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Groundwater Governance in the Rio Grande: Co-evolution of Local and Intergovernmental Management

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ABSTRACT: The physical interconnection of ground and surface waters is rarely acknowledged in inter-state and international agreements over surface water. This is especially true in the Rio Grande/Rio Bravo basin, where groundwater pumping is at the heart of several disputes and legal cases related to compliance with intergovernmental water agreements. This research considers the Upper and Middle Rio Grande basin to explore how groundwater use and management interact with interstate (i.e. intranational within the US) and international relations (US-Mexico). We consider three distinct geographic regions to address the following questions: how have intergovernmental surface water agreements affected local groundwater management and policies? And, how does groundwater management at local scale influence intergovernmental relations over water? We combine documentary data and interview data collected through extensive fieldwork during 2016 and 2017. The analysis reveals the emergence of both state-driven and community-based groundwater initiatives aimed at reconciling needs and obligations stemming from different geographical and institutional levels. The analysis uncovers strong institutional interplay across water management levels and suggests that compliance with intergovernmental agreements in federal and international contexts both affects and is affected by local groundwater management. Moreover, we observed that while local water managers are sometimes prevented from solving problems locally due to interstate rules, opportunities for innovation in local groundwater governance can also be triggered by compliance obligations at other levels.

KEYWORDS: Groundwater, transboundary water management, federal, interstate, institutional interplay, Rio Grande/Rio Bravo

INTRODUCTION

In arid regions of the world groundwater is arguably the single most indispensable resource for growing populations and economic development (Eckstein and Eckstein, 2005). In many regions groundwater plays a strategic role to support socioeconomic development and buffer the effects of drought. Nonetheless, groundwater "is often forgotten (…) by experts. (…) Even when it is not ignored, it is often misunderstood" (Campana, 2014). As the science of groundwater modelling and the understanding of its dynamics have progressed significantly over the past decades (Kinzelback et al., 2003), the policies deciding the use, allocation and conservation of groundwater are slow to catch up (Eckstein and Eckstein, 2005).

During the second half of the 20th century many arid and semi-arid regions experienced a 'silent revolution', a spectacular groundwater development by the initiative of millions of individual farmers to support irrigation (Llamas and Martinez-Santos, 2005). This resulted in aquifer depletion worldwide (Giordano, 2009). In sub-humid to arid regions groundwater depletion is estimated to have increased from 126 (±32) km^3/year in 1960 to 283 (±40) km^3/year in 2000 (Wada et al., 2010) and has already begun to drastically affect future supply (Villholth and Giordano, 2007). This holds true in the Rio Grande basin, where intensive groundwater pumping began in the 1950s. Its effects are evident today in groundwater table drawdown, subsidence, decreases in water quality and surface water quantity (Sheng, 2013). In the Rio Grande, the Hueco Bolson aquifer below the cities of El Paso and Ciudad Juarez is expected to be depleted beyond 'economically recoverable freshwater' range between 2020 and 2050 (Hume, 2000; Sheng et al., 2001) and in the 2000s the city of Albuquerque decided to gradually decrease its dependence from depleted local aquifers (ABCWUA, 2015).

As groundwater levels continue to decline, water managers and scholars alike are calling for a deeper understanding of the underlying science and legal issues and for comprehensive strategies to address overdraft, adapted to the specific social, economic, political and environmental settings of each region (Aeschbach-Hertig and Gleeson, 2012). In this context, efforts to improve groundwater policy need to be rooted in the understanding of key drivers that determine water users' behaviour and associated policy responses. Scholars have often identified and analysed the strong interlinkages existing between groundwater policy and other sector policies (Singh, 2008), such as agriculture (e.g. Mukherji and Shah, 2005; Shah, Singh and Mukherji, 2006; Steward et al., 2013; Pfeiffer and Lin, 2012; Hornbeck and Keskin, 2014; Fragaszy and Closas, 2016), energy (e.g. Mukherji, 2007; Closas and Rap, 2017), and the environment (e.g. Martinez-Santos et al., 2008; Novo et al., 2011).

This rich literature, however, has rarely considered the influence of surface water-related regulations on users' decisions and groundwater governance reforms at a local level. This is particularly important in contexts of international basins and federal political systems, where the territorial division of authority has motivated the development of intergovernmental surface water agreements. These agreements add a layer of complexity to groundwater policy dynamics. Groundwater and surface waters are often physically interconnected but this does not always translate into coordinated water management actions. This disconnect can be observed at all institutional levels but is especially apparent in transboundary management systems, where groundwater agreements are uncommon (Eckstein and Eckstein, 2005) and surface water agreements rarely mention groundwater (Giordano et al., 2014; Eckstein and Sindico, 2014).

This paper argues that, in basins having intergovernmental water agreements, obligations related to surface water use influence patterns of groundwater management at local level. In those basins, the emergence and implementation of groundwater policies cannot be fully understood without considering power dynamics and institutional interactions between local actors, state agencies, federal authorities and interstate organisations. Milman and Scott (2010) noted a similar gap in international transboundary aquifers shared by federal countries, where domestic (interstate) arrangements for water management have important and often unexplored impact on international dynamics and vice versa.

In this paper we focus on the US portion of the Rio Grande river basin, which is shared by three US states before crossing the international border with Mexico. It has been well established there is a hydrologic connection between the Rio Grande River and the underlying groundwater, in which the river either recharges the aquifers or receives base flows depending on the hydrologic conditions (Sheng, 2013). Despite the fact that in the Rio Grande groundwater use is at the heart of numerous disputes and legal cases between US riparian states, this resource is not mentioned in intergovernmental agreements governing surface water allocation. Considering three distinct regions characterised by intensive groundwater use within the Upper and Middle Rio Grande basin we address two questions: how have intergovernmental surface water agreements affected local groundwater management and policies over time? And, in turn, how does groundwater management at local level influence intergovernmental relations over water?

ANALYTICAL FRAMEWORK AND METHODS

Groundwater has received interest from scholars of common pool resource governance since the formation of groundwater districts in California (Ostrom, 1965). From the outset, these studies have explored the potential and limits of self-regulation by users and considered the influence of higher-level authorities (López-Gunn and Cortina, 2006; Ross and Martinez-Santos, 2010). This paper builds on this tradition of research by investigating two frontiers in the literature on collective action and common resource governance. First, we build on the recent progress accounting for the biophysical complexity of common pool resources (Schlager et al., 1994; Ostrom, 2007; Cox et al., 2010). Early studies in this field struggled to examine the environmental and physical characteristics of the resources being governed. One of the first studies in this tradition explored the implications of resource mobility and storage characteristics for self-organisation (Schlager et al., 1994: 296). Groundwater has "relatively stationary flow units and storage capacity" in comparison with fisheries (which are mobile) or grazing areas (which lack storage). These physical distinctions matter for governance. Governance arrangements account for biophysical attributes by devising institutions and allocation rules suited to the local conditions. For example, groundwater in Southern California is governed by quantity restrictions associated with a relatively stationary resource with storage characteristics, rather than the spatial or temporal restrictions associated with fisheries and irrigation systems, respectively.

Several scholarly works over the past 15 years have built on earlier work to examine the interaction of people, institutions and the environment systematically, leading to the proliferation of frameworks for investigating coupled human-natural systems (Cox et al., 2016). As one example, research on common-pool resources as social-ecological systems examines how distinct sub-systems interact to shape sustainability outcomes. This paper contributes to this expanding literature through its focus on hydrogeological complexity and interactions, building on the work of Blomquist et al. (2001), which focused on conjunctive use in three Western US states. It also accounts for spatial and temporal variability, particularly droughts, which affect management during temporary deficits in water availability (Villamayor-Tomas and Garcia- López, 2017). In this study we explore aspects of the hydrogeology, hydroclimatology and water infrastructure that influence local governance and cross-scale linkages.

The paper also contributes to our understanding of the role of scale in common-pool resource governance. Climate change, forest conservation and biodiversity have all illustrated the collective action challenges and political economy issues associated with resources involving large territories, group sizes and institutional diversity (Ostrom, 1999). Water governance shares these challenges and has been the focus of large bodies of research on cooperation and conflict in large rivers (Wolf, 2007; Garrick and De Stefano, 2016; De Stefano et al., 2017). Groundwater has received comparably less attention given its local use and management (Giordano, 2009; Shah, 2009; Aeschbach-Hertig and Gleeson, 2012). The literature on common-pool resource governance is associated with a wide range of theoretical and analytical lenses for understanding collective action. Multi-level governance, institutional fit and interplay, cross-scale linkages, institutional collective action, subsidiarity and polycentric governance all refer to related, yet distinct, bodies of literature for exploring the opportunities and limits of self-governance for complex resource systems (Young et al., 2006). A fuller treatment of this body of literature, along with their tensions and synergies, is presented by Huitema and colleagues (2009: 13-14). Their analysis highlighted research priorities, including the need to understand the structures that "resolve or prevent coordination problems" and "cope with the multiplicity of relevant natural, social and administrative boundaries".

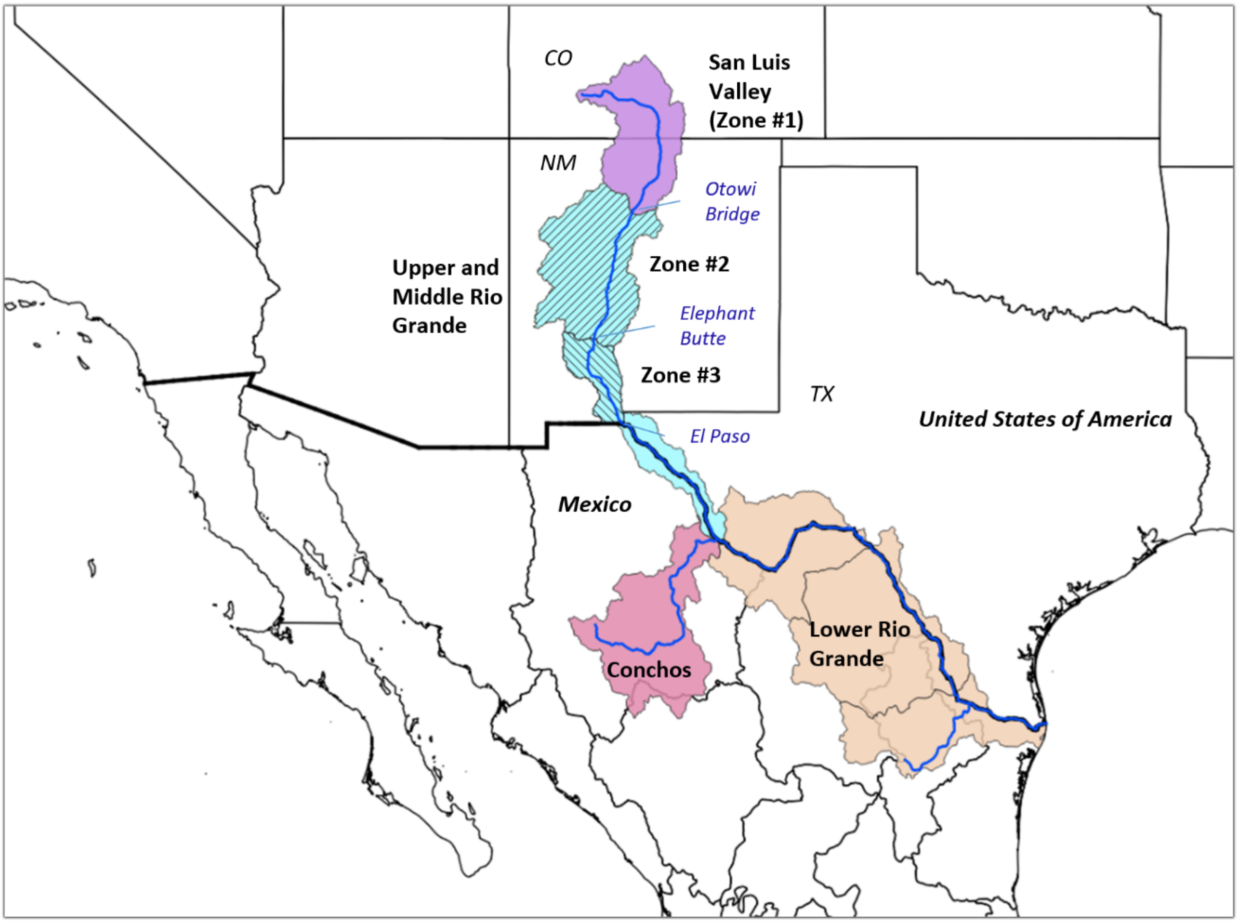
We contribute to this literature by examining the nature and evolution of interactions between jurisdictions or agencies (horizontal) and levels of governance (vertical). Specifically, we are concerned with upward and downward linkages associated with groundwater management in a river basin governed by interstate and international agreements. These agreements create a horizontal linkage between upstream and downstream jurisdictions, requiring upstream jurisdictions to deliver water downstream. In turn, implementation and enforcement have involved important vertical linkages in two directions. Local water users may turn to groundwater as an alternative to surface water earmarked for downstream uses. This constitutes an 'upward' vertical linkage whereby local action threatens agreements at higher levels. As a consequence, federal and state governments may restrict or threaten to restrict local groundwater use that jeopardises compliance with downstream commitments, creating a 'downward' linkage. In the absence of clear rules or conflict resolution venues, we expect that these vertical linkages will have important effects on local groundwater use and politics and their downstream effects.

The research design of this paper followed an inductive approach in the framework of a broader study analysing drought adaptation decision-making in a multi-jurisdictional area focused on the Rio Grande Basin. Interviews were carried out during three field visits in the San Luis Valley (Colorado) and in the Middle Rio Grande. Interviews were designed to explore major challenges and their management at multiple levels, as well as to understand the sources of conflict and cooperation in the Rio Grande. During fieldwork, interviewees consistently identified groundwater as a key element both in managing drought and in influencing interstate and international relations over water. This led to the formulation of the research questions detailed above that were addressed through a mixture of primary data (hydrological, water storage and water deliveries), secondary data (documentary evidence from annual reports, operating plans etc) and the analysis of the content related to groundwater in the interviews.

For this paper we have delineated three study areas or 'institutional catchments' meant as "the spatial portion of a basin defined by the compliance points for transboundary water agreements" (Garrick et al., 2018). The three regions closely mirror major irrigation districts and state-wide designated groundwater basins in the Rio Grande basin and have each developed a unique institutional interplay. The first one is the San Luis Valley (SLV), where the headwaters of the Rio Grande are located. Its southern limit is where Compact deliveries to New Mexico are measured (Otowi Bridge). The second study area includes what the New Mexico State Engineer's Office delineated as the Middle Rio Grande (MRG) groundwater basin and stretches between Otowi Bridge and the Elephant Butte Reservoir, New Mexico. The Elephant Butte Reservoir serves as New Mexico's Compact delivery compliance point with Texas. Finally, the third study area is between Elephant Butte Reservoir and El Paso County, Texas.

In total, we interviewed 35 water managers and stakeholders across the three study areas between May 2016 and March 2017. We began by asking open-ended questions to a pre-determined list of water professionals holding key positions in water management in the study areas. Then we used the snowball method (Kirchherr et al., 2018) to guide the selection of the remaining 20 interviewees. Interviews were conducted during field visits to the Upper and Middle Rio Grande, New Mexico (May 2016), San Luis Valley, Colorado (June 2016), and Lower Rio Grande Valley, New Mexico and Texas (January and March 2017). We interviewed farmers and irrigation district managers (N=10), staff of environmental non-profit organizations (N=2), practitioners in charge of urban supply (N=2), university scholars (N=4), state (N=7) and federal (N=7) level officers and staff working on international transboundary water management (N=3), until we reached saturation for the institutional interplay of transboundary groundwater governance (Guest et al., 2006). Appendix 1 includes a list of the interviewees categorized by study area and sector represented. Secondary data included an extensive groundwater governance literature review, federal, state and interstate status reports, litigation documentation and water data.

Figure 1. Location of the three study areas or 'institutional catchments'. Zone#1: San Luis Valley; Zone#2: MRG above Elephant Butte Reservoir; Zone#3: MRG below Elephant Butte Reservoir or New Mexico's Lower Rio Grande.



ONE RIVER, MULTIPLE WATER CHALLENGES

The analysis focuses on the US side of the transboundary Rio Grande/Bravo River basin. Although the three case studies are all within the Upper and Middle Rio Grande basin, the legal and social history of groundwater governance has resulted in the evolution of three distinct institutional arrangements and different key actors influencing groundwater development (Table 1).

The headwaters of the Rio Grande River are in the heart of the southern Rocky Mountains, 2350 meters above sea level (Cody et al., 2015). Beginning in the San Luis Valley, the river winds south through the New Mexico steppes before forming the 2000 km international border between the US state of Texas and Mexico. The entire 870,000 km^2 basin is characterised as mostly desert land with an average of 254 mm of annual rainfall (IBWC, 2010).

Collectively, in the US over six million people rely on the Rio Grande water for municipal, irrigation, industrial, environmental and recreation uses (USBR, 2016). As populations are expected to keep rising, both snowpack and precipitation are predicted to decrease (Schmandt, 2002; Dettinger et al., 2015). Snowpack is the main source of river water (Cody et al., 2015). Llewellyn et al.'s (2013) climate change research suggests that by 2100 Rio Grande flows will likely be reduced by 25% in the San Luis Valley, 35% in the Middle Rio Grande and 50% below Elephant Butte (Dettinger et al., 2015). Over the past two decades long stretches of the river have dried up seasonally, leaving groundwater to play a large role in water supply for municipal and irrigation uses (Carter et al., 2017).

There are two major intergovernmental agreements that apply to the study area of the Upper and Middle Rio Grande basin. First, the 1906 Convention, an international treaty between the US and Mexico, establishes that the US will annually deliver 740 Mm^3 to Mexico, which is proportionally reduced in drought years (Carter et al., 2017). Deliveries under this treaty are made through a system of diversion dams and canals in El Paso, US to Ciudad Juarez, Mexico. In addition to the Bureau of Reclamation, the water infrastructure along the border is administered by the International Boundary and Water Commission / Comisión de Límites y Aguas (IBWC-CILA), a binational commission established to represent federal interests of both Mexico and the United States. The IBWC has authority over surface water, not groundwater (Schmandt, 2002). The states of Colorado and New Mexico have to deliver 60,000 acre feet (74 Mm^3) of water annually to meet the obligations of the 1906 agreement. The agreement also stipulates that water deliveries to Mexico will be reduced during 'extraordinary drought' in proportion to reductions experienced by New Mexico and Texas. Since 1939, deliveries to Mexico have been reduced in approximately 30% of the years, and Mexico is not owed any repayments (Carter et al., 2017). The requirements under the 1906 convention mean that upstream groundwater development can affect the reliability of downstream deliveries to New Mexico, Texas and Mexico. The interaction between groundwater development and the international agreement illustrates the cross-level interactions that link local and intergovernmental governance arrangements.

Second, the 1938 Compact is an interstate agreement between the US states of Colorado, New Mexico and Texas to appropriate the amount of the Rio Grande surface water to flow between each state while still maintaining compliance with the international 1906 Convention (Wheat, 2015). Neither of the agreements mention groundwater. Finally, in 1944, the US and Mexico established a treaty to share water from the Colorado, Rio Grande and Tijuana Rivers, addressing the water downstream from Fort Quitman (below El Paso). The hydrology and management of the Upper and Middle Rio Grande have led to a disconnect with this lower Rio Grande region, which means that the binational interactions under the 1944 treaty are largely beyond the purview of this study.

During the 1890s to 1970s the Reclamation Era was instigated by the federal government's desire to settle the western United States with irrigated family farms (Tarlock, 2001). As a result, the Bureau of Reclamation (USBR) was formed in 1902 and has led the way for large scale water infrastructure projects to reroute and dam rivers for irrigation purposes (Tarlock, 2001). The USBR has constructed four major federal projects in the Rio Grande basin since 1905 (Dettinger et al., 2015). First, the Rio Grande Project provides water to 728 km^2 land on the US side of the basin (Wheat, 2015). The Project began with the construction of the Elephant Butte Reservoir in 1916, and has expanded today to include seven more dams and 139 miles (222.4 km) of canals (Billington et al., 2005). Second, during the 1950s the irrigation system for the Middle Rio Grande Conservancy District was rehabilitated (Dettinger et al., 2015). Third, in the 1970s the Closed Basin Project was completed in the San Luis Valley to deliver water to the valley not associated with the Compact (Benson, et al., 2014). Fourth, starting in 1976 the San Juan Chama inter-basin transfer provides 100 Mm^3 of water per year from the Colorado River to the Rio Grande; the transfer water is used for municipal use in Albuquerque and Sante Fe, irrigation use for the MRGCD and the Jicaralla Apache Tribe (Dettinger et al., 2015).

Table 1. Key actors influencing development and management of groundwater use in the three study areas.

	#1 San Luis Valley	#2 Middle Rio Grande above Elephant Butte	#3 Middle Rio Grande below Elephant Butte
Federal	US Bureau of Reclamation, US Fish and Wildlife Service, US Geological Survey	US Bureau of Reclamation, US Geological Survey, US Fish and Wildlife, Environmental Protection Agency	US Bureau of Reclamation, US Geological Survey, US Department of State: International Boundary and Waters Commission, Border Environment Cooperation Commission
State	Rio Grande Compact Commission, Colorado Division of Water Resources, Colorado Groundwater Commission, Colorado Water Conservation Board	Rio Grande Compact Commission, New Mexico Interstate Stream Commission, New Mexico Office State Engineer, New Mexico Bureau of Geology and Mineral Resources, New Mexico Water Quality Control Commission, New Mexico Environmental Improvement Board	Rio Grande Compact Commission, New Mexico Interstate Stream Commission, Texas Commission Environmental Quality, Texas Water Development Board
Local	San Luis Valley Advisory Committee, Rio Grande Water Conservation District (RGWCD)	City of Albuquerque, Middle Rio Grande Council of Governments, WildEarth Guardians, Elephant Butte Irrigation District (EBID), Lower Rio Grande Water Users Organisation, Municipalities (City of Las Cruces, Doña Ana County, Town of Mesilla, Anthony Water and Sanitation District, Village of Hatch)	El Paso Water Improvement District #1 (EPWID). El Paso Water Utilities

Note: There are six Native American Pueblos in the Middle Rio Grande (study area #2) that, according to Congress have 'Prior and Paramount' right for enough water to irrigate their 3580 ha of land (Benson et al., 2014). The Pueblo water rights are the subject of ongoing lawsuits in the Supreme Court and date back to time immemorial, predating Spanish law (Dettinger et al., 2015).

MAPPING VERTICAL AND HORIZONTAL INTERACTIONS

In this section we revisit the evolution of groundwater development and management reforms in the three study areas with the objective of pointing out key moments of vertical and horizontal institutional interaction in each study area. The narrative of groundwater development is complemented by a timeline (Figures 2, 3 and 4) that illustrates and categorizes those key interactions according to the following categories: lawsuits, infrastructure development, legal reform, financial support, self-organisation and intensive groundwater pumping to offset drought and reduced surface water supplies due to Compact compliance. We complement the timeline with information about biophysical variables such as groundwater depletion trends and occurrence of drought events, to observe how they could have contributed to trigger higher intensity of institutional interactions and different types of institutional reforms. These narratives and timelines, which are indicative rather than exhaustive, are then used to explore how physical and institutional interplay between local groundwater management and water management at different levels unfolds.

San Luis Valley

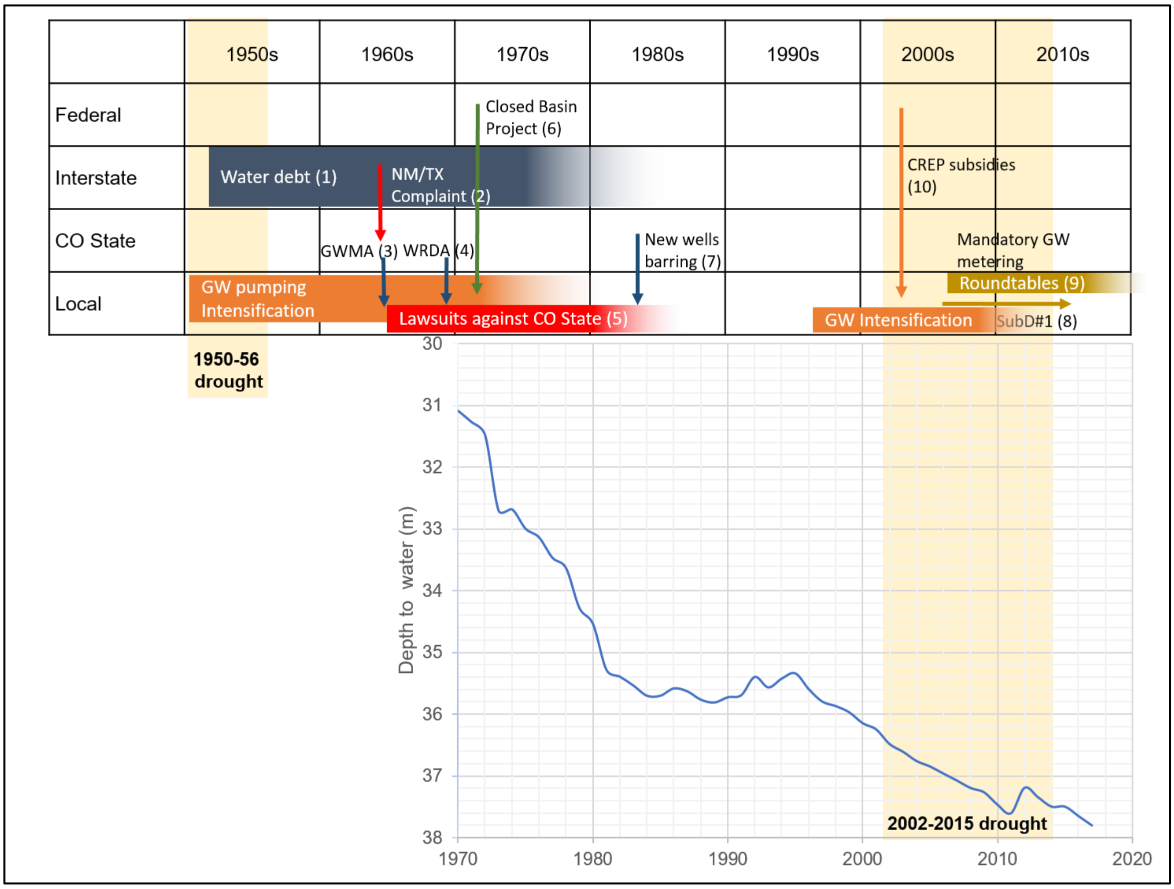
The 8300 km^2 alpine San Luis Valley stretches from southern Colorado into northern New Mexico. Although the valley receives less than 203 mm of rainfall annually, the cropland is composed of 95% irrigated agriculture which produces an average of US$325 million dollars in potatoes, alfalfa, native hay, barley, wheat, lettuce, spinach and carrots (Fencepost, 2011; RGBR, 2015; Cody et al., 2015). Irrigation is the main economic activity to support the 48,000 inhabitants living in the valley (Alamosa, 2009).

Groundwater pumping for irrigation began in the late 1890s with the discovery of the confined aquifers (Emery, 2013) and accelerated in the 1950s. Today the unconfined aquifer supplies 80% of large capacity wells and is the main source of groundwater for irrigation (Emery, 2013). Groundwater recharge has been affected by surface water depletion and surface water flows have decreased due to intensive groundwater withdrawal for irrigation (Cody et al., 2015).

Between 1950 and 1956 the valley suffered a severe drought that prompted intensive and unregulated groundwater development. During that period the number of wells increased from 808 to 2704, with surface right holders using groundwater as a buffer against years in which they may not receive any surface water. Additionally, roughly 600 new water users entered the water system due to uncontrolled well drilling (Cody et al., 2015). Due to a culmination of drought, growing populations, and limited groundwater pumping regulation, between 1952 and 1967 Colorado State accrued a 940,000 acre-feet (11,595 Mm^3) surface water debt to New Mexico (event#1 in Figure 2), which exceeded the flexible buffer limit of the Compact. As a result, in 1966, Texas and New Mexico states filed a formal complaint to the federal US Supreme Court (#2). Under the threat of a lawsuit, the Colorado State Engineer Office curtailed surface water use in the Conejos and Rio Grande basins, thus reducing the debt by 430,000 acre-feet (5304 Mm^3) in 1984 (Vandiver, 1999). In 1985 in New Mexico the Elephant Butte reservoir spilled over due to wet conditions associated with a strong El Nino event (Khedun et al., 2012), and according to the 1938 Compact cleared the remainder of Colorado's debt.

During that crisis the hydrological connection between in-stream flows and groundwater pumping in unconfined aquifer became apparent, urging Colorado State to take actions to regulate groundwater uses. The Colorado General Assembly adopted two groundwater acts (1965 Ground Water Management Act, GWMA and 1969 Water Right Determination and Administration Act, WRDAA; event #3 and #4 in Figure 2) in the attempt of limiting and controlling existing and future groundwater uses. This was perceived by irrigators as a threat to their activity so they opted to cooperate to sue the state for the rules for well regulation (#5). The Court issued a verdict in 1984 barring additional wells but protected existing well users from state regulation (#7) (Cody et al., 2015). In parallel to these regulatory efforts by the State of Colorado, in 1972 the federal Congress authorized the US Bureau of Reclamation to construct, operate and maintain the Closed Basin Project (#6). Its ultimate goal was to help the US meet treaty obligations with Mexico and to assist Colorado state agencies in ensuring water deliveries under the Compact. Completed in the early 1980s, the project pumps an average of 17,300 acre-feet (213 Mm^3) of water per year from the unconfined aquifer of the San Luis Valley into freshwater-dependent wildlife refuges and the Rio Grande River.

Figure 2. Timeline of key actions relevant to groundwater use in the San Luis Valley and evolution of water levels in the unconfined aquifer.



Note: (adapted from San Luis Valley Well and Water-Level Database, USDG Well #CB00107433DAA). Arrow colour code: Red=legal actions (complaints, lawsuits); Green: infrastructure; Blue: legal reform; Gold: self-organisation; Orange: financial support.

During almost two decades, water use arrangements put in place in the 1980s worked relatively well (Interviewee #13). The prolonged drought that started in 2002, however, showed that further actions needed to be taken in order to manage tensions emerging between surface and groundwater users in the Valley due to uncoordinated pumping and to curtailments to surface right holders.

> One of the main tensions has been between surface water and ground water users. And it stems from the fact that the surface water users are usually the senior water rights but, just because of physical limitations, when we have a drought they don't have water, they just physically don't have water. Whereas, the more junior groundwater users they do physically have that water (Interviewee #14).

As a response to drought and to tensions between users, in 2005 the state government passed the Colorado Water for the 21st Century Act, which aimed at creating dialogue through the so-called Basin Roundtables (#8) in order to raise awareness about the urgency of defining durable water use arrangements in the Valley. One of the conclusions of the process was the acknowledgement of the need to stabilize water table levels (Cody et al., 2015). Under the threat of state-mandated regulation of groundwater, key stakeholders and leaders in the Valley started to collaborate. In 2006 they formed the Special Improvement District No. 1 (Subdistrict #1; 70,415 irrigated hectares and approximately 3000 irrigation wells) (event #9) "in order to take action and help restore a balance between available water supplies and current levels of water use so that the San Luis Valley can continue to remain a sustainable agricultural community" (RGWCD, n.d.). Subdistrict#1 receives financial and technical assistance from the federal government through the Conservation Reserve Enhancement Program (CREP), which incentivizes producers to fallow their land and install a conservation practice (EDF, 2018) (#10).

Middle Rio Grande above Elephant Butte Reservoir

The Middle Rio Grande Groundwater Basin is a 792,000 ha unit defined by geologic Cenozoic deposits (Bartolino and Cole, 2002). The Rio Grande River and the groundwater are linked through complex interactions. The Santa Fe Group aquifer is confined locally, but it is considered unconfined as a larger part of the Rio Grande River basin (Bartolino and Cole, 2002). New Mexico State compliance to the Compact is measured at the Elephant Butte Reservoir. Both the groundwater and surface water are managed under the jurisdiction of the New Mexico Office of the State Engineer (NMOSE).

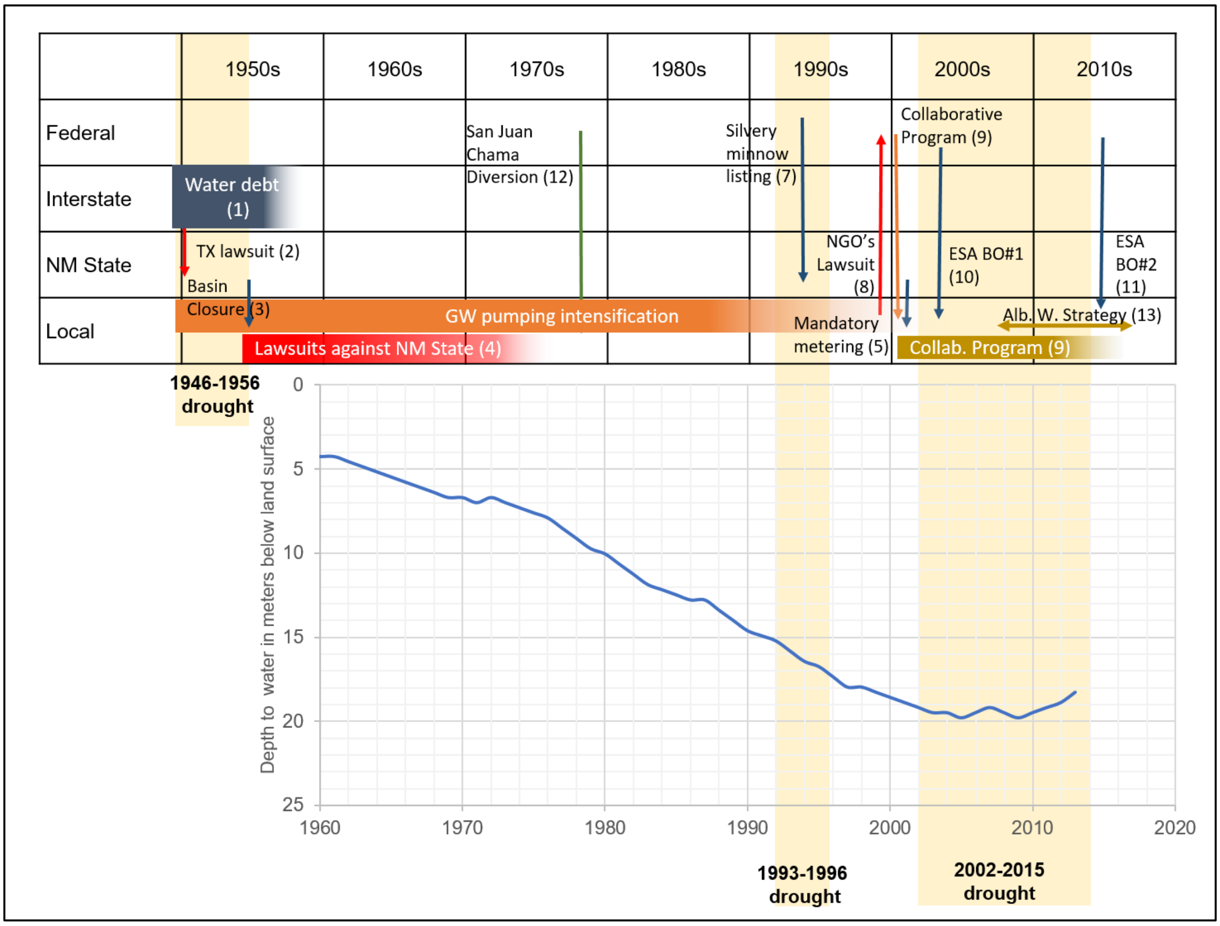
The Middle Rio Grande Project manages surface water in the Albuquerque Basin and is operated by the USBR to support river channel structure, irrigation infrastructure and operate small dams for flood control (Reynolds and Mutz, 1974). The Middle Rio Grande Conservancy District (MRGCD) located north of Elephant Butte reservoir accounts for 53,000 acres (21,448 ha) of irrigated cropland (Benson et al., 2014). Groundwater from the basin is the sole water source for about 40% of New Mexico's population (Bartolino and Cole, 2002). Abstraction rates are between 150,000-160,000 acre feet/year (1850-1973 Mm^3/year) (McAda and Barroll, 2002). Public water supply is the largest consumer of groundwater (67% of total groundwater uses), while irrigated agriculture only represents 11%, most irrigation being supported by surface water (311 Mm^3/year of surface water withdrawal vs. 18 Mm^3/year of groundwater abstraction) (SNMISC, 2017).

The Middle Rio Grande has been a fully appropriated stream system since 1907. In 1930 only 15% of the irrigated land in the region 527,000 acres (213,269 ha) used groundwater, while in 1955 aquifers supplied water for over half of the existing 873,000 irrigated acres (353,291 ha) (Jones, 2002). During the 1946-56 drought groundwater levels were decreasing while New Mexico faced difficulties to meet the delivery obligations stipulated under the 1938 Compact (event #1 in Figure 3), which caused Texas to file a lawsuit in the US Supreme Court in 1951 (#2). Being aware of the connection between groundwater pumping and in-stream flow decreases and concerned by a possible intervention of the federal government in domestic water management, in 1956 the New Mexico State Engineer Office designated the Middle Rio Grande Groundwater Basin, thus closing the basin to new appropriations (#3).

> The state engineer at the time (…) realized that because of the Rio Grande Compact, the Middle Rio Grande had to keep itself in balance, otherwise we would continue to get continued serious deficit for the deliveries to the Rio Grande Project (Interviewee #13).

This declaration triggered a number of legal actions by users and local actors (#4) but the court upheld the State Engineer's designation of the basin. As explained by Jones (2002: 944) "Reynolds' [the State Engineer at the time] memorandum recognized that the surface waters of the Rio Grande were fully appropriated (…) Because any appropriation of groundwater would affect surface flows, Reynolds required that all new permitted groundwater appropriations offset the effects of pumping by acquiring surface water rights". As expected by Reynolds' plan, groundwater pumping kept increasing in the following decades, with a gradual transfer of water from surface to groundwater rights. As a result, between 1956 and 2000, existing rights to appropriate groundwater multiplied by seven (from 30,000 to 217,600 acre-feet per year, i.e. from 370 to 2684 Mm^3/year), which led to further restrictions on groundwater appropriations in 2000 (#5) (Jones, 2002). Again, the new state regulation was (unsuccessfully) challenged in court, especially by large domestic users such as the city of Albuquerque (#6).

Figure 3. Timeline of key actions relevant to groundwater use in the Middle Rio Grande below Elephant Butte Reservoir and evolution of groundwater levels in the unconfined aquifer.



Note: (Adapted from Berman, 2012. Water levels in Site 70-city 1). Arrow colour code: Red=lawsuits; Green: infrastructure; Blue: legal reforms; Gold: self-organisation, collaboration.

In the meantime, a new institutional driver added complexity to water challenges in the MRG. The silvery minnow was listed as an endangered species by the US Fish and Wildlife in 1994 under the Endangered Species Act (ESA) (#7). The listing entails that minimum environmental flows in the Rio Grande River must be met to ensure the survival of the minnow. In 1999 local environmental groups filed lawsuits against the USBR claiming violation of the ESA (Benson et al., 2014) (#8). As a result, in 2000 the federal agencies and local water users created the Middle Rio Grande Endangered Species Collaborative Program (Collaborative Program; #9), an initiative managed by the USBR to improve the conservation of the silvery minnow and the southwestern willow flycatcher while meeting downstream delivery obligations. Restoration efforts include raising minnows in hatcheries and releasing pulse flows in the spring to trigger spawning. Since the listing, the federal agencies issued two biological opinions (2003 and 2016; events #10 and 11) in order to define criteria to guide efforts for maintaining the adequate flows in the river.

In addition to buying surface water rights, groundwater users can also offset the effects of pumping on the in-stream flow by returning treated wastewater to the river and by using imported surface water of the San Juan-Chama Diversion Project (#12), which captures part of New Mexico's apportioned share of the Colorado River waters under the 1922 the Upper Colorado River Compact and conveys it to the MRG.

> We've been buying and purchasing up agricultural rights south of Albuquerque or throughout the Middle Valley, transferring into our groundwater permit to pay that effect back and we also return wastewater back to the river at our wastewater treatment plant. So, we keep the river whole every year. On an annual basis, they calculate the effects. There's a 3-dimensional groundwater flow model where they calculate all of the effects of our pumping and everyone else's pumping, they subtract the amount that we've already returned to the river, subtract from our water rights, and then whatever's left we still have to pay back to the river (Interviewee #14).

In 2004 the Albuquerque Water Utilities decided to start using its share of the San Juan-Chama Diversion (Flanigan and Haas, 2008) in order to reduce the dependency of the city on groundwater by supplying up to 90% of the metropolitan area of Albuquerque with imported surface water (#13). Moreover, over the past two decades the city has reduced per capita water use by half by implementing a water conservation plan (ABCWUA, 2015). This has resulted in a decrease of groundwater pumping by Albuquerque from over 120,000 acre feet (1480 Mm^3) in the 1990 to 40,000 acre feet (493 Mm^3) in 2015 (ABCWUA, 2015). Nonetheless, groundwater levels continue to decrease and, despite water management and conservation efforts, the minnow populations are still declining.

Middle Rio Grande below Elephant Butte Reservoir

This study area begins at the Elephant Butte Reservoir in New Mexico, stretches along the Rio Grande River, across the New Mexico/Texas state border and ends at the southern point of the El Paso Water Improvement District (EPWID) in Texas. This area is within the Chihuahua desert and its main aquifers are Hueco Bolson and Mesilla Bolson (both confined aquifers) and the unconfined Rio Grande Alluvium.

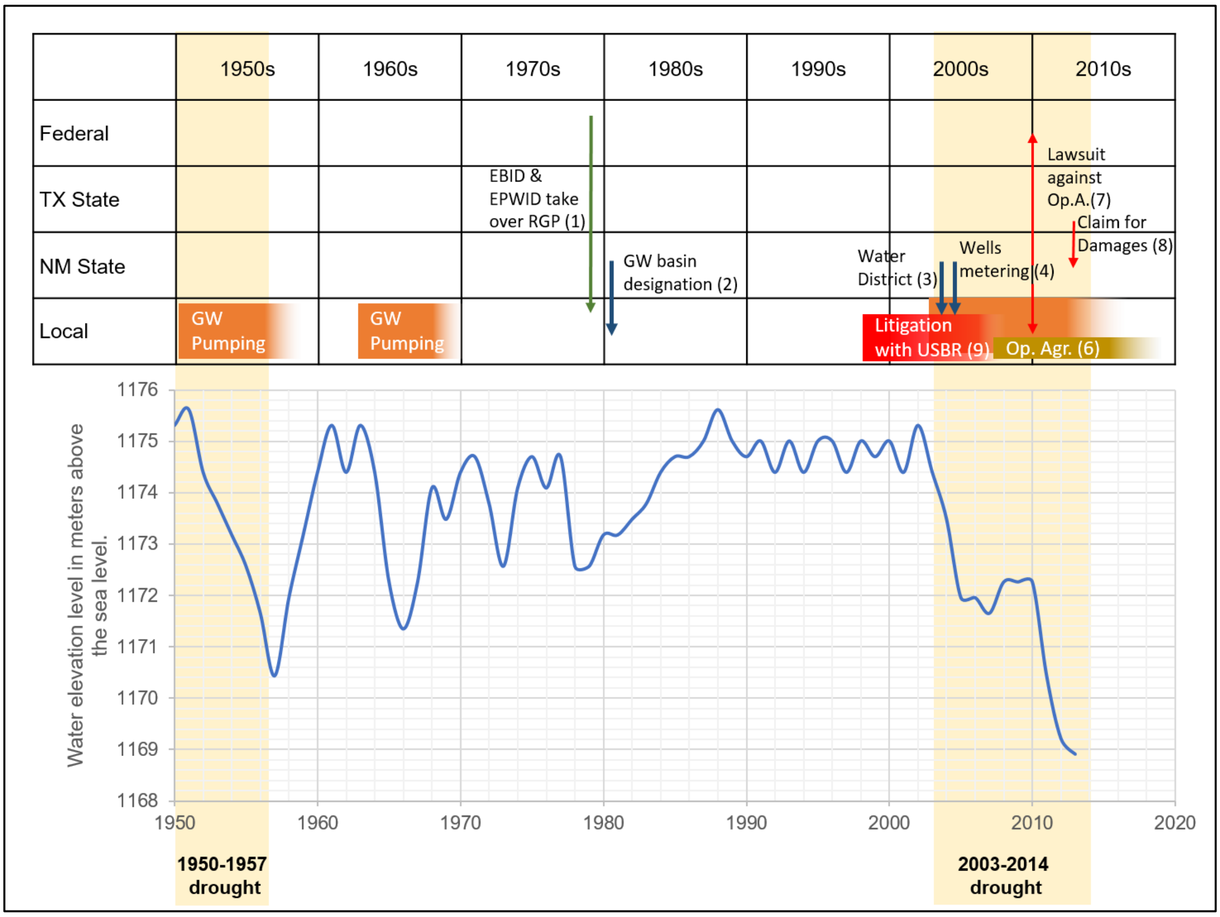
The northern part of the study area is scarcely populated compared to other parts of New Mexico but moving south towards the international border there are several larger urban areas that are predicted to continuing growing (Regional Stakeholders Committee, 2009). The Rio Grande River forms the international border between the industrial sister cities of El Paso, USA and Ciudad Juarez, Mexico with 865,000 and 1.2 million inhabitants respectively (City of El Paso, n.d.). Drinking water supply for Ciudad Juarez, Las Cruces and rural communities in New Mexico are 100% dependent on groundwater from the Hueco and Mesilla Bolson aquifers (Sheng et al., 2001; McCoy and Shoemaker, 2017). El Paso currently relies on the Hueco Bolson for about 42% of supply, Mesilla Bolson for 26% and Rio Grande surface water for about 32% (EPWU, 2007).

There are two large irrigation districts which receive surface water from the Rio Grande Project (Billington et al., 2005). The Elephant Butte Irrigation District (EBID) follows the Rio Grande River along 160 kilometres, from below the Elephant Butte Reservoir to the Texas state line (Wheat, 2015). The El Paso Water Improvement District (EPWID) stretches along the river in Texas. Predominant crops include pecans, cotton, wheat, alfalfa and vegetables (Dettinger et al., 2015). Water released from the Elephant Butte Reservoir is distributed between the two irrigation districts and Mexico (Grimsal, 2017). In years of water shortage, allocations for all three recipients are reduced proportionally. In 1980 (event #1 in Figure 4) the two irrigation districts took over control of the timing and the amount of water the USBR releases from the Elephant Butte Reservoir (Interviewee #26). The irrigation districts are responsible for determining how much water they want to sell to local municipalities. EBID is currently working on an agreement to sell surface water to Las Cruces (Interviewee #26) and EPWID already sells water to the city of El Paso (Fullerton, 2006).

Since the 1950s farmers in this region have consistently relied on groundwater to buffer surface water shortages, especially during drought years. Moreover, the aquifer is key to supply water to high-value crops that are sensitive to irrigation timing, to water-intensive crops that cannot be irrigated with EBID's surface water allotment and to municipal and industrial water uses (Winchester and

Hadjigeorgalis, 2009). The reliance on groundwater increases during drought, when withdrawals from the aquifer can double or triple those of a fully supply year (ibid). According to the 1938 Compact, New Mexico's delivery point to Texas is Elephant Butte Reservoir, which is located 160 kilometres north of the NM/TX border (Grimsal, 2017). Intensive groundwater pumping by EBID farmers is linked to the decrease in surface water flows before the water reaches the NM/TX state border.

Figure 4. Timeline of key actions relevant to groundwater use in the Middle Rio Grande below Elephant Butte Reservoir and evolution of groundwater levels in selected wells of the Mesilla Bolson aquifer.



Note: Adapted from Mexico Water Science Center, n.d.; Wells OLD USBR-13 and M-4C). Arrow colour code: Red=lawsuits; Green: infrastructure; Blue: legal reform; Blue: negotiated legal reform; Gold: self-organisation.

In 1980 the Office of State Engineer of New Mexico assumed special state jurisdiction over the appropriation and use of groundwater through the declaration of the Lower Rio Grande Underground Basin (NMOSE, 2006; event #2) as a way of addressing concerns of USBR and Texas about pumping. However, between 1997 and 2007, numerous lawsuits were initiated between New Mexico, Texas, EBID, EPWID and USBR about how groundwater pumping by EBID should be accounted for in the Rio Grande Project (#3). In this context and after 24 years of full supply, a severe drought set in 2003, exacerbating surface water shortages and triggering intensive groundwater pumping in the region. Tensions between the two riparian states continued to rise, forcing New Mexico State to mandate the appointment of a Water District Master to administer groundwater rights[1] (2004, #4) and the metering of groundwater wells[2] (2005, #5).

In 2008, the EBID, EPWID and the USBR settled years of litigations (#9) by negotiating a new Operating Agreement for the Elephant Butte Reservoir (#6). The new agreement specifically accounted for EBID's groundwater pumping by enabling the district to set aside a percentage of their overall allotment in the reservoir. EPWID and Texas were placated by the subsequent increase in water delivery. However, the State of New Mexico rejected the agreement and filed a lawsuit in the federal district court against the USBR in 2010 (#7). As a result, the state of Texas filed a lawsuit in the Supreme Court in 2013 claiming significant compensation for decades of lost water due to groundwater pumping (#8). The downstream state considers that New Mexico's issuance of permits for 2500 wells between the Elephant Butte Reservoir and the NM/TX border impacts the amount of water that reaches Texas (Wheat, 2015). Water 'lost' to Texas has important economic implications especially due to the fact that since 1962 El Paso Water Utility (EPWU) leases water from EPWID (Fullerton, 2006) for domestic uses. In 2017, the Special Master released a report denying New Mexico's motion to dismiss the case and ruled New Mexico should not divert or intercept Compact water before it reaches the Texas border (EBID, 2017).

DISCUSSION

In the previous pages we have described the evolution of a basin where several distinct, yet linked, jurisdictions interact vertically and horizontally. In this section we explore the implications of these interactions. We identify four main themes: (1) groundwater development involves several physical and institutional connections, which all require coordination; (2) local groundwater development is driven, in part, by the hard constraints created by interstate and international water sharing agreements; (3) water sharing agreements prompt diverse state and federal efforts to control groundwater pumping; and (4) diverging approaches to groundwater regulation create tensions between states. Together these themes underscore the need to understand the vertical and horizontal linkages associated with groundwater development in a water stressed river basin.

Physical connections

Many studies have identified the connectivity between surface water and groundwater. The Upper and Middle Rio Grande illustrates how interactions between groundwater and surface water propagate downstream, and across sectors and stakeholders. First, there is a strong linkage between upstream and downstream jurisdictions due to physical connections through infrastructure and streamflows. Intergovernmental agreements bind together upstream and downstream jurisdictions by requiring upstream states to deliver water to downstream signatory parties. Compliance with delivery obligations in turn may entail curtailment of local water rights, and intensive local water uses may jeopardise downstream deliveries. Due to the hydrological connection of the aquifers and the river, groundwater pumping impacts on streamflows and on economic activities that depend on surface water. As a consequence, any policy or management initiative taken to maintain water in the river will impact the aquifer and its exploitation, and vice versa.

The Rio Grande also reveals how groundwater development links sectors and stakeholders. Ecosystems depend on surface and ground waters, which has led to efforts to control groundwater use.

[1] State Engineer Order No. 169: In the Matter of the Requirements for Metering Groundwater withdrawals in the Lower Rio Grande Watermaster District, New Mexico

[2] State Engineer Order No. 172: First Amended Metering Order for Metering Groundwater withdrawals in the Lower Rio Grande Watermaster District, New Mexico

For example, wildlife refuges in the SLV and endangered freshwater species protected under the Endangered Species Act in the MRG suffer from decreased in-stream flows due to groundwater pumping. Cities like El Paso and Albuquerque largely rely on groundwater but have increasingly looked to surface water to diversify water supplies. These connections (aquifer-river; upstream-downstream; between sectors and stakeholders) create complexity whose management requires effective coordination among institutions with very different responsibilities, interests and capacities.

Intensifying competition for water has increased these connections, and past adaptations have established new human-driven connections that increase the complexity and potential for conflicts. In the SLV, the Closed Basin Project, managed by the USBR, pumps water from the confined aquifer to the river in order to augment in-stream flows; in the MRG the San Juan Chama River Project links the local aquifer-river system to surface water imported from the Colorado River basin; and downstream of Elephant Butte the river is used to transport groundwater pumped out of the aquifer to be delivered to downstream users. These institutional and infrastructural adaptations create a form of positive feedback by introducing new connections that overlay the physical and social linkages.

The complex connections create several sources of uncertainty. The functioning of the physical system and our (often limited) knowledge of it play an important role in the management of institutional interplay. In the three zones, concerns related to uncertainty about physical water-related trends consistently emerged in interviews as a constraining factor for decision making and as a source of tensions. Uncertainty relates mainly to estimates of available stored volume, natural recharge or exact river-aquifer interactions, which makes water adjudication challenging. While these sources of uncertainty are common in groundwater management, the presence of surface water agreements adds new layers of uncertainty that affect groundwater users. In the SLV, interviewees pointed out the challenge of forecasting the evolution of streamflows, which depends on the timing and volume of snowmelt. Since the Colorado State Engineer manages in-stream flows in order to ensure deliveries to New Mexico, an inaccurate forecast can lead to over-delivery to New Mexico and unnecessarily curtailment of surface water rights. Curtailment will determine how much water is pumped out of the aquifer to offset surface water restrictions, creating potential for a vicious cycle.

> (…) when we start our irrigation season, we have to use a forecast about what's going to come the rest of the seven or eight months of the year. And we don't know that for sure, it's just a forecast. And like I said, we've had some forecasts that have been less than accurate (Interviewee #1).

> I think, also, you know, no one knows how much groundwater we have. It's easier for me to manage the surface water because I can go up there and look and see what's in the lake. But I don't have a window into the future of what our groundwater's going to be (Interviewee #25).

In the MRG another important uncertainty is the amount of surface water that should be left in the river in order to maintain endangered species such as the silvery minnow. This information is key in order to determine operations of groundwater users in the area and in particular the Albuquerque Water Utilities. Thus, improved modelling and reliable forecasting remain at the heart of accurate decision making and adjustment to legal requirements and water needs originating at different levels.

Local effects of intergovernmental agreements: Droughts, development and downstream effects

Since the 1950s prolonged droughts coupled with agricultural development and population growth have triggered the emergence of intensive groundwater pumping. Growing water demands were initially largely met using surface water from the river but during drought users had to find ways to cope with two concurrent limitations: the temporary natural decrease in river flows due to below-average precipitation and the existence of intergovernmental water agreements that constrained local use of the resource. This constraint is also felt by local users in periods of full supply. This is because the river is declared fully allocated and no more dams can be built because local resources have been earmarked for downstream uses either under the 1938 Compact or the treaties with Mexico.

These constraints to surface water access create the conditions for what has been called the 'silent revolution' of groundwater (Llamas and Martínez-Santos, 2005), where individual or organized users gradually gain access to water through hundreds of wells often drilled without official supervision or control. In the Rio Grande localized groundwater 'revolutions' have unexpected ripple effects on water uses at hundreds of kilometres down the river and become sources for concern for water managers and law-makers in other states and in federal agencies. The river-aquifer hydraulic connection manifests in in-stream flow decreases, revealing that local users have found a way of physically 'bypassing' the constraints on surface water access imposed by intergovernmental commitments.

This has effects on the sequencing of events that lead to institutional groundwater reforms (Figures 2, 3 and 4). A prolonged drought, combined with several circumstances including intensification of groundwater pumping to buffer surface water shortages, contributes to the accruement of water debt under the Compact, which in turn, triggers formal complaints or even lawsuits by downstream states. While rains eventually help placate those formal complaints, the non-complying state is under close scrutiny and implements institutional reforms to regulate local groundwater uses. At the same time, domestic and international pressure forces the US Government to address the problem through infrastructure and funds. Finally, water users address mounting water stress through a portfolio of strategies, which range from technical approaches aimed at a more efficient functioning of the system to collective or individual legal actions to protect their interests. Water users tend to self-organise in order to gain voice in decision-making forums and influence regulatory developments that can negatively impact them. For instance, as the threat of tighter water regulations by the state became apparent, local irrigators in the SLV took a proactive lead in their own groundwater management by forming the Rio Grande Water Conservancy District and, more recently Sub-district #1. Similarly, after years of litigation, EBID and EPWID created a collaborative agreement with USBR to offset the impact of their groundwater pumping on the Compact compliance.

Federal and State efforts to reconcile local and transboundary uses

Under the US Constitution the federal government has no direct jurisdiction on groundwater. However, the physical linkages between groundwater pumping and compliance with interstate and international water agreements mean that federal interests are at stake in local groundwater management. In the study areas, the presence of federal interests is strongly felt also in relation to wildlife conservation under the Endangered Species Act. In the MRG (Zone #2) the drying up of the river in the 1990s and the subsequent listing of the silvery minnow as an endangered species locally acted as a shock similar to the noncompliance with intergovernmental agreements. Under the threat of legal actions by the federal government both the state and water users redoubled their efforts to manage the river-aquifer hydrological connection. Interestingly, the difficulties faced by New Mexico and its water users in complying with the ESA also have an impact on the behaviour of water users and authorities in the neighbouring states. The listing of endangered species in other stretches of the Rio Grande and the subsequent federal intervention act as a powerful incentive to address water problems at state and local levels.

Federal authorities play a key role in providing financial and technical means to address local groundwater-related problems whose effects can be felt in other states or in Mexico. In the three study areas there is USBR infrastructure that directly or indirectly contributes to offset the effects of groundwater pumping on in-stream flows. In the SLV, the Closed Basin Project pumps groundwater into the river in order to contribute to maintaining in-stream flows. In the Middle Rio Grande, part of the USBR-operated San Juan Chama River Project is devoted to offset negative impact of groundwater pumping on the river flows and on the endangered wildlife. Below Elephant Butte, water releases by the USBR are defined by the EBID and EPWID in order to meet their needs while meeting downstream obligations. Federal agencies also provide financial resources to encourage compliance with federal legislation and international commitments. An example is the Conservation Reserve Enhancement Program implemented in the SLV, where USDA incentivizes farmers to fallow large parcels of land as a means to reduce pressure on groundwater.

Finally, downward and upward interactions between the federal government and local groundwater management manifest in the numerous lawsuits presented before the Supreme Court by most of the key actors in the study areas at some point in time. The high level of litigation associated with the management of river-aquifer dynamics and the responsibility of the Supreme Court over legal disputes create incentives for the federal government to foster negotiated solutions to tensions that otherwise are likely to end up in federal courts.

As noted above, concerns related to compliance with Compact and federal regulations acted as a powerful catalyst for state-mandated groundwater regulation in Colorado and New Mexico. Thus, in Colorado groundwater pumping was intensive until the 1960s, when a formal complaint for unfulfilled Compact obligations forced the state of Colorado to start regulating groundwater uses. Similarly, in New Mexico the State Engineer Office declared state jurisdiction over groundwater because of mounting tensions around downstream deliveries and decreasing groundwater levels. Similar reasons pushed Colorado and New Mexico to require metering of wells in the 2000s.

In the three regions, the approach to a challenge originated from higher level obligations has been to look for local solutions instead of opening up the debate about the design of the Compact. States seem to prefer acting in institutional spaces where they do not need to negotiate with higher or equal levels of authority, perhaps to reduce the risk of unfavourable outcomes of the negotiation, and also to have more room of manoeuvre while looking for solutions. Locally driven solutions have the advantage of avoiding lengthy and sensitive negotiations between states. Moreover, they can usually count on the support of key local water users, as is the case of Subdistrict#1 in SLV and the 2008 Operating Agreement downstream of Elephant Butte. However, the development of these local initiatives needs support from higher institutional levels in order to thrive, showing the importance of building local capacity and looking for synergies across levels.

Groundwater regulation across borders

Unlike Texas, both Colorado and New Mexico recognize the hydrologic connection between surface and groundwater and manage water accordingly. While state permits to access groundwater are required in Colorado and New Mexico, groundwater in Texas is personal property of the landowner according to the 'rule of capture' (Schmandt, 2002). Similarly, well metering is required since the 2000s in the two upstream states but not in Texas.

Differences in groundwater regulation across boundaries do matter in determining when and how each state regulates groundwater use. For instance, New Mexico State Engineer regulated groundwater differently in the regions above and below Elephant Butte in order not to cause prejudice to New Mexican farmers that were competing for groundwater access with Texans.

> In the Lower Rio Grande he did not declare that groundwater basin until the 1980s. One of the reasons for that is because Texas doesn't have groundwater administrative control. (…) And because there were no controls on the development of groundwater in Texas, New Mexico was slow in declaring the groundwater basin in the Lower Rio Grande compared to the rest of the state (Interviewee #20).

Differences in legal treatment of water resources at a local scale also have important upward implications. As Wheat (2015: 179) explains

> A complicating factor to the Compact (…) is that Texas does not treat surface and groundwater as part of the same water system, meaning it does not use a conjunctive water management approach (…) Texas

landowners have the right to capture, which gives them the ability to use the groundwater on their land (…). The Compact, Texas, and Colorado all have separate legal regimes for surface water and groundwater, with Texas placing very few restrictions on water use and New Mexico as the only state operating a conjunctive water management system. When trying to reach a judicial resolution for Compact disputes, this wide variation of legal doctrines makes it difficult".

CONCLUDING REMARKS

The Rio Grande in the US illustrates the tight connections between local groundwater management and transboundary governance. This relationship is reciprocal and dynamic. Obligation to comply with surface water agreements combines with drought and demands to intensify pressure for groundwater pumping. In turn, groundwater pumping strains compliance with surface water agreements, which triggers disputes between upstream and downstream jurisdictions, surface and groundwater users as well as the state and federal levels.

These dynamics suggest several implications for research and practice. First, research on water governance needs to account for the physical, social and institutional complexity associated with groundwater management in a transboundary context. This will involve greater attention to issues of uncertainty, water variability and resource monitoring. Second, the growing literature on the role of scale in water governance can advance our understanding of local groundwater challenges. Competition, complexity and rapid change mean that problems that were historically local are now increasingly spilling over through the systemic linkages of basins and political borders. This consideration is of special relevance in federal and transboundary river basins like the Rio Grande, where independent jurisdictions govern water at different levels with limited coordination. Globally there are over 300 large river basins located within or shared by a federal political system (Garrick and De Stefano, 2016). Groundwater governance in federations connects local issues with national policy and interstate governance arrangements. Existing intergovernmental agreements should integrate groundwater when feasible and create the formal and informal coordination mechanisms to monitor and share data, resolve disputes and make amendments. The Rio Grande illustrates the challenges of retroactively combining groundwater uses with interstate and international agreements; however, it also illustrates the opportunities for local and cross-level coordination relying on informal networks or involving more effective application and implementation of existing institutional mechanisms for joint decision making and dispute resolution. Third, the analysis of the Rio Grande suggests that timelines and pathways of change are useful for moving beyond the binaries of horizontal versus vertical coordination and top-down versus bottom-up arrangements. Our analysis illustrates how institutional reforms should be based on a multilevel analysis of needs and constraints related to water, in order to pre-empt negative spillovers and to take advantage of possible synergies due to interest alignment at different scales.

Trends since the 1950s in the Upper and Middle Rio Grande reveal the emergence of both state-driven and community-based groundwater initiatives aimed at reconciling needs and obligations stemming from different geographical and institutional levels. Moreover, we observed that while local water managers are sometimes prevented from solving local problems due to interstate rules, opportunities for innovation in local groundwater governance can be triggered by compliance obligations at other levels.

Finally, this analysis has implications for policy and practice. The case studies illustrate the increasing need to strengthen the capacity of local institutions to handle groundwater pressures sustainably. The conditions and resources for such institutional development represent a fertile area for research and policy learning, illustrating how higher level investments can prove complementary and constructive, rather than crowding out local initiatives. For example, studies, modelling initiatives and infrastructure programs for groundwater offsets can create the platform for local efforts as illustrated by the SLV.

However, coordination and conflict resolution are needed. A better understanding is needed of formal and informal venues for decision making and conflict resolution, as well as an appreciation of the associated politics. New research and long-term observatories of basins under pressure can identify the opportunities and limits for strengthening existing and crafting new forums.

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APPENDIX. ANONYMIZED LIST OF INTERVIEWS BY STUDY AREA

ID	Study Area	State	Sector
1	SLV	Colorado	State
2	SLV	Colorado	State
3	SLV	Colorado	State
4	SLV	Colorado	Irrigation
5	SLV	Colorado	Irrigation
6	SLV	Colorado	Irrigation
7	MRG	New Mexico	Environmental NGO
8	MRG	New Mexico	Federal
9	MRG	New Mexico	Federal
10	MRG	New Mexico	Federal
11	MRG	New Mexico	Federal
12	MRG	New Mexico	Irrigation
13	MRG	New Mexico	Irrigation
14	MRG	New Mexico	Municipal
15	MRG, LRG	New Mexico	Federal
16	MRG, LRG	New Mexico	Federal
17	MRG, LRG	New Mexico	State
18	MRG, LRG	New Mexico	State
19	MRG, LRG	New Mexico	State
20	MRG, LRG	New Mexico	State
21	MRG, LRG	New Mexico	Academia
22	MRG, LRG	New Mexico	Academia
23	LRG	New Mexico	Academia
24	LRG	New Mexico	Irrigation
25	LRG	New Mexico	Irrigation
26	LRG	New Mexico	Irrigation
27	LRG	New Mexico	Irrigation
28	LRG	New Mexico	Environmental NGO
29	LRG	Texas	Irrigation
30	LRG	Texas	Municipal
31	LRG	Texas	Federal
32	LRG	Texas	Academia
33	Multiple	US	International
34	Multiple	US	International
35	Multiple	US	International

*SLV = San Luis Valley, MRG= Middle Rio Grande, LRG= Lower Rio Grande