Institutional Analysis of Water Governance in the Colorado River Basin, 1922-2022

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Abstract

In 1922, the Colorado River Compact was established, beginning the long history of water governance in the Colorado River Basin. Over the last century, the institutional structure has shaped water governance in the basin. However, understanding of the institutional structure's long-term evolution is lacking. The purpose of this research is to understand how water management strategies have evolved over time at a large spatial scale. This study of water governance in the basin incorporates spatial, temporal, and network structure analysis methods to examine long-term changes. Content analysis was employed to systematically investigate encouraged and/or discouraged water management actions over time at different rule levels. The water governance network was examined at four points in time to map the institutional structure, actors, and governance level at which rules are issued and targeted. Using institutional analysis, I found constitutional, operational, and collective-choice level rules for water supply, storage, movement, and use have been altered via layering new water governance rules without major rule or responsibility alteration. The network analysis results indicate that key decision-making positions have remained and actors who issue and are targeted by the rules lack significant change. I found that original positions of power have been maintained, potentially stagnating the space for problem-solving and management strategy renegotiation. The results indicate that path dependency has shaped the evolution of water governance and who is able to influence decision-making. This analysis provides insights into the long-term history of large-scale water governance and institutional network structure evolution over time.

1. Introduction

On June 14, 2022, the U.S. Bureau of Reclamation (USBR) instructed Colorado River Basin (CRB) states to develop a plan to reduce annual water use by 2-4 million acre-feet (MAF) within 60 days (James, 2022; Stern, 2023). Although negotiations are ongoing, the 60-day period passed, and, as of the time of writing, the seven states have yet to deliver a consensus plan. Meanwhile, a Tier 2a shortage is in effect, resulting in reduced water availability for Arizona and Nevada (Schlageter, 2021; Stern, 2023). The shortage operation guidelines were produced via multiple negotiated agreements, illustrating long-term rule accumulation (Department of the Interior, 2007; USBR, 2019). USBR's instruction demonstrates the scale of the regional water security challenges. The states' delay illustrates the complexity of negotiation in the context of a century's worth of accumulated rules and agreements in the CRB. In addition to the current request to reduce water use in the short term, the Basin States are negotiating new long-term rules for coordinated operations of Lake Powell and Lake Mead. Insight into how we have arrived at the current water crisis can help inform the redesign of operating rules. Such insight requires better understanding of the evolution of water governance institutions.

Water has been the source of tension, contestation, and disagreement for over a century in the CRB (Mirumachi et al., 2021; Sullivan et al., 2019). Prior to 1900, communities used water locally without basin-wide impact (Kuhn & Fleck, 2019). From the early 1900s, questions arose about equitable allocations of Colorado River water with the expansion of irrigation and other water diversion projects (National Research Council, 2007). Consequently, the 1922 Colorado River Compact was created to clarify allocations. During the 1920s, the water management paradigm shifted from pre-modern to industrial modernization via federal investments in large, regional water diversions and storage projects, resulting in basin-wide changes to the spatial and temporal distribution of water (Allan, 2003; Mirumachi et al., 2021). Specifically, these changes led to altered streamflow variability, habitat degradation, and salinization (Barnett & Pierce, 2008; Furnish & Ladman, 1975; Glenn et al., 2001; Hwang et al., 2021). Water scarcity and infrastructure research hypothesize that increases in water storage capacity can lead to increases in water consumption, unintentionally defeating the goal of expanding reservoir storage to boost water supply reliability by decreasing the cost and risk of water use – a dynamic called the reservoir effect (Di Baldassarre et al., 2018; Kallis, 2010; Kellner, 2021). The reservoir effect hypothesis aligns with the Colorado River's history; water stored in Lower Basin aquifers was readily available, and concurrently more people migrated to the region resulting in increased water demands, that, coupled with large agricultural demand, exceeded supplies even with 34 MAF of reservoir storage (Sullivan et al., 2017).

While the physical infrastructure is critical to the sustainability of the CRB, so is the social infrastructure, or the institutions that govern water access and infrastructure operation. Institutions are norms and rules that influence and shape human-human and human-nature interactions, including the way people make decisions and manage water resources (Cave et al., 2013). Institutional analysis (IA) can provide insights into water governance action situations, where actors interact to make decisions, and the outcomes of these action situations (McGinnis, 2011). Outcomes of action situations include new or altered rules, governance strategies, or management regimes. Examining the institutional context in the CRB illuminates how institutions evolved over time under social and environmental change.

One century later, the 1922 Colorado River Compact remains in place and is supplemented by new agreements, court decisions, and other rules. Despite a substantial body of water governance research, the long-term evolution of the institutional structure that shaped the CRB over the last century is not fully explained. We know that current management actions and our understanding of these actions have not kept pace with increasingly arid conditions and growing demand (York et al., 2019). Water scarcity in the American Southwest is exacerbated by increasing water demands and climate changes, particularly higher temperatures that increase evapotranspiration (MacDonald, 2010; Udall & Overpeck, 2017). Williams et al. (2022) found that from 2000 to 2021 the Southwest has been in the most severe drought at least 1,200 years. If water stored in reservoirs is not sustainably managed, then the physical and institutional water structures serving the seven Basin States (California (CA), Arizona (AZ), Nevada (NV), Colorado (CO), Wyoming (WY), Utah (UT), New Mexico (NM)) and Mexico (MX) may fail, with potentially catastrophic consequences.

To avoid a break down in the institutional and physical infrastructure of the water system in the Southwest, we need to adapt water management to our changing environment. This need motivates two research questions: 1) How have CRB action situation outcomes shaped subsequent water management decisions?; 2) How has the distribution of authority across actors and institutional levels in the CRB changed over the last century? I anticipate constraints created by early decisions have stayed in place, shaping subsequent action situations, and creating path dependency. Repetitive practices and patterns resulting from socially constructed rules and norms give rise to path dependency (Schmidt, 2010). I examine path dependency by extracting and analyzing the incentives and constraints that guide water governance choices from formal water management rules. Further, I hypothesize that the distribution of authority changes over time from a few central actors to a larger number of actors as the network increases. This is measured based on the actors involved and the alteration of responsibilities for water management actions to examine how the distribution of authority is split across actors and institutional choice levels over the last century.

2. Theoretical Framing

2.1 Water Governance

Water governance is a set of interacting social, economic, and political systems that enable society to develop, plan, and manage water resources across time and space (Larson, Wiek, et al., 2013; Pahl-Wostl et al., 2010; Rogers & Hall, 2003; Wiek & Larson, 2012). Water governance challenges are distinctive because water has characteristics of both public (non-excludable, non-rival) and private (excludable, rival) goods (White, 2012). Common pool resources are rival, meaning usage diminishes others ability to use the resource, and non-excludable, meaning excluding users is prohibitively difficult (Ostrom, 2005). Use of common pool resources often results in conflicts when resource supply does not align with demand. Governance of natural resources can alleviate this conflict with rules that are created to allocate and distribute resources, such as water (Ostrom, 2005, 2011).

Water systems' nested, dynamic, and layered, and institutional arrangements must fit the characteristics of water (Lebel et al., 2013; Young, 2002). Nested systems include connections and networks within a larger analytical unit. For example, smaller spatial entities (e.g., sub-basin, state) are nested in larger systems, such as watersheds or river basins (Akamani & Wilson, 2011; Mirumachi et al., 2021). Dynamics can persist over time, as is characteristic of water systems with water management regimes that last for decades or centuries (Elshafei et al., 2014; Garcia et al., 2016). The introduction of new dynamics and conflicting institutional arrangements can limit and direct water governance decision-making and actions (Olivier & Schlager, 2021). Layering can be conceptualized as concurrent system inputs, where impacts accumulate as each layer is considered (Green & Dzidic, 2014). For example, the CRB system simultaneously experiences layered challenges of global climate change, regional climate impacts, uncertain water supplies, and extreme weather events (Gerlak et al., 2021; Rivera-Torres & Gerlak, 2021). Multi-level water governance responds to these system characteristics. Broadly, level pertains to institutional jurisdictions such as government at International, National, Sub-national, or Local levels (McGinnis, 2015). Between levels there is a hierarchy; the higher levels of organization are arranged in a formal way by law. Within transboundary water resource research (Akamani & Wilson, 2011; Milman et al., 2013; Rivera-Torres & Gerlak, 2021; White et al., 2019), there is a lack of understanding of tensions between system level and local objectives.

The field of multi-level governance offers relevant insights, as it is concerned with how actors operating at different institutional levels collaborate to solve shared problems (Cash et al., 2006; Heinen et al., 2021; Pahl-Wostl, 2009). Multi-level governance scholarship is characterized by strong descriptive elements that document changes in governance arrangements (Bisaro et al., 2020; Liu & Lo, 2021). While multi-level governance is concerned with common goals, it acknowledges that power and authority are split among governance levels (Harmes, 2006). Thus, it is important to note that multi-level governance processes and outcomes are influenced by relationships and power dynamics between actors and decision-makers (Ishtiaque et al., 2021; Nunan, 2018). Current multi-level governance research challenges include uncertainty and nested relationships stemming from actor's differing goals and agendas coupled with a changing climate (Jones & White, 2022; Sullivan et al., 2019). Prior multi-level governance research has established a strong theoretical base, and further empirical research is needed test and refine theory.

2.2 Institutional Theory

The Institutional Analysis and Development (IAD) Framework (Figure 1) aids in evaluating and understanding institutional arrangements (Heikkila & Andersson, 2018). Within the IAD Framework, the action situation describes actors (i.e., decision-makers) involved in decisions and the decision context, which is shaped by the rules in use, characteristics of the community, and biophysical conditions. The IAD Framework facilitates analysis of how governance unfolds, in this case water use and management. Institutional change can be examined to understand how water governance has evolved (Olivier, 2019). When action situations linked over time through outcomes and changes to the decision context are examined, the IAD Framework enables analysis of the evolution of governance regimes. Action situations are a central unit of analysis in the IAD Framework and identified via rules each actor must abide by, their rights, obligations, and constraints based on formal (i.e., written), legislatively specified rules (Cole, 2014; McGinnis, 2015; Ostrom, 2011). The framework provides a foundation for examining rules and is well established through insights from hundreds of natural resource case studies (Ostrom, 2005; Sullivan et al., 2019). Rules specify authority and constraints by creating or restricting authority via limits, timing, and how infrastructure can be used. "Rules-in-use" are formal rules within official and other written documents that provide clarity on governance arrangements (i.e., roles, responsibilities, incentivized and disincentivized actions, and goals), but are not limited to official and other written documents, as this study focuses on given the large scope of rules (Hardy & Koontz, 2009; Heikkila & Andersson, 2018; McGinnis, 2015; McGinnis & Ostrom, 2014; Ostrom, 2011; Ran et al., 2020). The IAD Framework can be extended to consider feedbacks from policy outcomes to rules-in-use and action situations (Figure 1). These feedbacks help us understand the changes to the institutional structure as action situations layer upon each other over time.

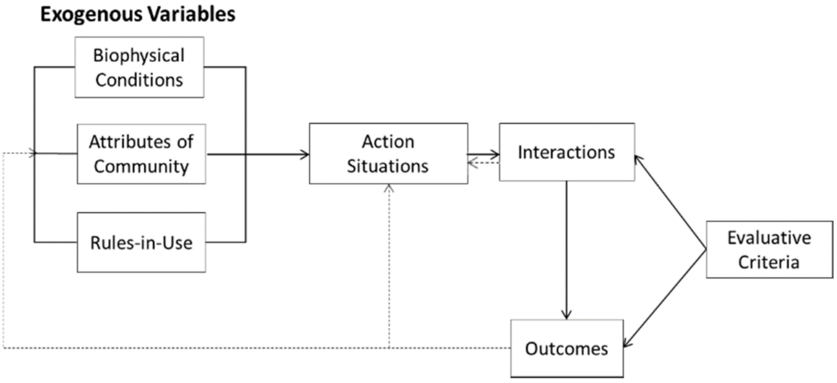

Figure 1: IAD Framework (Ran et al., 2020) adapted from Ostrom (2005)

One IAD Framework strength is that it connects outcomes at different levels of analysis explicitly (Ostrom, 2005). Moreover, internal institutional changes occur from one action situation to the next, thus, changing the structure and process for future rule change. Dynamics over time are captured as additional rules created from action situation outcomes. To sort linkages between specific rules and help identify the structure of ensuing action situations, rules can be organized based on their level of decision-making (e.g., constitutional, collective, or operational). The IAD Framework characterizes three decision-making levels where different types of choice processes occur: constitutional, collective-choice, and operational. According to McGinnis & Ostrom (2014) constitutional level rules specify decision-makers who are or should be making collective-choice and operational level rules; collective-choice level rules determine the strategies, norms, and rules available for decision-makers with defined roles cooperatively set by the broader group; and operational level rules describe how decision-makers make choices amongst the options available.

2.3 Network Analysis

Social network analysis is commonly used to assess the relationship between nodes through their connections (Jones & White, 2021; Olivier et al., 2020; Prell et al., 2009). Such relational information helps identify institutional network structures. Network analyses can be used to examine multi-level networks, often found in natural resource governance (Friemel, 2017). Network metrics, betweenness and degree centrality, provide information on actor connectivity within the network. Betweenness centrality indicates how much control a node has via being a part of the connection between other nodes. Thus, high betweenness denotes entities that act as key bridges in the network, as they have more information flow control compared to other entities (Olivier, 2019). Degree centrality is comprised of the in-degree, number of connections directed to a node and out-degree, number of the node's outgoing connections. High in-degree values indicate which nodes are the main rule targets, on the other hand high out-degree values indicate which nodes are the main rule issuers.

Identifying actors that issue rules and are the targets of rules can help improve understanding power dynamics within and across institutional levels. Institutional level refers to formal government jurisdictions (e.g., National, Basin, Sub-basin, State, Sub-state). Water governance rules have three types of power that interact: power dynamics within and across institutional levels, power as a theoretical understanding of how rules affect actors empowerment to achieve their own objectives, and power in the policy making process (Kashwan et al., 2019). Path dependency can occur early on in policy making processes when one strives to maintain their negotiating position as an exertion of power and is shaped by lock-in effects that direct decision-making into existing, often perpetuating, directions (Gillette, 1998; Mirumachi et al., 2021; Wilson, 2014). Path dependency refers to regularized patterns and routine practices that result from socially constructed and framed norms and rules (Schmidt, 2010). Lock-in effects within institutions indicate that "institutional choices at one point in time significantly shape later choices" (Seto et al., 2016, p.9). These choices are locked into the institutional structure and become apparent when institutions do not adjust to system changes (Gillette, 1998). Network structure changes can be evidence of changes in power dynamics.

3. Water Governance of the Colorado River Basin

Priority rights to water in the West are based upon the doctrine of prior appropriation; whoever first diverts river or stream water and puts it to beneficial use may claim priority rights to that amount of water. In 1922, the Colorado River Compact (1922 CRC) was crafted by the seven Basin States (BS) and the Federal Government and established the Upper Basin (UB) and Lower Basin (LB) boundaries (Figure 2). The goal of the 1922 CRC was to equitably allocate water across the basin with an average of 7.5 MAF allotted annually to each sub-basin (Fleck, 2016). The LB was allotted an additional 1 MAF for treaty obligations to Mexico (Owen, 2018). AZ chose not to ratify the 1922 CRC, partially due to the treatment of its tributary rivers (Gila and Salt) (Hundley, 2009; Sullivan et al., 2017). In 1928, the Boulder Canyon Project Act (1928 BCPA) approved Hoover Dam construction so long as the 1922 CRC was ratified by six BS and authorized splitting the LB's 7.5 MAF of Colorado River (CR) water between the LB states: CA allotted 4.4 MAF, AZ allotted 2.8 MAF, and NV allotted 300,000 MAF annually. The ratification appointed the Secretary of Interior (SOI) as the authority for LB water use (Kuhn & Fleck, 2019). Arizona opposed this and filed Supreme Court cases from 1930-1936 to nullify the 1928 BCPA, but the Supreme Court declined to hear the cases and in 1936 the Hoover Dam was completed.

The 1940s to the early 1990s was a period of water allocation and infrastructure development in the CRB. The 1944 Mexican Water Treaty allocated 1.5 MAF of CR water to MX in normal flow years, marking the first time MX had a formally identified role in managing CR water. In 1944, the AZ legislature ratified the 1922 CRC. Post-WWII, the population in the

Southwest increased massively, driving a subsequent growth in water demand (Terrill, 2022). The Upper Colorado River Basin Compact of 1948 (1948 UCRB) addressed demand growth by creating the Upper Colorado River Commission for new water projects and apportionment of water. Under the 1948 UCRB of the Colorado River Storage Project Act of 1956 was created and approved two major UB water storage projects: Flaming Gorge Dam and Glen Canyon Dam. Plans for the Central Arizona Project (CAP), a system of canals and pumps to deliver water to Phoenix, Tucson, AZ farmers, and Tribes, were introduced in the 1940's. Congressional approval was required to move the CAP forward and Congress would only approve if AZ and CA settled their differences. Ultimately, the Arizona v. California U.S. Supreme Court Decision of 1964 provided resolution and upheld the 1928 BCPA water allotments. Later, the 1968 Colorado River Basin Project Act was passed, and Congress agreed to fund the CAP, which finished construction in 1993.

Since the mid-1990s CR water governance has focused on demand management under variable hydrology. Initially, during this period, the basin had high flows and policy innovation to allocate and locally store surplus supplies. This is evident via the 1999 interstate banking rule allowing LB states to store water in AZ aquifers and the 2001 Surplus Sharing Agreement (Sullivan et al., 2017). Around 2000, the Millennium Drought began, shifting the basin to low flows, resulting in management aimed at stabilizing and decreasing demand. From 2005 to 2007, water scarcity and drought increased, and in 2005 Lake Powell storage dropped to 33% of capacity (Water Education Foundation, 2022). In 2007 the Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations of Lake Powell and Lake Mead (2007 IG) were signed. These operations included guidelines to conserve water in Lake Mead and equalize storage between the main reservoirs (Lake Mead and Lake Powell).

Also, during this period, the criteria for decision-making expanded to include diverse human and natural uses of CR water supplies. The 1992 Grand Canyon Protection Act required Glen Canyon Dam water releases to meet tribal, environmental, cultural, and recreational needs. In 1992, the Ten Tribes CRB Partnership was established to strengthen tribal influence among the BS for CR supply use and management (CRWUA, 2021). Further expansion of actors formally included as decision-makers took place from 2014 to 2018, expanding consideration of ecology and extending tribal rights. Regarding ecology, a pulse flow released in 2014 to a 24-mile stretch along the US-MX border and Delta that historically was 2 MA of riparian habitat and wetland (Owen, 2018). Furthermore, the US and MX signed Minute 323 in 2017, supporting increased conservation and storage in Lake Mead to help offset drought, prevent triggering shortages, and dedicating 210,000 AF over nine years for CR Delta environmental restoration (Water Education Foundation, 2022). Regarding tribal rights, the USBR released a Tribal Water Study in 2018 that described how tribal water use fits into CR management and ways future tribal water resource development could influence CRB operations.

The current water management period is focused on responding to drought, climate change, aridification, and increasing demand. The 2019 LB and UB Drought Contingency Plans encouraged the seven BS consider all water users, beyond junior rights holders, as having a stake in keeping the CR system intact via voluntary water reductions. In 2021, the first-ever Tier 1 shortage was declared and required AZ, NV, and MX to reduce their CR water delivery (Schlageter, 2021). In 2022, as water shortage conditions continue, a Tier 2a shortage was declared, which has cut 2023 CR supply for AZ, NV, and MX. The USBR further demanded in 2023 that water use be cut an additional 2-4 MAF by the BS and tribes reliant on the CR (Stern, 2023).

Presently, tensions are elevated about CRB's water governance amidst an uncertain climate and water supply (Gerlak et al., 2021; Karambelkar & Gerlak, 2020; Sullivan et al., 2019). In part, some tensions result from differing goals between the UB and LB (i.e., separate drought contingency plans). Furthermore, the UB has not historically used its full allocation while the LB has, and at times, used more. Today, we have detailed records showing the average annual flow through the basin was 14.67 MAF from 1906 to 2021 and 12.3 MAF from 2000 to 2021 (Salehabadi et al., 2022), both less than the 17.5 MAF early western water decision-makers assumed (Kuhn & Fleck, 2019). While water governance management strategies and water action responsibilities have changed over time, we do not fully know what outcomes resulted from these changes. This research assesses these changes across high institutional levels to understand incentives and constraints that guided water governance decisions, and how authority has been distributed across actors and institutional levels based on formal rules.

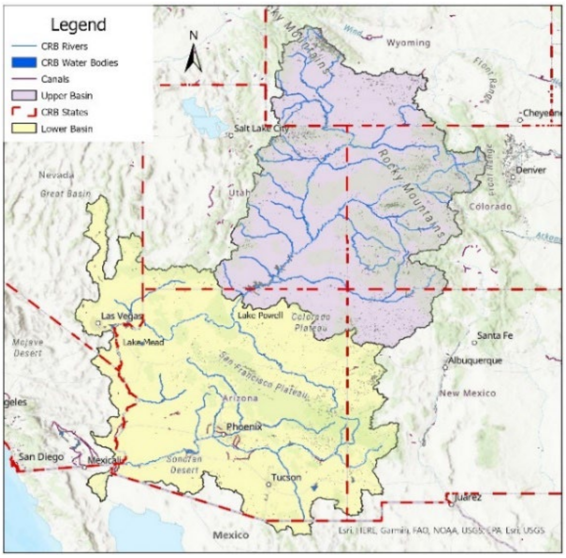

Figure 2: Case Study Location, Colorado River Basin, U.S.

4. Methods

4.1 Research Approach

The IAD Framework guides this analysis because it helps identify, organize, and categorize factors that are important to understand complex institutions (McGinnis, 2011). For this analysis I examined written rules about governing the physical supply of water in the CRB (Ostrom, 2011). Then, content analysis was used to determine how internal decision-making processes are expressed in formal documents. To identify rules that guide governance decisions, a systematic approach was used to determine how water management actions are described in written formal governance documents to address concepts related to water governance at the basin and sub-basin scale. Next, each rule was characterized based on spatial scale and whether the rule grants or constrains authority based on rule issuer and target.

4.2 Data and Rule Selection

To understand the evolution of the water governance structure, I analyzed documented rules and agreements from 2002 to 2022. Only formal documents with legal or regulatory standing pertaining to CRB water governance were considered. The scope of the document population was specified via the following document selection criteria: 1) address formal rules pertaining to at least one of the following: the Upper CRB, the Lower CRB (including Mexico), and the CRB (excluding water export areas); 2) fit within basin or sub-basin institutional level boundaries; 3) published between 1922 and 2022; and 4) directly address the Colorado River Basin, physical water availability, and/or water management activities. This search and screening process yielded 14 documents for further analysis (Table 1).

Table 1: Colorado River Water Governance Document Selection

Documents	Abbreviation
Colorado River Compact of 1922	1922 CRC
Boulder Canyon Project Act of 1928	1928 BCPA
California Seven Party Agreement of 1931	1931 CSPA
Mexican Water Treaty of 1944	1944 MWT
Upper Colorado River Basin Compact of 1948	1948 UCRB
Colorado River Storage Project Act of 1956	1956 CRSP
The Arizona v. California U.S. Supreme Court Decision of 1964	1964 AZCA
The Colorado River Basin Project Act of 1968	1968 CRBP
The Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs of 1970	1970 CLRO
Minute 242 of the U.S.-Mexico International Boundary and Water Commission of 1973	1973 M242
2001 Surplus Sharing Agreement	2001 SSA
2007 Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations of Lake Powell and Lake Mead	2007 IG
2019 Lower Basin Drought Contingency Plan	2019 LDCP
2019 Upper Basin Drought Contingency Plan	2019 UDCP

Empirical and theoretical governance literature was drawn upon for the thematic rule selection. Existing natural resource governance case studies were used to ascertain broad categories with specific aims related to water systems (Larson et al., 2013; Wiek & Larson, 2012). From the literature, four main domains associated with water system management were identified: water supply, storage, movement, and use activities (Garcia et al., 2019; Mirumachi et al., 2021; Wiek & Larson, 2012). Next, I defined and created keywords based on theoretical water resource concepts (Kallis, 2010; York et al., 2019) and mapped these to the four types of water management to create a water management type coding guide (Table 2). Rules were selected if the rule is within at least one of the institutional level boundaries of interest and it addresses at least one CRB water management domain.

Table 2: Water Management Action Type Coding Guide

Management	Definition	Keywords
Supply	Physical water amount	water right, water permit, physical availability, quantity, apportion*, allocat*, water source, allot*
Storage	Containment of the physical water amount	storage, reservoir, ICS, storage credit, surplus, accumulat*, groundwater bank*, aquifer storage, stock
Movement	Relocation of the physical water amount	deliver*, conveyance, interbasin transfer, releas*, interstate, withdraw*
Use	Consumption of the physical water amount	water use, water demand, demand management, water conservation

4.3 Content Analysis and Coding Scheme

Content analysis was conducted using codes derived from theory and prior knowledge of water governance and institutions (Akamani & Wilson, 2011; Mirumachi et al., 2021). To better understand and document the institutional arrangements, I characterized the decision-making level, spatial scale, issuer, and target of each rule without mutual exclusion. Decision-making level pertains to the range of actions that actors are allowed, required, and/or prohibited to take. Three decision-making levels defined in the IAD Framework were utilized. To understand the network of actors, I coded each rule's spatial scale based on politically defined boundaries, issuer(s) based on actor(s) that impose rules, and target(s) based on actor(s) that rules are imposed upon. Consensus coding was used to reach intercoder agreement with my advisor, Dr. Margaret Garcia (Cascio et al., 2019; Hill et al., 1997).

4.4 Network Analysis

A directed network was constructed based on the rule characterizations above using the igraph package (Gabor & Nepusz, 2006) in R. Directed networks indicate the flow of information, or in this case, rule direction from the issuer to target. To test the hypothesis that the distribution of authority changes over time and is split as the network size increases, I looked at the degree (number of ties) and linkages (betweenness) within the network (Hermans et al., 2017; Kharanagh et al., 2020). As is commonplace to examine network linkages, also called bridging behavior, I calculated the measure of in- and out-degree centrality and betweenness centrality (Friemel, 2017; Jones & White, 2021; Olivier, 2019). To clarify, I counted the rule issuer and target separately via using both the in- and out-degree centrality measures.

5. Results

5.1 Evaluation of Rules

Constitutional, operational, and collective-choice rules related to water supply, storage, movement, and use were effectively modified by the addition and layering of new rules (Figure 3a). In total, 118 rules were extracted and examined from the 14 documents. The rules are spread across the documents ranging from two in both the 1956 Colorado River Storage Project Act and 1973 Minute 242 to the highest amount of 41 in the 2007 Interim Guidelines (Figure 3b). While the 2001 the Surplus Sharing Agreement was established one year into the Millennium Drought, the significant increase in rules via the 2007 Interim Guidelines indicates a delayed, but robust policy response. Additionally, no rules have been rescinded since the action situations layer upon each other. This is an important finding because the water management activities and responsibilities have been maintained and lack substantial modifications over the long term. Through this analysis I found that through lock-in effects rules have, as anticipated, stayed in place and shaped sequential action situations over time across the CRB. These findings contrast others who have found that water resource governance networks significantly evolve, change, and shift over time in other cases (Hileman & Lubell, 2018; Möck et al., 2022).

Rule level occurrence per water management action type was calculated using rules extracted and characterized from the formal documents (Figure 3a). Rule levels lean heavily towards operational and collective-choice levels of analysis, indicating that the rules are set formally. This signals that actors exercise their power at the operational and collective-choice levels. To further investigate rule levels, I examined the occurrence of each rule level by document (Figure 3b). As the documents were developed over time, this allowed me to parse out the timing and context of additions of rules by level. Constitutional level rules, which identify the actors that can be involved in collective decisions, occurred least, signalling that there are informal processes for selecting decision-makers or that these are out of scope given the selection criteria. In contrast, operational level rules, which guide how water management activities can take place, govern how decisions can be made, and how rules can be changed, are in each document. Such findings demonstrate that the operating rules are formally set, and the way decisions are made has not been the focus of change.

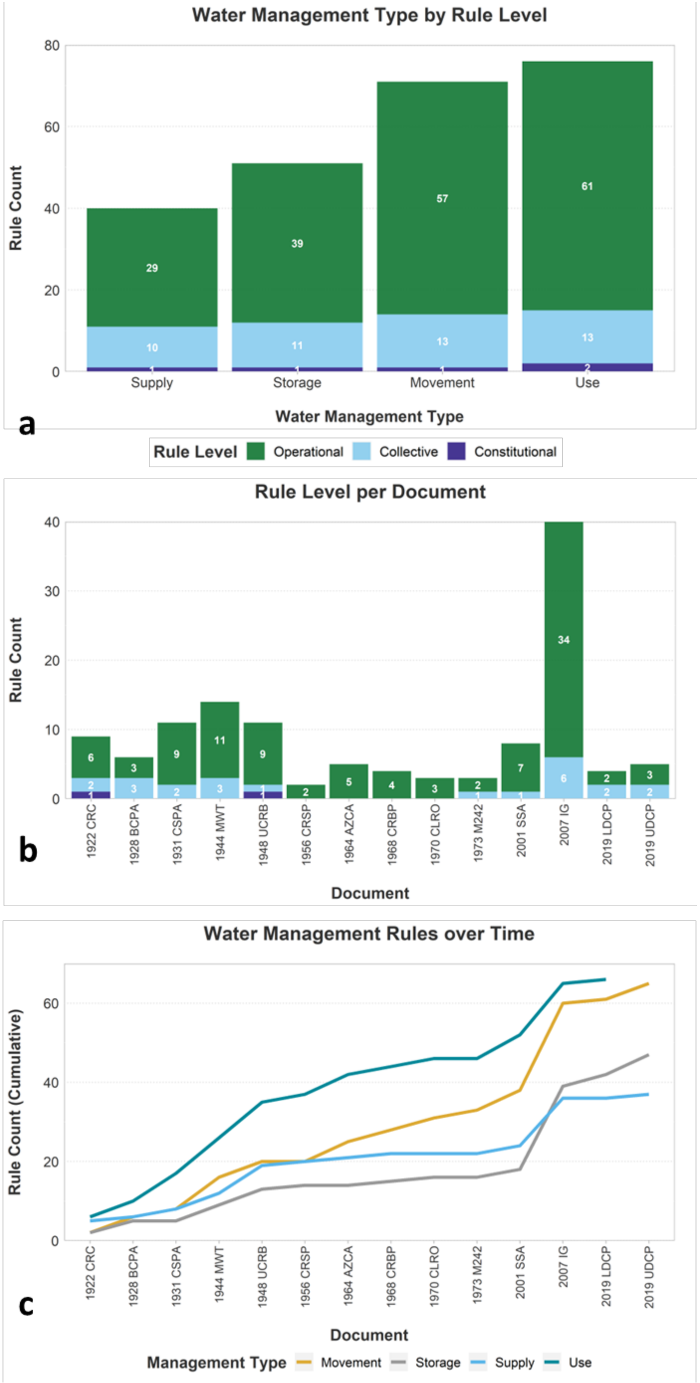

Figure 3: a) Rule Level per Water Management Type; b) Rule Level Count per Document; c) Cumulative Water Management Rules Over Time

I analyzed the occurrence of each water management type per document based on the extracted rules. Since the rules in these documents have stayed in place since their implementation, I examined the cumulative count of rules over time based on the type of water management (Figure 3c). Use and movement rules follow similar increasing patterns while storage and supply rules follow similar, but slower, increasing patterns over time. Rules pertaining to water use and movement actions occurred most often in the documents. Surprisingly, rules regarding water supply occurred least in the documents even though the CRB has historically struggled with water supplies and overallocation. This speaks to the persistence of early allocation agreements despite system changes.

5.2 Water Governance Network

Figure 4a-d illustrates the water governance network in 1922, 1948, 1973, and 2019, respectfully. The circular nodes represent actors while the arrows represent and indicate the rule direction between the rule issuer and target. The color-coding in Figure 4a-d aligns with the governance level of the actors as listed in Table 4. When comparing the 1922 (Figure 4a) with the 1948 network diagram (Figure 4b) there is a significant increase in the number of actors in the network from 6 to 27 and the number of connections. This finding aligns with the addition of national, state, and sub-state actors to the water governance network, particularly via the 1944 MWT. The most notable finding is the increase in the number of actors involved and the total number of rules connecting the rule issuers and targets when comparing the 1922 (Figure 4a) and 2019 (Figure 4d) networks. These substantial differences demonstrate the network structure change via a six-fold increase (from 6 to 35) in the number of actors involved and by one order of magnitude (from 10 to 178) in the number of connections between actors via the rules. Collectively, Figure 4a-d shows changes in the distribution of authority over time. Additionally, a record of the number of actors and rules for each diagram was kept. I found that the distribution of authority does not significantly change over time due to a lack of alteration to responsibilities for water management actions.

Table 3: Summary of Rule Issuers and Targets by Governance Level

Governance Level	Actors	Rules Issued	Rules Targeted
National	US, MX, USBR, SOI, Congress, Supreme Court, Dept of State, non-Fed Parties, USGS, IBWC	153	48
Basin	CRB	0	9
Sub-basin	Upper and Lower Basin, UCRC	23	17
State	Basin States, AZ, CA, CA Suppliers, NV, CO, WY, NM, UT, CRCN	2	48
Sub-state	MWD, SNWA, PVID, IID, CPSC, LA, SPSC, Contractors, Suppliers, SD, SD County	0	51

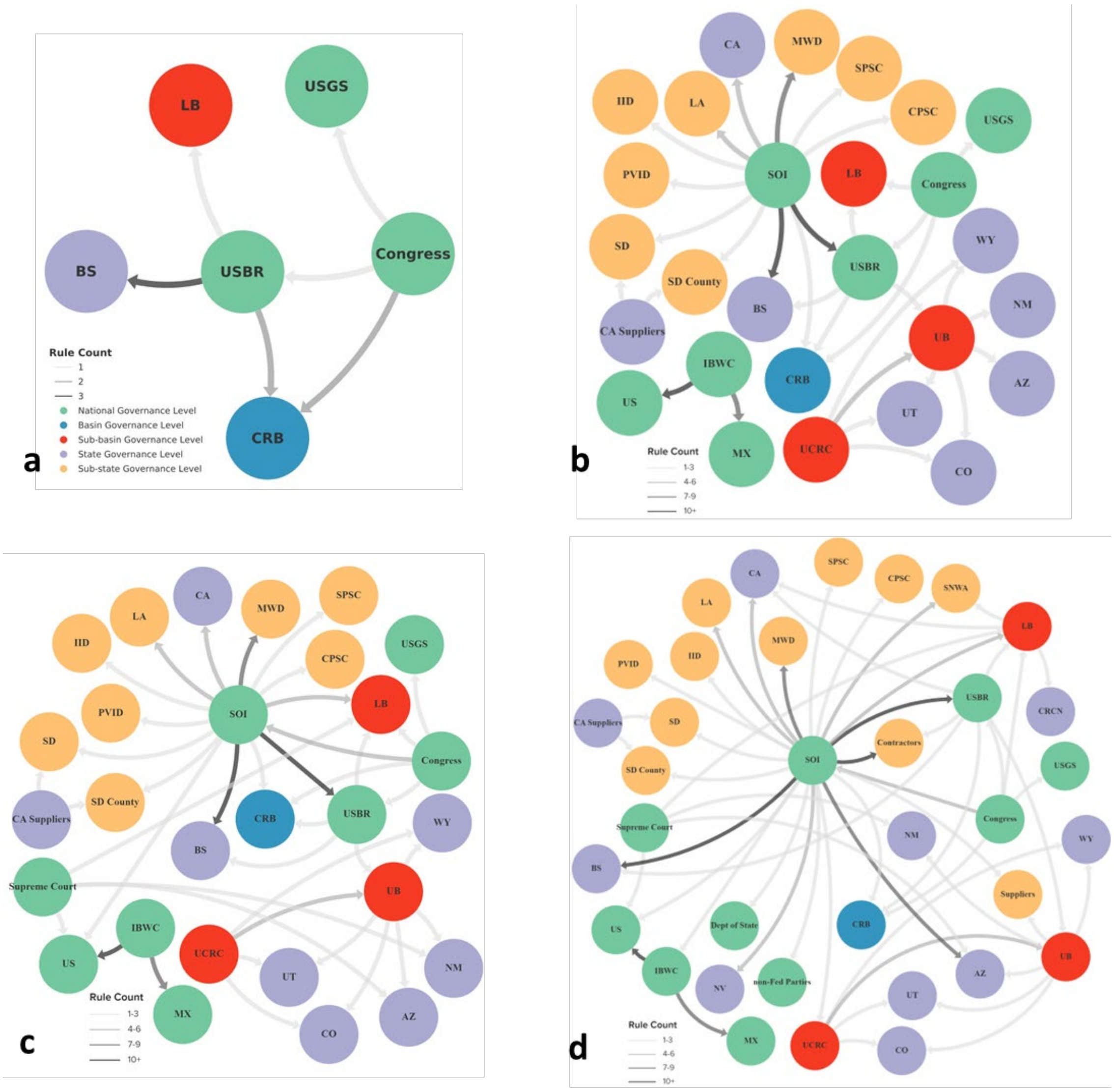

Figure 4: Network Diagram Snapshots a) 1922; b) 1948; c) 1973; d) 2019

Different processes, rule issuing and targeting, are dominant at different governance levels (Bodin & Crona, 2009). A significant portion of the rules are issued, thus originate, at the national level (Table 3). Rule targets at the national level delegate rule implementation to lower levels of governance, most notably (51) to the sub-state level. The second most rules are issued at the sub-basin level. This makes sense because as actors, the Upper and Lower Basins receive rules from actors at the national level and then make specific operational rules for states and sub-state actors. The distributions of rules in the sub-basins is possible via state member's voluntary agreement permitting both basins the power to issue rules.

Sub-state actors are the most targeted by the rules. Rules can grant or constrain authority, thus, even if an actor is the target of several rules, they are not necessarily heavily constrained or without authority for decision-making. Interestingly, the second most targeted levels are both the national and state, even though the national is the main rule issuer. These findings are consistent with a top-down structure of authority where actors with higher levels of governance (national) have more authority and use this authority to issue rules than actors with lower levels of governance (sub-state).

The CRB, USBR, U.S., SOI, and UB stay as the five most central nodes over time. The SOI dominates the network over time as the entity who issues the most rules, as indicated by high out-degree values (Table 4). In contrast, the U.S. is the main rule target, indicated via high in-degree values, thus the U.S. plays a major role in responding to rules. Actors that act as intermediaries have high betweenness values. In the case of the highest betweenness value per time snapshot, the USBR, UB, and SOI are indicated as the top intermediaries, but we know that there are multiple intermediaries that receive rules and then make specific operational rules for other entities (i.e., states and water suppliers). I found that actors who issue rules and the actors the rules target do not vary widely. There are no major changes in actors with the top centrality measures over time. Additionally, the bureaucratic hierarchy has remained the same. Actors in positions of power have maintained a status quo for the last 100 years.

Table 4: Top Actor by Network Centrality Measure and Year

Year	Actor	In-Degree	Actor	Out-Degree	Actor	Betweenness
1922	CRB	4	USBR	6	USBR	2
1948	US	13	SOI	24	UB	17
1973	US	17	SOI	29	UB	17
2019	US	19	SOI	103	SOI	23

6. Discussion

This research is novel because it goes beyond existing descriptive studies and their critiques by taking an analytical approach to examine the content within the majority (14) of "Law of the River Documents" (Ingram et al., 1984; Wescoat, 2023). This study also goes beyond other institutional studies of Colorado River water that focus on water quality, hydropower operations, the state-level, reservoir operation, and the decision-making process by using an analytical lens including a 100-year time scale, five levels of governance, and management actions related to supply, storage, movement, and use (Berggren, 2018; Karambelkar, 2018; Sullivan et al., 2019; Turley et al., 2022).

This study acknowledges the long, but not full, history of the evolution of the CRB water system from open access to a highly regulated resource. Indigenous peoples' water use and management of the basin has an even longer history that I do not cover in this study but recognize as an important piece of the larger story of water in the West. Over this period, CRB water management shifted from managing demand growth to managing conflict over time, marked by the evolution of water resource management to reservoir development, then to managing water scarcity. However, since the inception of U.S. water governance of the basin, a Western, utilitarian approach has been followed.

The water governance network has changed and evolved over the last century. As the network expanded, more attention was paid to diversity, equity, and inclusion with the addition of different actors (Tribal Nations, Mexico, etc.). In contrast to Olivier & Schlager (2021), I found the addition of dynamics and institutional arrangements did not limit or change the direction of water governance decision-making and actions. The governance system complexity increased and became highly institutionalized as more water management rules were created. Highly institutionalized governance systems are fragile and have limited opportunity for flexibility because there are tensions and constraints for change and limits on possible choices (Gillette, 1998; Ishtiaque et al., 2021). Actors in these types of governance systems are required to maintain the system and there is less space for experimentation and innovation between the rules. Thus, the finding that water management responsibilities also remained stable over time aligns with and empirically contributes to the literature on institutions. Although the network has evolved with the addition of rules and actors and an increase in the number of connections between actors, issues recur as there has been no major structural change or reform the institutional network. These findings are important as substantial differences in governance outcomes and processes cannot be expected without changes to the water governance network (Bodin & Crona, 2009; Das et al., 2019). Improved understanding of current CRB governance and how it has evolved in the past will help pave the way to more effective evolution to the governance structure moving forward.

Overall, the central structure remained stable without actor replacement or removal, only additions. Consistent with other water management studies (Elshafei et al., 2014; Garcia et al., 2016), I found that water system dynamics persist over time with the layering of rules. The layering of new rules has permitted CRB water governance to remain viable through new operating conditions and infrastructure integrations. Moreover, there are limitations to what incremental adaptations can do to sustain systems over the long-term (Kates et al., 2012; O'Brien et al., 2012). The layered incremental adaptation approach for the CRB has not kept pace with accelerating climate change, drought, aridification and increasing demand. This is evident via the USBR's demand to reduce an additional 2-4 MAF of water for use in 2023. USBR's demand gives an example of the challenge of negotiating new rules in the context of 100 years of history and evolution of water governance in the CRB. The findings that approaches we have used over the last century have not kept pace with water management challenges in terms of climatic and governance regime changes align with other water governance studies (Hileman & Lubell, 2018; Olivier et al., 2020). This examination of the network structure over the last century provides additional knowledge of how institutions in the CRB have and have not changed.

I found that key decision-making positions remained the same and the actors who issue and are targeted by the rules lack significant change over the last century. Such cross-scale interactions help us understand the network structure and interface between actors involved in natural resource governance (Cash et al., 2006; Ostrom, 2005). Original positions of power have been maintained over time, narrowing the space for problem solving and renegotiation. Generally, in systems with centralized power, substantive changes are harder to make because powerful actors may use their power to maintain the status-quo or exert their power over less powerful actors (Ishtiaque et al., 2021; Partzsch, 2017). The findings support the hypothesis that path dependency has shaped how water governance evolves and who is able to influence decisions.

7. Conclusion

Integrating water governance, institutional analysis, and social network analysis concepts, I present a 100-year temporal analysis, drawing on formal documents and rules that shape Colorado River Basin water governance. Despite struggles with water overallocation since the early 1920s, there are few supply rules, demonstrating how early allocation agreements endure even with changes over time. I found that actors exercise power to shape water management at both operational and collective-choice levels. Despite rule changes at these levels, no major alterations to management rules and responsibilities occurred. These findings support the hypothesis that the distribution of authority is split across actors and institutional choice levels. The original power structure has proved robust to past shocks to the system. It appears the way decisions are made has not been the focus of change and processes for selecting decision-makers is informal or that constitutional level rules are not within the selection criteria scope.

In this combined spatial, temporal, and network analyses covering the past century, I observed how Colorado River Basin water governance has been influenced by the legacy of policy. This includes a varied set of rules that have evolved water management strategies over time, changed (level and management) types, and split and changed power/authority across actors and levels. These rules spread across multiple scales from sub-state to national, hence indicating the multi-level governance system structure that is characteristic of Colorado River Basin water governance. I found that the institutional network is not responsive to environmental and social changes as it has remained relatively unchanged over the last 100 years. Due to the lack of alteration, the water governance structure has not kept pace with an increasingly changing climate in the Anthropocene and is unable to respond sufficiently. These findings contribute to the broader discussion on future adaptation by shedding light on the deficiency of past water management and incremental changes to keep up with rapid climatic change. Identifying the short comings of historic and legacy water governance can inform more effective strategies for future adaptations. This study adds to water governance knowledge regarding changes to water management strategies and responsibilities over time and how the outcomes of these changes, based on formal rules, arose across high institutional levels via rule layering and distributed authority to shape water governance decisions. Additionally, this research contributes to multi-level governance empirical research and scholarship through a focus on water governance as multi-level and evolving, with an institutional structure that has been influenced by path dependency and layered rules over time.

Further, from a policy perspective, this research is timely given the upcoming 2026 deadline for updated Colorado River Basin Guidelines that will impact Colorado River Basin water governance moving forward. In context of the ongoing water crisis, the operational decisions made now are a product of the rule accumulation over the past 100 years. Current negotiations may result in incremental changes that continue this accumulation or broader revisions. The results of this study offer insights into the plausible path of further rule accumulation and suggest that while the layering of new rules permitted CRB water governance to remain viable through new operating conditions and infrastructure integrations, these incremental adaptations have not achieved sustainable water management. Challenges of climate change, overallocation, and demand growth are not unique to the Colorado River and the results could be broadly useful in other river systems trying to negotiate terms of operation and allocation across multiple water users in a changing climate.

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