Chapter 7
Water Security and Adaptation to Climate Extremes in Transboundary Rivers of North America

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Abstract Three basins in North America are used to examine how transboundary water governance arrangements have developed and performed in the face of recent severe droughts: the Colorado and Rio Grande Rivers on the US-Mexico Border and the Columbia River on the Canada-US border. The chapter delivers insights about water governance responses to the key problems in each basin, as well as the opportunities and limits to transfer policy lessons across basins. The findings illustrate the: (a) importance of proportional resource sharing mechanisms that spread risk and benefits in ways that are more likely to be perceived as fair; (b) potential for economic instruments and fiscal decentralization to reduce risks of natural hazards by enabling more localized responses; and (c) the need to establish, and strengthen, coordination mechanisms (e.g. river basin authorities, joint monitoring, conflict resolution venues) that are well matched to local conditions, including informal institutions (e.g. working groups, networks, joint studies). The chapter concludes with lessons about adaptation to extreme climate events in transboundary rivers of North America, including governance insights and practices that have enhanced (or reduced) freshwater security.

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7.1 Introduction

Climate variability and extreme events, such as droughts and floods, are superimposed on the chronic pressures associated with freshwater scarcity. Together, water stress and climate hazards pose a growing threat to freshwater security for people and ecosystems. The world's federal countries confront such water security challenges in a situation of institutional fragmentation: authority for managing transboundary rivers and aquifers is splintered across independent territorial and national jurisdictions, which can impede integrated water management and contribute to geopolitical tensions and instability.

North America is an ideal laboratory to investigate water security and adaptation to climate extremes in three contrasting federal political systems: Canada, Mexico and the United States. Transboundary water management varies across and within the three countries in terms of the level of centralization and institutional mechanisms for power sharing, conflict resolution, information gathering and planning, and fiscal arrangements. This raises fundamental questions about the evolution, design and performance of transboundary water governance arrangements at multiple scales – both within and across national borders.[1]

Three basins in North America are used to examine how transboundary water governance arrangements have developed and performed in the face of recent severe droughts. The case studies include the Colorado and Rio Grande Rivers on the US-Mexico Border and the Columbia River on the Canada-US border. The chapter delivers insights about water governance responses to the key problems in each basin, as well as the opportunities and limits to transfer policy lessons across basins. The findings illustrate the: (a) importance of proportional resource sharing mechanisms that spread risk and benefits across governance arrangements in ways that are more likely to be perceived as fair (b) potential for economic instruments and fiscal decentralization to reduce risks of natural hazards by enabling more localized responses; and (c) the need to establish coordination mechanisms (e.g. river basin authorities, joint monitoring, conflict resolution venues) that are well matched to local conditions, including informal institutions (e.g. working groups, networks, joint studies). The chapter concludes with lessons about adaptation to extreme climate events in transboundary rivers of North America, including governance insights and practices that have enhanced (or reduced) freshwater security.

[1] Governance has been defined by Young (1992) as "the structures and processes through which people in societies make decisions and share power" as cited by Davidson and de Loe (2014). A focus on governance is distinct from government by accounting for formal and informal institutions and actors. Transbounary governance accounts for the special coordination challenges when resources cross political borders.

7.2 Climate Change and Difficult Hydrology in North America

The observed historic and projected impacts of climate change are highly dependent on context. The 5th Assessment of the Intergovernmental Panel on Climate Change (IPCC) characterized the impacts and adaptation needs in North America (Romero-Lankao et al. 2014). It reviewed the observed climate changes relevant for water resource governance in North America, including the increasing prevalence of severe hot weather events (affecting outdoor water use) in the USA and heavy precipitation events throughout North America, which influences flooding extremes and strains stormwater infrastructure. The attribution of individual extreme weather and climate events to anthropogenic remains complex (Trenberth et al. 2015). However, climate change has been linked with observed changes to earlier snowmelt and declining spring snowpack in cold mountain rivers of the Western USA and Canada (Romero-Lankao et al. 2014). Future climate change is projected to cause a series of water-related climate hazards in North America associated with risks of shortage and flooding (low snow years, earlier runoff, intense droughts and increased precipitation variability, storm surges and higher sea levels). Climate change impacts also combine with other factors including urbanization, poor governance and mounting resource demands for food, energy and water security (Grafton et al. 2013).

7.2.1 Difficulty Hydrology and Extreme Climate Events

Extreme climate and weather events are a prominent feature of this observed climate record in North America. The IPCC's Special Report on Climate Extremes, known as the SREX report (Field 2012), defined climate extremes as the 'occurrence of a value of a weather or climate variable above or below a threshold value near the upper or lower ends of the range of observed values of the variable.' Droughts and floods are two prominent types of water-related extreme climate events; drought is the prime focus of this chapter.

It is important to note that droughts and floods are a natural feature of hydroclimatology and there is a long history of adaptation and maladaptation to their impacts. David Grey and Claudia Sadoff (2007) introduce the concept of 'difficulty hydrology' to describe the water security challenges posed by climate variability – both seasonal and inter-annual (year over year) fluctuations in runoff. Such variability has been linked with persistent poverty through the recurrent economic losses and impacts associated with droughts, floods and unpredictable timing of monsoonal events. Maladaptation to existing climate variability and extremes is viewed as an impediment to sustainable development; hence, enhanced adaptive capacity to deal with climate extremes is considered a prerequisite for addressing future climate change. These arguments have since been bolstered by empirical analysis and econometric modeling linking variability and economic growth (Brown and Lall 2006; Hall et al. 2014).

The North American context is noteworthy for its examples of regions confronting the challenges associated with difficulty hydrology, including the Colorado and Rio Grande Rivers. Grey and Sadoff cite the Colorado as an example of a 'harnessed hydrology' for its potential to decouple, or buffer, its economic development from the water-related risks posed by climate variability and extremes. They acknowledge that water security in regions with harnessed hydrology is precarious and requires ongoing vigilance and innovations in institutional reform, infrastructure development and information systems. They also note that past water security has come with a high social and environmental cost. Therefore, the lessons from adaptation in North America are also of increasing interest internationally. Past drought and flood adaptation provide an analog for both future climate change adaptation and may offer lessons from both successes and failures for many of semi-arid and subtropical rivers and regions in the developing world.

7.3 Adaptation

Climate change adaptation in human systems refers to 'adjustment to actual or expected climate and its effects' and 'seeks to moderate or avoid harm or exploit beneficial opportunities' (Agard et al. 2014).

This chapter highlights the *institutional options* for adaptation in the multi-layered context of transboundary rivers shared by multiple political jurisdictions. Dovers and Hezri (2010) identify three types of 'institutional resilience strategies'[2] for adapting to climate change: resistance and maintenance, change at the margins and openness and flexibility. Each can be deployed with a range of positive and negative outcomes, or strengths and weaknesses. **Resistance and maintenance** characterizes the 'no action' or status quo based on a reluctance to adapt prematurely or pursue maladaptive strategies. This can lead to efforts to prioritize stability and optimization of resource use (positive outcomes) or resistance to change and delay until crisis triggers change (negative outcomes). Strategies based on incrementalism favor **change at the margins**. Recognition of the need for learning and iterative adaptation can favor gradual approaches (positive outcome) but miss opportunities to address major changes and adopt long-term, strategic approaches (negative outcome). Finally, strategies based on **openness and adaptability** may embrace uncertainty and the need for rapid changes by preserving flexibility (positive outcome) while also permitting rash changes and maladaptation (negative outcome). These three dominant strategies also align with the recent distinctions between incremental and transformational adaptation with the latter restricted to

[2] For a thorough treatment of the concept of resilience applied to social-ecological systems, please see Martin-Breen and Anderies (2011).

conditions when vested interests and path dependencies can be overcome due to the stakes (i.e. risks and benefits) motivating reform (Kates et al. 2012).

7.3.1 Water-Related Adaptation in a Transboundary Context

Pittock (2013) adapts the approach developed by Dovers and Hezri (above) to examine adaptation options in a transboundary river context. He identifies at least five prevalent strategies:

1. **Iterative or cyclical water planning**. Coordinated and multi-layered planning processes incorporate opportunities for adaptation and learning, as well as integration of knowledge and stakeholders within (horizontal) and across (vertical) tiers of governance.
2. **Cap-and-trade water allocation reforms**. Water markets enable allocation in response to changing supply and demand conditions by using price to signal the scarcity value of water and to cue reallocation. In large transboundary rivers, such reforms involve the development of a nested set of caps on water diversions and trading rules to account for social and physical connections between water users.
3. **Reallocation of water for the environment**. In overallocated rivers, efforts to address environmental water requirements involve reallocation to preserve or restore ecosystem functions and enhance resilience to climate change impacts.
4. **Expansion or modification of water infrastructure**. Physical and natural water infrastructure, particularly different forms of storage (including reservoirs) has been proposed as a means of buffering the impacts of climate variability by addressing shortage and flood risk.
5. **Ecosystem conservation**. Following # 3 and #4, ecosystem conservation enhances the resilience of rivers as ecosystems and their capacity to provide ecosystem services related to floods and water storage.

In practice, these elements are almost always pursued in combinations to adapt to the impacts of 'difficult hydrology' and extreme climate events associated with droughts and floods. Almost all major rivers traverse political borders. The roles and responsibilities in water governance and climate adaptation are divided across multiple levels of governance and between the public and private sector at a range of scales. This has led to calls for decentralization or retention of adaptation tasks at the lowest level of governance possible (Field 2012), following the principle of subsidiarity (Marshall 2008). This raises the challenge of balancing decentralization and subsidiarity with complementary mechanisms for coordination and conflict resolution (Marshall 2008, Pahl-Wostl and Knieper 2014). These challenges are particularly pronounced in federal political systems where authority and capacity are divided and shared across national and sub-national levels, and include nation-to-nation relationships with indigenous communities.

7.3.2 The Special Challenge of Adaptation in Federal Political Systems

Water management poses unique coordination challenges in federal countries because authority over water is divided and shared between national and sub-national governments (Garrick et al. 2016). Extreme climate events exacerbate these governance dilemmas by creating situations ripe for opportunism: shirking of responsibility and burden-shifting by states or provinces and encroachment and crowding out by the federal government.

Federalism affects adaptation to climate extremes in a wide range of geographic and political economic contexts. Garrick et al. (2013) document the global influence of federalism in over 300 of the world's 554 major river basins, including approximately half of the world's international rivers. These include iconic freshwater bodies as varied as the Colorado, Nile, Indus and the Great Lakes. Prior research has examined the character and evolution of state-federal relations in water management, particularly in the older federations such as the US, Canada and Australia (Heinmiller 2009). However, comparative research remains surprisingly rare. Existing research also emphasizes policy responses to chronic water stress (e.g. competition or pollution), although there has been growing attention over the past 15 years to the management of climate variability and extreme weather events (Schlager et al. 2011; de Loë et al. 2001; de Loë and Plummer 2010).

7.4 North America as a Laboratory for Transboundary Adaptation

North America is an ideal laboratory to investigate the relationship between federalism, climate extremes and adaptive capacity. The federal approaches to adaptation to climate extremes and the relative roles and responsibilities across the central, sub-national and local levels vary across the three countries in terms of the level of centralization and of institutional mechanisms for power sharing, fiscal arrangements and conflict resolution in the management of water resources and climate extremes. In the broadest terms, federal political systems in Canada and Mexico form a spectrum from more decentralized to more centralized with the US occupying an intermediate point with high levels of internal diversity, although these attributes vary over time and across policy issues. Below, the review looks for commonalities that apply and differences across these diverse contexts.

This section reviews lessons from adaptation experiences in three North American rivers – the Colorado (US-Mexico), Columbia (US-Canada) and Rio Grande (US-Mexico) – which together traverse all three countries – Canada, Mexico and the United States (Table 7.1). The basins share conditions of water stress and overallocation, and are also prone to extended drought (from a year to decade) and periodic flooding. After briefly introducing the geographic context of each basin below, lessons from recent severe droughts in each basin are elaborated based on the adaptation options and insights outlined above.

7.4.1 Colorado

The Colorado River straddles seven states in the US and two in Mexico (637,100 km^2), as well as several Indian tribes, cities and irrigation districts. It has supported extensive irrigation development (4.5–5.5 million acres of irrigated agriculture), hydropower production and rapid urban growth for up to 40 million people in the major population centers of the Western US (U.S. Bureau of Reclamation 2012). There is a chronic imbalance in lower basin deliveries from Lake Mead, which has been described as a 'structural deficit' with total outflows and losses of approximately 12.6 billion m^3 and inflows of only approximately 11.1 billion m^3. The annual imbalance is buffered by reservoir storage, but this cushion has been depleted during sustained drought.

Drought is a prominent feature of the observed and paleoclimate records. The 1922 Colorado River 'Compact' – an interstate apportionment scheme – was famously negotiated after an unusually wet period, causing an overestimate of supply and a system of fixed volumetric allocations dividing water between the Upper and Lower Division states and between the US and Mexico. The four Upper Division states in the US (Wyoming, Colorado, Utah and New Mexico) devised a proportional allocation scheme after recognizing the variability of inflows and the limited likelihood of developing the full allocations under the 1922 agreement. Subsequent severe drought (in the late 1940s and 1950s) was followed by tree-ring studies in the 1970s identifying the prevalence of mega-droughts in the paleoclimate record and also revising the long-term annual average flows available (Stockton and Jacoby 1976; Woodhouse et al. 2006).

Drought conditions interact with demand pressures to shape contemporary transboundary adaptation efforts. Long-term supply and demand intersected in the late 1990s after nearly a century of infrastructure development and population and economic growth. In the context of this river basin closure, the Basin has experienced an unprecedented sequence of dry years since 2000, which has left the Basin's vast storage (4:1 ratio of storage: annual runoff) at 50 % capacity as of September 2015. This has triggered a spate of transboundary adaptation efforts, including the development of shortage rules (2007) for reducing interstate downstream deliveries from Lake Mead – the Lower Basin's primary storage at specified reservoir levels.

A comprehensive Basin Study in 2012 assessed supply-demand imbalances under projected climate change impacts through 2060 and examined vulnerability of different states sharing the river. The 1944 international treaty allocating Colorado River water to Mexico specified the sharing of shortages under ‘extraordinary drought’ conditions but did not define this term. In 2012, the US and Mexico also agreed to an international shortage sharing rule to include Mexico in shortages as part of “Minute 319” – a form of amendment – to the 1944 international water treaty governing the Colorado and Rio Grande Rivers (Gerlak 2015).

7.4.2 Columbia

The Columbia Basin is one of the most developed rivers in Western North America with more than 200 dams supporting approximately 5 million acres of irrigation; 16 000 MW of hydropower; a population of more than 7 million with increasing development in the rural, semi-arid interior; and a salmon fishery with high ecological, cultural and economic significance. Like the Colorado, the Columbia straddles an international border, but between the US and Canada. The basin drains almost 700,000 km^2 across seven US states, one Canadian province and a number of First Nations and tribal nations. The Columbia River Basin is comparable in size with the

Table 7.1 Selected transboundary rivers in North America

	Colorado	Columbia	Rio Grande
Political geography			
Size	637,137 km^2	668,000 km^2	471,900–870,000 km^2
Jurisdictions (Sub-national)	7 US, 2 Mexico	7 US, 1 Canada	3 US, 5 Mexico
Transboundary framework			
International	1944 US-Mexico Treaty	1964 Columbia River Treaty	1944 US-Mexico Treaty; 1906 International Convention
Drought provisions	Proportional reduction under “extraordinary drought”	N/A	Proportional reduction under “extraordinary drought”
Interstate	1922 Colorado River Compact	N/A	1938/9 Rio Grande Compact
Drought provisions	Tiered Shortage (Lower Basin and Mexico); Proportional Rule (Upper Basin)	N/A	Proportional Reduction

All three rivers have several indigenous First Nations (Canada) and Tribal Nations (US/Mexico); A range is provided for the size Rio Grande due to the endorheic (closed) sub-basins within the Basin.

Colorado in terms of drainage area but not in volume. It has an average volume at the Dalles Dam of 165 billion m^3, an order of magnitude higher than the Colorado. However, like the Colorado, stream flow is characterized by spatial and seasonal variability due to a snowmelt dominated hydrograph. Tributaries still experience seasonal variability and exhibit scarcity conditions characteristic of semi-arid irrigation regions. Chronic seasonal water deficits in the tributaries occur in late summer (August, September), when peak agricultural use coincides with natural low flows after snowmelt.

Semi-arid conditions, irrigation development and recurrent drought affect the tributaries of the interior basin with drought years causing economic losses in the 1930s, 1977 and early 2000s (Xiao et al. 2014). Most recently, droughts have tested water allocation institutions in 2001, 2005 and 2015. The Columbia lacks interstate or international allocation agreements for water quantity, which concentrates adaptation actions at the local, state and federal level within each country. Transboundary basin planning and conflict resolution during extreme events is restricted primarily to flood control, hydropower production, and ecosystem restoration. States and provinces issue drought orders and associated water use restrictions. Adaptation to climate extremes is therefore concentrated *within* individual states on the US and Canadian sides of the basin. In the US, shortage conditions have typically been managed at the level of tributaries (where water scarcity is prevalent) because the main 'stem' of the river is relatively abundant and its vulnerability to climate extremes is limited primarily to fluctuations in hydropower production. In the Yakima River of Southern Washington, for example, federal and state agencies in cooperation with irrigation districts and tribal governments have developed drought plans, undertaking climate change studies under the 2009 Water Smart Act program, and developed reverse auctions for dry-year leasing to acquire water from farmers during dry years to protect salmon fisheries.

The Okanagan River of British Columbia and Washington and the Walla Walla of Southwestern Washington and Northeastern Oregon are among the only major international and interstate tributaries, respectively. The Walla Walla has been subject to a US Supreme Court dispute in the 1930s. More recent programs in Washington promote "Flow from Flexibility" to work outside the priority based system of water allocation ('prior appropriation' or 'first in time, first in right' in the US) by entering into collaborative agreements, the development of water markets and mitigation bank agreements. These have been concentrated within Washington due to the lack of interstate agreements (Siemann and Martin 2007). Changing snowpack and winter precipitation under climate change promises to increase the transboundary nexus within the US (across states) and internationally (between the US and Canada) as changing streamflow patterns affect hydropower production, salmon recovery and other water uses and infrastructure operations on the main stem (Cosens and Bankes 2014).

7.4.3 Rio Grande

The Rio Grande is shared by the US and Mexico and forms the international border between them. The river originates in the San Juan Mountains in Colorado and flows through New Mexico (43 $m^3\ s^{-1}$) until it reaches the border cities of El Paso, Texas and Ciudad Juarez, Chihuahua where the river is reduced to irrigation return flows and wastewater. The Rio Conchos is a major tributary originating in Mexico that joins the border reach upstream of the border cities of Presidio, Texas and Ojinaga, Chihuahua increasing average flows by an order of magnitude from 3 $m^3\ s^{-1}$ to 30 $m^3\ s^{-1}$ (Woodhouse and Stahle 2012).

The geography of the Basin creates an ideal setting for comparative institutional analysis. Both countries occupy an upstream position on a major tributary – the US on the Rio Grande, Mexico on the Rio Conchos – which creates mutual obligations for downstream deliveries and involves internal, interstate dynamics associated with meeting international commitments. The Rio Grande is a snowmelt-dominated hydrograph with runoff peaking in the spring. The Rio Conchos is heavily influenced by the North American monsoon with over half of the annual precipitation occurring between the middle of June and middle of September. This creates a situation where drought can affect one or both parts of the basin.

Drought in the Rio Conchos and Rio Grande is not strongly coupled in the instrumental record with the exception of the 1930s and 1950s (Woodhouse and Stahle 2012). The continental scale drought in North America (2012) is another recent example (Cook et al. 2013). However, the drought of record in the Upper Rio Grande is the most recent drought, which did not extend to the Rio Conchos. The drought patterns differ partly due to the contrasting hydrology of the snowmelt-dominated Upper Rio Grande and the monsoon-driven Rio Conchos. Since the 1990s there have been at least three major events, one in the US, two in Mexico, which overlap only partially. In the Upper Rio Grande, flows at the Del Norte Colorado gauge, which are used to establish Colorado's downstream water delivery requirements, have been below the 1895–2010 average for at least two of every 3 years since 2000. The diminished flows have affected the major water users in New Mexico and Texas (cities of Albuquerque, Santa Fe, and Las Cruces, New Mexico; irrigation districts of the San Luis Valley of Colorado Middle Rio Grande and Elephant Butte, and the El Paso Irrigation District in Texas). In the Rio Conchos, there are two events of drought and/or shortage: 1994–2003 and 2010–2014. Droughts that affect part of the basin may create asymmetries in the compliance issues as both countries are upstream on at least one major tributary, while basin-wide drought is likely to create compliance problems in both directions. However, because drought interacts with water demand characteristics, even minor anomalies have led to compliance problems.

Two international agreements govern the Rio Grande/Bravo: the 1906 Convention[3] and 1944 Treaty[4] between the US and Mexico. Both international agreements provide fixed volumetric commitments from the US to Mexico (60,000 acre feet per year) and Mexico to the US (350,000 per year assessed over a cycle), respectively. Both agreements also referred to “extraordinary droughts” as the basis for reducing deliveries proportionally. However, neither agreement defined such droughts in operational terms (e.g. triggers or thresholds). Under the 1906 Convention, deliveries to Mexico can be reduced in proportion to reductions in the US. Deliveries to Mexico have been reduced approximately one in 3 years on average since 1939, and the US is not required to “repay” the deficit. The reductions have been severe in recent years with the US delivering 39 % and 6 % of Mexico’s allotment in 2012 and 2013, respectively (Carter et al. 2013). Under the terms of the 1944 Treaty, Mexico has accrued water debts during two consecutive drought cycles during the drought from 1994–2003. As of the cycle concluding on October 2, 2002, Mexico’s water debt had reached 1.5 MAF over two consecutive cycles (Marin 2003). The accumulated deficits prompted political negotiations between Presidents G.W. Bush and Vicente Fox in spring 2002. Despite these intense negotiations and mutual suspicions of opportunism in the interpretations of ‘extraordinary drought’, the drought prompted a period of coordination between the US and Mexico sections of the International Boundary and Waters Commission.

Within both countries, different transboundary approaches are taken for interstate adaptation, governed by the Rio Grande Compact and its proportional allocation rules (US) and through central government and river basin council deliberations (Mexico). Internal arrangements within both countries have been marked by high degrees of conflict and Supreme Court cases (US) or threats of legal action (Mexico). Limited pockets of water trading in the Upper Rio Grande and recent sub-basin studies of climate change vulnerability under the 2009 Water Smart program have aimed to reduce impacts of drought and water shortage in the US portion of the Basin. Groundwater development and infrastructure efficiency investments have been the focus of adaptation efforts on both sides of the border causing challenges for meeting downstream compliance obligations.

7.5 Lesson from Adaptation to Climate Extremes in Transboundary Rivers

The three rivers of North America exhibit contrasting roles for water users, other stakeholders and different levels of governance, including local, regional, and federal bodies. This section reviews the institutional mechanisms and strategies proposed by Pittock. In Canada, the decentralized system of water governance vests allocation and many related planning and adaptation decisions at or below the

[3] Equitable Distribution of the Waters of the Rio Grande.

[4] Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande.

provincial level. In Mexico, water governance and climate adaptation remain comparably centralized despite over 20 years of decentralization since the 1992 National Water Law. In the US, context matters greatly, but transboundary adaptation is shaped by strong state governments and the existence of horizontal coordination through interstate river 'compacts.' International agreements between the US and Canada (administered by the International Joint Commission) and between the US and Mexico (administered by the International Boundary and Water Commission) are therefore shaped by these underlying and internal agreements. While the agreements between the US and Mexico reference 'extraordinary drought', and the agreements between the US and Canada on the Columbia address flood control benefit sharing, the scope of international agreements for climate adaptation remains limited to data exchange and allocation agreements with mixed downstream compliance (relatively high in the Colorado from the US to Mexico, relatively low, or at least disputed, in the Rio Grande). Despite these contrasting systems for transboundary adaptation, the Canadian, Mexican and US experiences generates some broad lessons.

7.5.1 Proportional Allocation Rules

The allocation of water based on proportional shares, rather than fixed volumes, is expected to be viewed as fair and hence more likely to be well-matched to drought prone areas (Schlager and Heikkila 2011). All three rivers include instances of proportional rules for sharing water across political borders. In the Colorado River, interstate agreements include both fixed (between Lower Division US States) and proportional (between Upper Division US States) rules, while shortage sharing measures have been expanded to include tiered reductions in downstream deliveries to Mexico when official shortages are triggered in the US. The Rio Grande is governed by a nested set of interstate and international agreements with both governed by proportional rules related to water allocation (US Rio Grande Compact) and triggers related to 'extraordinary drought' that reduce international deliveries from the US to Mexico by a proportional amount when the Upper Rio Grande experiences shortages within the US. Contrasted with fixed allocation rules (e.g. Lower Division US Colorado River states), proportional allocation rules enhance flexibility.

7.5.2 Water Markets and Efficiency Improvements

Water markets and associated cap-and-trade allocation reforms have been applied unevenly within all three rivers, although principally in the US portions. Pockets of water leasing have developed in portions of the Colorado (e.g. Arizona, California, Colorado), Columbia (all major US states) and the Upper Rio Grande (New Mexico and Colorado), including the development and use of dry-year leasing for both urban and ecosystem water security. Water allocation flexibility via water markets is projected to enhance adaptive capacity by containing or managing conflicts at lower levels (Olmstead 2010). However, the development of such cap-and-trade-mechanisms has depended heavily on multi-layered planning and associated monitoring/metering, information sharing and modeling at higher levels of governance through coordinated state, federal and tribal government actions (Garrick 2015).

7.5.3 Multi-Layered Planning and Conflict Resolution

New physical infrastructure (storage) programs constitute a popular supply side strategy for adaptation to both drought and flood extremes. However, all three rivers feature commitments to soft infrastructure through transboundary and multi-layered planning efforts to, inter alia, conduct water supply and demand studies, undertake drought and climate change vulnerability assessments and coordinate infrastructure operations. The Colorado River Basin is perhaps the most successful example with new rules passed to coordinate reservoir operations under a range of supply conditions (2007) followed by a 50-year basin study under the Water Smart program. The potential renegotiation of the Columbia Basin Treaty has opened potential for similar initiatives across the US-Canada border with a range of international networks and the International Joint Commission fostering data sharing and a platform for dialogue.

7.5.4 Subsidiarity

Subsidiarity, or the notion that governance tasks should be assigned at the lowest level possible, offers a potential guiding principle for transboundary adaptation in the North American context. Subsidiarity involves the assignment of tasks (planning, monitoring, conflict resolution) as close to the water user level as possible, but also implies its corollary, namely complementary higher-level coordination institutions for tasks that span jurisdictions (Marshall 2008). Following the work by Schneider (2008), the transboundary frameworks in the three rivers share a focus on local and horizontal coordination until stakeholders 'pull' in additional funding, conflict resolution and related institutional mechanisms for coping with climate variability and the impacts of extreme climate events. When local (water user, state/provincial) measures have proven insufficient, international and interstate frameworks offer the binding conflict resolution mechanisms, although these decisions have often been met with high transaction costs, low compliance and lingering disputes.

7.6 Pathways to Water Security and Transboundary Adaptation in Federal Rivers: Implications for Canada and Future Research

Natural hazards are projected to cost the Canadian economy up to $43 billion in losses annually by 2050 (TD Economics 2014). Drought conditions across Canada in 2001–2002 reduced GDP by almost $6 billion (Canada 2015). Droughts pose special governance challenges in federal political systems like Canada due to the division of powers and functions between national and sub-national governments and the blurring of roles and responsibilities during shortages. These governance challenges elevate the importance of conflict resolution and other institutional mechanisms to share risks and enhance resilience to extreme climate events.

The lessons from this chapter are relevant because Canada is not alone in facing these challenges: during the summer of 2015, the impacts of droughts and water shortages were felt from Brazil and British Columbia to California, South Africa and Saskatchewan. In this context, sharing knowledge, experiences and best practices developed across a spectrum of federal countries is a powerful way to build capacity to address present and future challenges posed by droughts and other extreme climate events.

What are the pathways to climate resilience in Canada's international and inter-provincial rivers? The IPCC's Working Group II report on adaptation defines the concept of 'climate-resilient' adaptation pathways as a:

> Continuing process for managing changes in the climate and other driving forces affecting development, combining flexibility, innovativeness, and participative problem solving with effectiveness in mitigating and adapting to climate change (Denton et al. 2014).

In this context, the institutional resilience strategies and options adopted in the Colorado, Columbia and Rio Grande form part of multi-dimensional, dynamic and path dependent decision-making to build adaptive capacity in the face of uncertain changes to climate (Haasnoot et al. 2013). The elements, design and sequencing of these pathways depends on context but also exhibits potential for building adaptive capacity over the long term through a portfolio of the elements noted above.

Ongoing and future work aims to build on a growing tradition of comparative research by responding to the challenge set out by James Wescoat who noted the need to harness the global circulation of ideas and water policy expertise to support mutual learning and policy transfer across diverse contexts facing similar challenges (Wescoat 2009). Directions for future research include systems-based, interdisciplinary analysis of triggers, sequencing and portfolios of investment in institutions, information and infrastructure to achieve water security and build capacity to adapt to climate variability, change and extremes. It also requires networks of interdisciplinary researchers and practitioners working with a common framework and set of coding procedures to diagnose the risks and governance challenges of climate extremes in transboundary rivers (Armitage et al. 2015; Srinivasan et al. 2012). Doing so will involve establishing a global, multi-scale data architecture and set of institutional and governance indicators that can be used in risk assessment, planning and evaluation, and can be analyzed in combination with established datasets for international and shared waters.

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