in the timing of rainfall deficits but also in how runoff is generated across the basin, with snowmelt being the main source of runoff in the Upper Rio Grande, monsoon rainfalls in the Conchos subbasin, and hurricanes in the Lower Basin. Additionally, there are a number of reservoirs that shape hydrological flows and water availability and help understand the boundaries of a series of institutional catchments within the basin (see below).

Exposure. The exposure to drought in the basin varies according to water use (irrigation and urban demand), population (urbanization), and environmental assets (species and habitats at risk). We catalog and compare these dimensions across the four institutional catchments to illustrate the heterogeneity of the basin in terms of the level (low, moderate, or high) in each of these aspects of exposure (Table 3).

As in many other regions of the world, *irrigated agriculture* is the largest water user across the basin, and the availability of groundwater and storage capacity provided by reservoirs influence vulnerability to drought in each zone. In the San Luis Valley, confined and unconfined aquifers are key water sources for irrigation both in average and dry periods, while in-stream flows rapidly decrease and are affected by surface water curtailments during dry spells. Groundwater overdraft, however, has caused the decline of water tables and of in-stream flows where the river and the aquifer are hydraulically connected. This has reduced the buffering capacity of aquifers during drought and questions the viability of the current water exploitation model.

In the Middle Rio Grande, groundwater pumping emerged in the 1950s as a way for farmers to compensate curtailment of surface water rights during droughts. As in San Luis Valley, this adaptation strategy has brought about water table declines and conflicts over in-stream flows that are affected by groundwater pumping. Groundwater pumping by farmers downstream of Elephant Butte Reservoir led the Bureau of Reclamation, which operates the reservoir, and the city of El Paso to express concerns over the effects of groundwater pumping on surface water flows, illustrating how upstream adaptation decisions cause downstream spillovers in a transboundary context. While the Elephant Butte Irrigation District (EBID) attempted to negotiate with the Bureau, El Paso Water Improvement Distrct (EPWID), and Texas to resolve the issue,

Table 3
Institutional Catchments

	Reservoirs (capacity)	Groundwater development	Urban growth (# of cities > 50,000 inhab)	Irrigation development	Environmental issues
Institutional catchment	RS8	RU3/RS8	A8	A8	RU6/A8
San Luis Valley, CO, USA	445 Mm3;	HIGH	None	HIGH	Emerging
Upper and middle Rio Grande, USA	3804 Mm3;	HIGH	4	HIGH	Endangered species (silvery minnow)
Rio Conchos, Chihuahua, Mexico	6116 Mm3;	HIGH	4	HIGH	Habitat (desert riparian)
Lower Rio Grande Valley, TX, USA	10237 Mm3	LOW	4	HIGH	Water quality (industrial pollutants)

New Mexico chose not to participate in the process. Rather, once the parties reached and implemented an agreement, New Mexico filed suit claiming the agreement violated the Compact. Texas, in turn, filed a lawsuit with the U.S. Supreme Court. The U.S. Supreme Court, in 2013, agreed to hear the case. In 2017, the special master appointed by the Supreme Court to oversee the proceedings found in favor of Texas. If the U.S. Supreme Court accepts the special master's findings, New Mexico will have to address the impacts of groundwater pumping on surface water flows. Furthermore, Texas is requesting compensation for decades of lost water.

In the Conchos basin, irrigated agriculture withdraws about 2,900 Mm^3/year, with similar shares of surface water stored in eight dams and groundwater abstracted from 17 aquifers (González, 2008). Efforts to meet downstream commitments to the United States under the international treaty have required reductions in water for local agriculture, illustrating how downstream compliance can lead to spillovers upstream and set up complex efforts to improve local water use efficiency and changes in reservoir operations (Barrios et al., 2009).

Environmental issues are particularly salient in the Middle Rio Grande upstream of Elephant Butte reservoir, where compliance with the Endangered Species Act requires the maintenance of specific in-stream flows to help in recovering the silvery minnow, which was listed as endangered in 1994. Since that time, the major federal water agencies and local water users have created a collaborative program to protect and possibly recover the species, illustrating how drought interacts with exposure of environmental assets within a transboundary context. In the Conchos basin and in the San Luis Valley, environmental nongovernmental organization are increasingly drawing public attention to environmental degradation of aquatic ecosystems and lobbying for the assignment of dedicated water volumes for the implementation of environmental-flows regimes to protect or restore aquatic ecosystems.

Vulnerability. The capacity to manage droughts varies significantly across the basin, influenced by water resource development and the distribution of water and shortage risks under transboundary water agreements. Water resources development affects vulnerability to droughts through the availability of reservoir storage and groundwater pumping capacity. In the upper basin, surface water users have to rely almost exclusively on in-stream flows generated by snowmelt during spring (April–June), as surface storage capacity in the San Luis Valley is very limited. In this institutional catchment, groundwater serves as a significant buffer during droughts, when water users with junior entitlements switch to the aquifer to compensate for curtailment of surface water. In the other institutional catchments, the effects of meteorological drought are buffered by well-developed surface storage capacity and, in the Middle Rio Grande, also by the availability of groundwater resources. Stored volumes at each time are determined by both rainfall and operation decisions, which, in turn, have to address legal obligations applicable in each case (interstate Compact; International treaty; minimum in-stream flows required by the Endangered Species Act) and the needs of local water users.

The existing intergovernmental water sharing agreements and governing arrangements are especially important determinants of vulnerability, which influence the distribution of impacts and capacity for responding to droughts (Table 4). The design of these transboundary water sharing agreements matters in three ways: (1) rules for sharing water, (2) provisions for declaring droughts and sharing shortage risks, and (3) their mechanisms for dispute resolution and adjustment. In the United States, the interstate river

Table 4
Institutional Catchments and Transboundary Governance Arrangements for Droughts

Institutional catchment	Constitutional agreements (intergovernmental)	Boundaries	Allocation rules	Transboundary drought management
	GS8	RS2	GS4	GS4
San Luis Valley, CO, USA	1938 Rio Grande Compact; 1906 International Convention	Headwaters to Otowi Bridge, NM	Proportional share of available water (interstate)	Credit and debit system (interstate) Proportional shortage sharing (international)
Upper and Middle Rio Grande, USA	1938 Rio Grande Compact; 1906 International Convention	Otowi Bridge, NM to Fort Quitman, TX	Proportional share of available water (interstate) Fixed volume from the United States to Mexico (international)	Credit and debit system (interstate) Proportional shortage sharing (international)
Rio Conchos, Chihuahua, Mexico	1992 National Water Law; 1944 Water Treaty	Headwaters of Conchos to Rio Bravo	Water use right concessions Coordinated by national government (interstate) 432 million cubic meters based on the estimated volume from 33.3% of runoff from six Mexican tributaries (international)	Central coordination (interstate) 5-year cycle of water accounting with debit scheme (international)
Lower Rio Grande Valley, TX, USA	1944 Water Treaty	Falcon and Amistad Reservoirs to Gulf of Mexico	Texas adjudicates municipal and agricultural water rights in Falcon and Amistad Reservoirs	Municipal water rights always receive full water allocation; agricultural water rights receive reduced allocation, depending on type of right (intrastate)

compact's water allocation rules are of a proportional character, which takes into account variability in river flows (Vandiver, 1999). A proportional rule allocates water among recipients based on a percentage or portion of the actual flow of water, which distributes the risk of water shortages among the recipients. At higher river flows, Colorado is to deliver a larger volume of water to New Mexico. Likewise, at higher river flows, New Mexico is to deliver a larger volume of water to the Elephant Butte Reservoir. Thus, both states' water delivery obligations are a function of river flows (Reynolds & Mutz, 1974). The Compact provides for additional flexibility by recognizing that during times of water scarcity, states may underdeliver the required amounts of water. Underdelivery may occur for a variety of reasons, such as the condition of the riverbed and seepage or the difficulty of shutting down irrigation midseason. Colorado and New Mexico are allowed to run water debits up to a specified volume. They are also allowed to overdeliver water and build up credits, which are stored in the Elephant Butte Reservoir and which they may use to meet their water delivery requirements at a later date. These transboundary arrangements also require institutional capacity. The compact commission relies on a technical committee to monitor interstate water deliveries and debits and credits. The commission meets annually to review the technical committee's report. In addition, the proportionate sharing of water is applied to the 1906 Agreement with Mexico. During years when the two U.S. irrigation districts received a full allotment of water, the Mexican Irrigation District receives a full allotment of 74 million cubic meters. During drought years, each irrigation district's allotment is reduced proportionally, For instance, if the U.S. irrigation districts receive 75% of a full allotment, the Mexican Irrigation District receives 75% of the 74 million cubic meters. Under this allocation rule, water deliveries to Mexico under the 1906 agreement have been reduced in approximately one of every three years since 1939 (Carter et al., 2015).

While the two upstream institutional catchments are governed by a series of proportionate water allocation rules, the Lower Rio Grande Valley, Texas, is governed by a different set of water allocation rules (Wurbs, 2004). Under the 1944 Water Treaty, Mexico owes the United States 432 million cubic meters of water per year, or a third of the estimated annual runoff of six major tributaries that is accounted for over a 5-year time period to permit variability in year-to-year water availability. In other words, the water allocation rule in the treaty is a fixed amount rule. A fixed water allocation rule places the burden of water scarcity on the upstream actor, in this case the Rio Conchos, Mexico water users. The 1944 Treaty incorporates flexibility and buffers drought impacts through its 5-year accounting period and allows Mexico to repay debts during the subsequent 5-year period. The Treaty also created an implementing body—the International Boundary and Water Commission—which offers technical support and a platform for developing “minutes,” or memoranda of understanding, between the countries over emerging issues, which has included the management of droughts and repayment of debts (e.g., Minutes 307 and 308 amending the 1944 treaty and adopted in the early 2000s). The water users of the Lower Rio Grande Valley have had their rights in the water stored in the Amistad and Falcon Reservoirs adjudicated in a court proceeding. Municipal and industrial water rights are fully satisfied, regardless of the type of water year (drought or normal). The water rights of irrigation districts are divided into two types, A and B, based on priority. B rights are the first to lose water during drought. Depending on the severity of drought, A rights may also not receive water. Agriculture absorbs the impacts of drought under this system.

Spillovers. The characterization of drought in the Rio Grande/Bravo system illustrates how the distribution of drought impacts is influenced by the combination of the spatial and temporal patterns of drought coupled with differences in exposure and vulnerability. Transboundary water institutions create a set of downstream water delivery obligations that connect upstream and downstream adaptation decisions and create potential for spillovers. These spillovers have included both beneficial linkages and risks. Positive spillovers include improved compliance and cooperation between states and countries via implementing organizations. For example, the San Luis Valley took several steps in the 1970s to improve its compliance with the 1938 Compact, delivering water for the Middle Rio Grande above and below Elephant Butte. The implementing organizations for the transboundary agreements—both the Rio Grande Commission and IBWC—have also fostered positive spillovers through monitoring and information gathering, dispute resolution and risk sharing. For example, the IBWC has 323 min since the 1940s (as of 15 March 2018), many involving cooperation between the United States and Mexico to deal with the impacts of droughts, such as the repayment sources (Minute 307) and schedule (Minute 308) for Mexico’s debt to the United States.

Spillover risks have been prevalent and caused disputes, however, in part due to the location of the compliance points and the ability to account for groundwater. For example, the location of the compliance point at Elephant Butte has meant that New Mexico’s deliveries to Texas must travel almost 150 km within New Mexico before reaching the Texas border, leaving the water vulnerable to interception by groundwater pumping. Groundwater pumping in both the San Luis Valley and Middle Rio Grande (in the region between Elephant Butte and the Texas border) have created spillover risks. Another spillover risk is illustrated by the investments in infrastructure improvements (paving of ditches, sprinkler irrigation) in the upper Rio Conchos, which have reduced runoff downstream of the river but potentially also reduced silting in the main reservoir that serves the payments to the Lower Rio Grande Valley. At the same time, some institutional catchments are functionally distinct with limited or no direct interaction. For example, the Middle Rio Grande (and upstream) are largely disconnected from the Rio Conchos and Lower Rio Grande Valley, which are primarily linked to one another. The examples above illustrate a sequencing, or cycle, of spillovers, starting with the agreement, followed by the risks associated with failure to comply, which triggers cooperative efforts. Thus, conflict between institutional catchments prompts dispute resolution that has often been cooperative. The next two propositions therefore address spillover risks and integration mechanisms in turn.

3.2. Proposition 2

Meeting downstream water delivery obligations during droughts will lead to conflict between jurisdictions and confusion about key roles and responsibilities.

Spillovers. Upstream and downstream jurisdictions are linked by both hydrology and institutional arrangements, as examined above. Consequently, as water users and managers respond to drought, they may create spillovers for adjoining users and jurisdictions. Expected water deliveries may not materialize, or increased groundwater pumping may reduce surface water flows, or failure to communicate may mean opportunities to use water more efficiently are missed. Thus, compliance with water-sharing agreements during droughts will lead to conflict between jurisdictions and across levels of governance and confusion about key roles and responsibilities (Proposition 2).

10.1002/2018EF000823

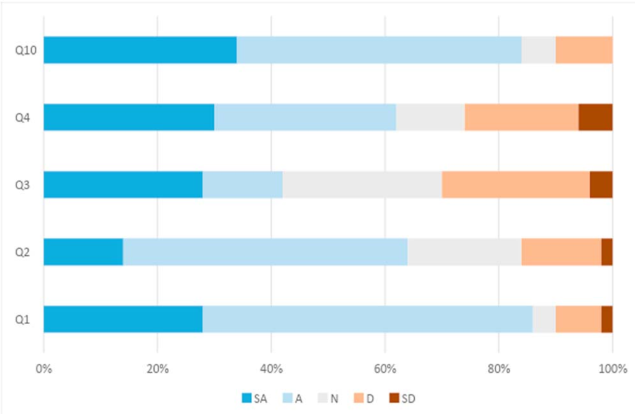

Figure 6. Water manager perceptions of spillovers: Basin-wide results (n = 50). SA = Strongly Agree; A = Agree; N = Neither Agree nor Disagree; D = Disagree; SD = Strongly Disagree. Q1: The roles and responsibilities of water management agencies are clear during normal times. Q2: The roles and responsibilities of water management agencies are clear during drought. Q3: The role of federal agencies has expanded to cover functions historically reserved for states or water users. Q4: Compliance with downstream delivery requirements under a specified international surface water agreement causes conflicts between upstream jurisdictions. Q10: Droughts lead to conflicts between states.

We assess evidence for the second proposition by examining the Likert scale responses to five statements associated with the spillover risks of droughts (see supporting information). We summarize results at the basin level, by institutional catchment and across sectors.

Basin-wide. At the basin level, we find evidence for the proposition (Figure 6). Most of the water managers interviewed (>85% of responses, Q1) agreed with the statement “the roles and responsibilities of key actors are clear during periods of normal water availability.” The institutional arrangements supported stable expectations about water managers' actions. The level of agreement declined to 65% (Q2) when asked if roles and responsibilities are clear during droughts.

Furthermore, most water managers (almost 85%, Q10) agreed that droughts lead to conflict between states sharing water within the basin. Compliance with downstream water delivery obligations under treaties and interstate compacts causes tensions among upstream jurisdictions according to over 60% (Q4) of respondents. Droughts are often associated with increasing central government responsibility as the severity and duration of the dry spell increase; yet perspectives on the role of the federal government were mixed. Only 40% agreed with the statement (Q3), “the federal government has expanded its scope to cover functions historically addressed by states or local governments” (Figure 6). This implies that horizontal (between states) coordination challenges are perceived as more severe than vertical tensions between states and the federal government.

3.3. By Institutional Catchments

We expect that local conditions (including the exposure and vulnerability to drought) will shape perceptions of water managers, leading to variation between the different institutional catchments regarding their perceptions of spillover risks and responses. In breaking down the responses to the same questions by the San Luis Valley, Upper and Middle Rio Grande, Rio Conchos, and Lower Rio Grande Valley, some significant differences emerge among water managers. Over a third of water managers in the Upper and Middle Rio Grande perceive water management roles and responsibilities to be unclear during drought, while none of the managers in the Lower Rio Grande Valley claimed that roles were clear unclear during drought (see Fisher exact tests in the supporting information). The water allocation arrangements in the Lower Rio Grande Valley are well specified during normal water years and drought years. Municipalities receive their full water allocations during normal and drought water years. In contrast, irrigation districts share water scarcity during drought as a function of their water rights. The water allocation arrangements in the Upper and Middle Rio Grande catchment are not as well specified and therefore more contentious, particularly due to the effects of groundwater pumping and the additional pressure of meeting downstream obligations.

Upstream versus downstream position also appears to affect perceptions regarding roles and responsibilities and regarding compliance (Q2 and Q4 respectively). All of the water managers interviewed in the Conchos and most of them in the Lower Rio Grande Valley agree that compliance with international surface water agreements to deliver water to downstream countries cause disputes among the upstream jurisdictions with responsibility to make the deliveries, but for different reasons. For the Conchos managers they consistently experience pressure to deliver water to meet international treaty obligations. For the Lower Rio Grande Valley managers they consistently perceive that Mexico underdelivers water, and they observe upstream-downstream disputes within Mexico to meet international obligations. In contrast, in the Upper Rio Grande and San Luis Valley, approximately 20% of interviewees agreed that downstream delivery obligations to Mexico cause disputes among upstream jurisdictions within the United States. Colorado and New Mexico water managers meet their water delivery obligations at the Otowi Bridge and the Elephant Butte reservoir, respectively. The delivery of water from the United States to Mexico under the 1906 Convention is seen as “riding above” the other downstream commitments and is the responsibility of the Bureau of Reclamation and IBWC.

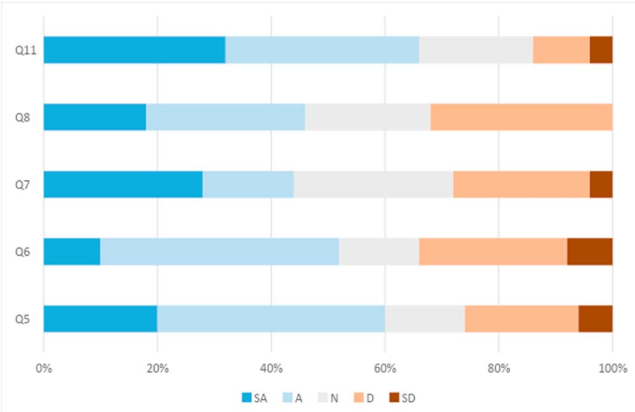

Figure 7. Water manager perceptions of integration mechanisms: Basin-wide results (n = 50). SA = Strongly Agree; A = Agree; N = Neither Agree Nor Disagree; D = Disagree; SD = Strongly Disagree. Q5: Organizations and agencies at different levels openly share data. Q6: Organizations and agencies at different levels are transparent about decision-making processes. Q7: Adaptation decisions are well coordinated between states. Q8: Adaptation decisions are well coordinated between states and the federal government. Q11: Droughts lead to cooperation between states.

We generally find support for proposition 2. Across the basin, water managers perceive drought as leading to a lack of clarity around roles and responsibilities of water agencies. In addition, droughts are perceived as creating conflicts among states and among upstream Mexican states with international delivery obligations to the United States under the 1944 Water Treaty. However, at the catchment scale perceptions become a bit more nuanced and appear to be conditioned by institutional arrangements and location in the river basin, which underscores the need for effective integration mechanisms tailored to local conditions and spillovers.

3.4. Proposition 3

3.4.1. Low-Cost Integration Mechanisms

Proposition 3: Actors will cooperate by using relatively low-cost integration mechanisms available to them in responding to drought impacts, but informal arrangements will not be sufficient on their own to address spillovers during severe, sustained droughts.

The spillovers of droughts have prompted coordination and conflict resolution between sectors, states, countries, and tiers of governance with varying success, ranging from self-regulation in Colorado to meet delivery requirements for New Mexico to Supreme Court litigation between New Mexico and Texas. We expect that a range of decision-making venues will be available for states and other stakeholders and that they will rely on informal venues, including data sharing, when feasible. We explore evidence based on the level of agreement with the close-ended questions on data sharing, the transparency of decision making processes, and efforts to cooperate and coordinate.

3.4.2. Basin-Wide

At the basin level, we find evidence for the proposition about integration mechanisms (Figure 7). There is broad agreement (60%, Q5) among water managers, that “organizations and agencies openly share data.” A narrow majority of respondents also agree with the statement that “organizations and agencies at different levels are transparent about decision-making processes” (Q6). There is also broad agreement (>60%, Q11) that drought leads to cooperation among states. This cooperation can take many forms, ranging from operational phone calls for reservoir coordination to working groups and memoranda of agreements between irrigation districts and cities in different states. However, perceptions of efforts to coordinate drought responses between states or between states and the national government were somewhat less positive. Just over 40% of respondents agreed that drought responses were well coordinated among governments (Q7, and Q8). In other words, conflict appears to lead to cooperation, but cooperation does not guarantee effective coordination.

3.4.3. By Institutional Catchments

Again, we expect that local conditions (including the exposure and vulnerability to drought) will shape perceptions of water managers, leading to variation between the institutional catchments. The Lower Rio Grande Valley respondents were less likely to agree with the statement that organizations and agencies openly share data, compared to the San Luis Valley and Upper and Middle Rio Grande respondents (Q5). This is likely due to the IBWC, an international agency that some respondents claimed is not forthcoming with data on reservoir operations, storage, and releases. Respondents in the Conchos respond similarly, with less than 40% agreeing that data is openly shared. In that instance, some managers noted constraints on data sharing by the national water agency with local stakeholders.

Perceptions regarding the effectiveness of coordination between states and the federal government also differ among institutional catchments. The participants in the Rio Conchos (>60%) held a far more favorable view of state-federal relations than those in the Upper Rio Grande (<10%, p = 0.05). This result, is an unsurprising symptom of levels of decentralization. In Mexico, the vast majority of interviews included employees of the national water agency including the managers of irrigation districts. Many respondents signaled the importance and challenges of internal coordination from the central headquarters in Mexico City, the regional offices and the irrigation districts, which are managed by employees of the national water agency. Conversely, in the Upper Rio Grande, the federal government has more limited formal authority. Coordination between states and the federal governments has been challenging in relation to decisions about reservoir operations and the administration of the Compact in the Upper and Middle Rio Grande. Unlike the San Luis Valley and the Lower Rio Grande Valley, there is a history of lawsuits involving the federal government and endangered species and groundwater pumping in the Upper and Middle Rio Grande.

We find some support for proposition 3, across the basin water managers' perceptions are that data are openly shared and that decision making is more transparent than not. In addition, water managers believe that drought can lead to cooperation among states. These perceptions differ by catchment and are conditioned by experience. These results suggest that informal, low-cost arrangements may be beneficial, but not sufficient on their own, to address the spillover risks associated with severe, sustained droughts experienced in the Rio Bravo/Grande. Further, the contrasting perspectives about state-federal and interstate coordination between the United States and Mexico suggest that the "character," or design, of federalism matters. The distribution of authority between the national and state governments has an important influence on both the types of spillovers between jurisdictions and across levels of government. In Mexico's more centralized federation, the state-federal coordination is perceived to be comparably more effective than the United States' more decentralized federation.

4. Conclusions

Our analysis offers a baseline assessment of a set of propositions about the nature of droughts and decision-making in transboundary river basins. First, drought cannot be seen as a "uniform" risk in a large transboundary basin. The spatial and temporal characteristics of droughts in large basins are uneven, and this variation is overlaid by sharp contrasts in urbanization, irrigation development, groundwater depletion, and associated environmental quality impacts.

We advanced the IAD-SES framework in two ways. First, we integrate concepts from risk management and the literature on the human dimensions of natural hazards to characterize droughts in terms of hazards, exposure, and vulnerability. The subsystems of SES enable a finer-grained identification of relevant variables and interactions. Second, we identify the spillovers associated with "upstream" adaptation decisions in large-scale transboundary river basins, highlighting the need for appropriate coordination venues.

The risk-based IAD-SES framework is used to elaborate the concept of an "institutional catchment"—a self-contained administrative unit whose boundaries are defined by transboundary water sharing agreements rather than watersheds. In the case of a large river basin, an institutional catchment is defined by the compliance locations for meeting downstream obligations. Over time, efforts to adapt to droughts upstream can cause risks to spillover, but they can also spur new cooperative efforts, conflict resolution, and venues for coordinating decision making across jurisdictional boundaries. The concept of an institutional catchment conveys how the geographic boundaries around drought adaptation are defined in relation to historic water-sharing agreements, which have often proven ill-equipped to handle the combination of sustained droughts and intensifying competition between sectors and jurisdictions. The agreements include compliance requirements and delivery obligations that have led to sharp differences in the vulnerability, and the impacts and management of droughts upstream will spillover.

A global map illustrates how severe droughts combine with jurisdictional fragmentation. The Rio Grande/Bravo emerges as a paradigmatic example of a river basin with a history of severe droughts and a complex institutional landscape that requires coordination across international borders and multiple states within each country. We found evidence supporting three propositions. First, we demonstrated how the design and implementation of transboundary water agreements influence vulnerability to drought risks within and across institutional catchments, illustrating the nature and sources of heterogeneity within a transboundary context. Second, interviews with 50 water managers across the four "institutional catchments" allowed us to examine evidence about the spillovers of droughts. We found that roles and responsibilities become less clear during drought, and drought leads to conflicts between states as a result of the tensions associated with meeting obligations to deliver water downstream. However, local conditions and geographic positions matter and expose asymmetries in exposure to spillovers.

Finally, we explored the perceived effectiveness of different integration mechanisms, or decision-making venues, for responding, including the opportunities and limits of informal mechanisms. Conflicts between states over downstream compliance led to problem solving and coordination, suggesting that spillover risks can lead to positive spillovers depending on the institutional arrangements and their capacity to resolve conflicts both informally and formally. We expected that informal venues would be prevalent and found broad agreement about data sharing. Informal arrangements ranged from operational phone calls for reservoir operations to working groups among upstream and downstream irrigation districts and cities. Yet the lack of federal-state and interstate coordination, particularly in the United States, suggests that there will be limits to cooperation during severe, sustained drought when roles and responsibilities are unclear. Groundwater pumping may weaken the ability of upstream jurisdictions to comply with water-sharing agreements, or lead to informal coordination that is not deemed acceptable by state, federal, or international bodies. These findings suggest that informal coordination can prevent droughts risks from spilling over but may require more formal coordination and conflict resolution mechanisms for severe, sustained events.

There are some important implications for policymakers, including the need to (i) assess institutional vulnerability to drought to identify and address governance deficits that may exacerbate conflicts between jurisdictions; (ii) understand trade-offs and interdependencies between jurisdictions by explicitly measuring and mapping the "spillovers" associated with upstream adaptation decisions; and, finally, (iii) build a portfolio of informal and formal decision-making venues to facilitate adaptation decisions that pass through informal channels before they cascade or escalate. In the context of cascading drought impacts, risk-based observatories of institutional adaptation can generate evidence to guide policy and practice.

Acknowledgments
The research for this article was supported by the Social Sciences and Humanities Council of Canada, grant 430–2014-00785. D. G. was also supported by the Water Economics, Policy and Governance Network (WEPGN), funded by a Social Sciences and Humanities Research Council (SSHRC) Partnership Grant. S. V. T.'s work on this paper has been supported by European Commission funding under the Marie Curie Actions -Individual Fellowship H2020-MSCA-IF-2014 (contract 660089-COMOVE). The anonymized data set for the study is available at www.waterwonk.org/data. Shapefiles for the institutional catchments (Figure 4) were generously provided by Rachel O'Connor, AMP Insights. The authors wish to thank the participants (water managers) interviewed in the study in 2016 and 2017. The paper benefited from feedback provided by participants during panels at the International Association for the Study of the Commons (July 2017) and European Consortium for Political Research (September 2017) in Utrecht and Oslo, respectively. All responsibility for errors and omissions lies with the authors.

References

Anderies, J., Janssen, M., & Schlager, E. (2016). Institutions and the performance of coupled infrastructure systems. *International Journal of the Commons*, *10*(2), 495–516.

Barrios, J. E., Rodríguez-Pineda, J. A., & De La Maza Benignos, M. (2009). Integrated river basin management in the Conchos River basin, Mexico: A case study of freshwater climate change adaptation. *Climate and Development*, *1*(3), 249–260.

Brown, J. R., Kluck, D., McNutt, C., & Hayes, M. (2016). Assessing drought vulnerability using a socioecological framework. *Rangelands*, *38*(4), 162–168. https://doi.org/10.1016/j.rala.2016.06.007

Carrão, H., Naumann, G., & Barbosa, P. (2016). Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change*, *39*, 108–124. https://doi.org/10.1016/j.gloenvcha.2016.04.012

Carter, N. T., Seelke, C. R., & Shedd, D. T. (2015). US-Mexico water sharing: Background and recent developments. *Current Politics and Economics of the United States, Canada and Mexico*, *17*(1), 229.

Castelan, E. (2001). Los Consejos de Agua en Mexico. In P. W. C. Scott & B. Maranon (Eds.), *Asignacion, Productividad y Manejo de Recursos Hidricos en Cuencas* (pp. 175–234). Colombo, Sri Lanka: International Water Management Institute.

Cody, K. C., Smith, S. M., Cox, M., & Andersson, K. (2015). Emergence of collective action in a groundwater commons: Irrigators in the San Luis Valley of Colorado. *Society & Natural Resources*, *28*(4), 405–422.

de Loë, R. C., & Patterson, J. J. (2018). Boundary judgments in water governance: diagnosing internal and external factors that matter in a complex world. *Water Resources Management*, *32*(2), 565–581.

Feiock, R. C. (2013). The institutional collective action framework. *Policy Studies Journal*, *41*(3), 397–425.

Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (Eds.) (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change*. Cambridge University Press.

Fleischman, F. D., Loken, B., Garcia-Lopez, G. A., & Villamayor-Tomas, S. (2014). Evaluating the utility of common-pool resource theory for understanding forest governance and outcomes in Indonesia between 1965 and 2012. *International Journal of the Commons*, *8*(2), 304–336.

Freire-González, J., Decker, C., & Hall, J. W. (2017). The economic impacts of droughts: A framework for analysis. *Ecological Economics*, *132*, 196–204.

Garrick, D., De Stefano, L., Fung, F., Pittock, J., Schlager, E., New, M., & Connell, D. (2013). Managing hydroclimatic risks in federal rivers: A diagnostic assessment. *Philosophical Transactions of the Royal Society A*, *371*(2002), 20120415. https://doi.org/10.1098/rsta.2012.0415

Garrick, D., Schlager, E., & Villamayor-Tomas, S. (2016). Governing an international transboundary river: Opportunism, safeguards, and drought adaptation in the Rio Grande. *Publius: The Journal of Federalism*, *46*(2), 170–198.

Garrick, D. E., & De Stefano, L. (2016). Adaptive capacity in federal rivers: Coordination challenges and institutional responses. *Current Opinion in Environmental Sustainability*, *21*, 78–85.

González, G. J. (2008). El Valle de Delicias en la Cuenca del Río Conchos.

Grafton, R. Q., McLindin, M., Hussey, K., Wyrwoll, P., Wichelns, D., Ringler, C., et al. (2016). Responding to Global Challenges in Food, Energy, Environment and Water: Risks and Options Assessment for Decision-Making. *Asia & the Pacific Policy Studies*, *3*(2), 275–299.

Hearne, R. R. (2004). Evolving water management institutions in Mexico. *Water Resources Research*, *40*, W12S04. https://doi.org/10.1029/2003WR002745

Kallis, G. (2008). Droughts. *Annual Review of Environment and Resources*, *33*, 85–118.

McCord, P., Dell'Angelo, J., Baldwin, E., & Evans, T. (2017). Polycentric transformation in Kenyan water governance: A dynamic analysis of institutional and social-ecological change. *Policy Studies Journal*, *45*(4), 633–658.

McGinnis, M., & Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, *19*(2), 30. https://doi.org/10.5751/ES-06387-190230

McGinnis, M. D. (2011). An introduction to IAD and the language or the Ostrom Workshop: A simple guide to a complex framework. *Policy Studies Journal*, *39*(1), 169–183.

Meinzen-Dick, R. (2007). Beyond panaceas in water institutions. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(39), 15,200–15,205.

Ostrom, E. (2005). *Understanding institutional diversity*. Princeton, NJ: Princeton University Press.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419–22.

Ostrom, E. (2011). Background on the institutional analysis and development framework. *Policy Studies Journal*, *39*(1), 7–27. https://doi.org/10.1111/j.1541-0072.2010.00394.x

Ostrom, V., Tiebout, C. M., & Warren, R. (1961). The organization of government in metropolitan areas: A theoretical inquiry. *American Political Science Review*, *55*(4), 831–842.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., et al. (2014). Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3262–3267.

Reynolds, S. E., & Mutz, P. B. (1974). Water deliveries under the Rio Grande compact. *Natural Resources Journal*, *14*, 201–205.

Sheffield, J., & Wood, E. F. (2008). Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics*, *31*(1), 79–105. https://doi.org/10.1007/s00382-007-0340-z

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, *16*(3), 282–292.

Stern, P. C. (2011). Design principles for global commons: Natural resources and emerging technologies. *International Journal of the Commons*, *5*(2), 213–232.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I., Stahl, K., Hannaford, J., et al. (2016). Drought in the Anthropocene. *Nature Geoscience*, *9*(2), 89–91.

Vandiver, S. (1999). The administration of the Rio Grande compact in Colorado.

Villamayor-Tomas, S., Fleischman, F., Ibarra, I. P., Thiel, A., & van Laerhoven, F. (2014). From Sandoz to Salmon: Conceptualizing resource and institutional dynamics in the Rhine watershed through the SES framework. *International Journal of the Commons*, *8*(2), 361–395.

von der Meden, J. H., Rodriguez, A., de la Maza, M., Zapata, J., Martinez, A., Cleghorn, A., et al. (2010). Cuenca Transfronteriza del rio Bravo/Grande. In E. Cotler Avalos (Ed.), *Las Cuencas Hidrograficas de Mexico* (173–179). Mexico D.F.: SEMARNAT.

Wilhite, D. A. (2000). Drought as a natural hazard: Concepts and definitions.

Woodhouse, C. A., Stahle, D. W., & Díaz, J. V. (2012). Rio Grande and Rio Conchos water supply variability over the past 500 years. *Climate Research*, *51*(2), 147–158.

Wurbs, R. A. (2004). Water allocation systems in Texas. *Water Resources Development*, *20*(2), 229–242.

Wyrwoll, P. R., Grafton, R. Q., Daniell, K. A., Chu, H. L., Ringler, C., Lien, L. T. H., et al. (2018). Decision-making for systemic water risks: Insights from a participatory risk assessment process in Vietnam. *Earth's Future*. https://doi.org/10.1002/2017EF000777