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Institutional analysis of water governance in the Colorado River Basin, 1922–2022

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The 1922 Colorado River Compact started 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, an understanding of the long-term evolution is lacking. This study examines how water management strategies have evolved at the basin scale by incorporating institutional, 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 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, we found constitutional, operational, and collective-choice level rules for water supply, storage, movement, and use have been altered via layering of new 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. We found original positions of power have been maintained, potentially stagnating the space for problem-solving and management strategy renegotiation. Our results indicate that path dependency has shaped water governance and who is able to influence decision-making.

KEYWORDS

Colorado River Basin, institutional analysis, network analysis, path dependency, water governance, water management

1 Introduction

Water has been the source of tension, contestation, and disagreement for over a century in the Colorado River Basin (CRB) (Mirumachi et al., 2021; Sullivan et al., 2019). Before 1900, communities used water locally without basin-wide impact (Kuhn and 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 (CRC) 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 and Pierce, 2008; Furnish and Ladman, 1975; Glenn et al., 2001; Hwang et al., 2021). The Colorado River in the American Southwest is one of the most important rivers in the world as it supplies drinking water, water for livelihoods, and has significant cultural and ecological value to 40 million Americans, including Tribal and

Indigenous Peoples (Elias et al., 2023; Juricich, 2022; USBR, 2012). 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 can provide insights into water governance as actors interact to make decisions about new or altered rules, governance strategies, and management regimes (McGinnis, 2011). Examining the institutional context in the CRB illuminates how institutions evolved under social and environmental change.

On June 14, 2022, the U.S. Bureau of Reclamation (USBR) instructed CRB states to develop a plan to reduce 2–4 million acre-feet (MAF), or 19 to 38% respectively, of annual water use within 60 days (USBR, 2024a, 2024b). The 60-day period has passed without a consensus and shortly after the USBR declared a Tier 2a shortage for the following year, 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 to the Basin States 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 a better understanding of the evolution of water governance institutions.

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 et al., 2013a; Pahl-Wostl et al., 2010; Rogers and Hall, 2003; Wiek and Larson, 2012). Common pool resources, such as water, are rival, meaning usage diminishes others' ability to use the resource, and non-excludable, meaning excluding users is prohibitively difficult (Ostrom, 2005). Common pool resource use often results in conflicts when supply does not align with demand. Governance of natural resources can alleviate this conflict with rules that are created to allocate and distribute resources (Ostrom, 2011).

Water systems are nested, dynamic, and layered, therefore institutional arrangements must be able to 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. 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 and Schlager, 2021). Layering can be conceptualized as concurrent system inputs, where impacts accumulate as each layer is considered (Green and Dzidic, 2014). 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.

Multi-level governance is concerned with how actors operating at different institutional levels collaborate to solve shared problems (Cash et al., 2006; Heinen et al., 2021; Marks, 1993; Pahl-Wostl, 2009). Multi-level governance scholarship is characterized by strong descriptive elements that document changes in governance arrangements (Bisaro et al., 2020; Liu and 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 actors' differing goals and agendas coupled with a changing climate (Jones and White, 2022; Sullivan and White, 2019).

One century later, the 1922 CRC 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 and Overpeck, 2017). Williams et al. (2022) found that from 2000 to 2021 the Southwest has been in the most severe drought in at least 1,200 years. This raises the question of why water management has not changed more significantly in response to increasing scarcity. Path dependency of institutions may play a role. Repetitive practices and patterns resulting from socially constructed rules and norms give rise to path dependency (Schmidt, 2010).

Understanding how the tension between changing environmental conditions and path dependency have shaped past changes in water management can inform policy responses to the current challenge. This motivates two research questions: (1) How has the emphasis on different water management actions and rule levels changed over time? (2) How has the distribution of authority changed across actors and institutional levels in the CRB over the last century? We examine path dependency by extracting and analyzing the incentives and constraints that guide water governance choices from formal water management rules. We anticipate that path dependency has shaped the emphasis on different water management actions and rule levels over time. Further, we hypothesize the distribution of authority changes 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 authority is distributed across actors and institutional choice levels over the last century.

2 Theoretical framing

2.1 Institutional theory

Institutional theory has foundations in organizations and organizational theory (Barnard, 1968; Scott, 1987; Selznick, 1948), economics (Nee, 2005; Williamson, 1981), and sociology (Fligstein, 1997; Meyer, 2010; Zucker, 1987). North (1991) distinguishes institutions from organizations stating that organizations play the game per the rules and that institutions set the rules of the game and the players. Institutional theory is concerned with procedural rules and posits that certain aspects of government structure can empower or obstruct political interests (Kraft and Furlong, 2013; Peters, 2022; Peters et al., 2005). According to Scott (2005), institutional theory combines components from historical and comparative research and focuses on deeper social structures such as norms and routines. Institution refers to the "rules used to structure patterns of interaction within and across organizations," thus the rules that govern or induce behavior (Ostrom, 2007, pg. 22). Rules specify authority and constraints by creating or restricting authority via limits, timing, and how infrastructure can be used. Institutional scholars and theorists Gary Libecap (1989) and Ostrom (2005), view institutional change through a design-based lens where change is conceptualized as collective-choice processes of rule creation outcome. Further, the analysis of how institutions change over time is a key field of research within institutional theory (Coccia, 2018). Institutional change is shaped by higher-level rules and is dependent on decision-maker's perception of the probable effects of rule changes (Libecap, 1993; Ostrom, 2005). Institutional change can be examined to understand how resource, water, in this case, governance has evolved (Olivier, 2019).

The Institutional Analysis and Development (IAD) Framework (Figure 1), aids in evaluating and understanding institutional arrangements (Heikkila and Andersson, 2018). While the Social-Ecological Systems Framework is suitable for policy studies similar to ours, we chose to use the IAD Framework because it facilitates analysis of how governance unfolds, in our case, water use and management and focuses on institutional arrangements as opposed to the interaction between actors and ecological systems and the biophysical context (Anderies et al., 2018; Anderies and Janssen, 2013; McGinnis and Ostrom, 2014; Schlager and Cox, 2018). The IAD 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 each actor must abide by, their rights, obligations, and constraints based on official (i.e., written), legislatively specified rules, are called rules-in-form. Rules-in-form 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) and help provide a picture of the rules-in-use (Brady et al., 2018; Cole, 2017; Ostrom, 2011). Rules-in-use are rules that are in action and include both rules-in-form and informal rules (i.e., norms and customs that are not explicitly stated or written) (Ostrom and Basurto, 2011; Schlager and Cox, 2018). The IAD Framework can be extended to consider the feedback loops from policy outcomes to rules-in-use (Figure 1) to aid in understanding the changes to the institutional structure as rules layer upon each other over time, enabling analysis of the evolution of governance regimes (Hardy and Koontz, 2009; Heikkila and Andersson, 2018; McGinnis, 2015; McGinnis and Ostrom, 2014; Ostrom, 2011; Ran et al., 2020). The Action Situation, within the IAD Framework, is a social space where actors are positioned, interact, and act under rules that determine a set of potential actions that can or must be taken regarding a given theme that is linked to and produces potential outcomes (Kellner, 2021; Ostrom, 1999, 2005; Ran et al., 2020). One IAD Framework strength is that it connects outcomes at different levels of analysis explicitly (Ostrom, 2005). Moreover, as policy decisions are made rules-in-use are added or revised, thus changing the structure and process for future rule change.

To sort linkages between specific rules and help assess the institutional structure, rules can be organized based on their rule level, also known as level of analysis. Rule level pertains to the range of actions that actors are allowed, required, and/or prohibited to take. The IAD Framework characterizes three rule levels where different types of choice processes occur: constitutional, collective-choice, and operational. Constitutional level rules define the scope and identify actors that can be involved in collective decisions; collective-choice level rules determine the strategies, norms, and rules available for policy-making for actors with defined roles; and operational level rules describe how actors make choices amongst available options set by the collective choice processes (Cole, 2017; McGinnis and Ostrom, 2014; Ostrom, 2005).

2.2 Path dependency theory

Path dependency theory, stemming from historical institutionalism (Mahoney and Rueschemeyer, 2003; Peters et al.,

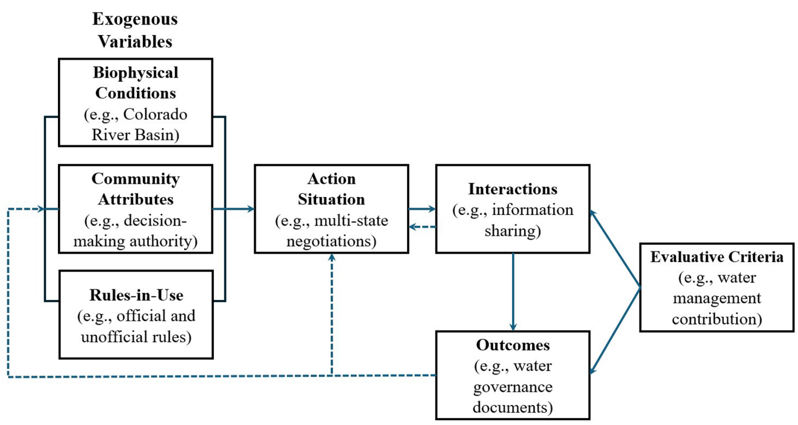

FIGURE 1
IAD Framework adapted from (Ran et al., 2020; Ostrom (2005).

2005; Thelen, 2003), is well-established in social science and institutional change literature (Gains et al., 2005; Kessy, 2018; Krasner, 1984; Peters et al., 2005). Path dependency is referred to as routine patterns and practices that are formed by socially framed and constructed, norms and rules (Schmidt, 2010). The theory argues that there is an inertial tendency for original choices to persist once an organization or governmental program instigates a particular policy or style of action (Krasner, 1984; Peters, 2019; Pierson, 2000). The causal structure of path dependency theory proposes that essential decisions at starting points result in outcomes whose self-reinforcing processes and lock-in of system features make the initial selection difficult to break from (Arthur, 1989; Katznelson et al., 2003; Kay, 2005; Newig 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). These choices are locked into the institutional structure and become apparent when institutions do not adjust to system changes (Gillette, 1998).

Conversely, network structure changes can be evidence of changes in power dynamics. To investigate such network changes, social network analysis is commonly used. Social network analysis is commonly used to assess the relationship between nodes (actors in our case) through their connections (Jones and 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, the number of connections directed to a node, and out-degree, the 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 the understanding of power dynamics within and across institutional levels. The institutional level refers to formal government jurisdictions (e.g., National, Basin, Sub-basin, State, Sub-state).

2.3 Power dynamics and water governance

Power dynamics impact how natural resource governance is conducted and carried out. The concept of power dates back to Aristotle (Lukes, 2005; Malik and Abeuova, 2023). More recent contributions from theorists include Lukes (1974, 2005) and Foucault (1980) work on the dimensions of power; power as domination which is frequently considered *power over* others using coercion and manipulation, power as empowerment is commonly considered the *power to* act as an individual and in an indirect relational way including the ability to resist and empower others, and *power with* is theorized as a concept of learning and cooperation between actors including the ability to act collectively (Haugaard, 2012). There are other ways power has been conceptualized in natural resource governance studies (Mehta, 2010; Morrison et al., 2019; Werker et al., 2018). We conceptualize power as a socially constructed and multi-faceted influence, with multiple related dimensions, that shape how actors engage with natural resource governance regimes (Arts and Van Tatenhove, 2004; Molle, 2008; Partzsch, 2017). Power by design (i.e., the power written in incentives, rules, institutions, and legislation) is a type of power that is useful to consider for studying governance rules because actors are given power via written rules and legislation (Morrison et al., 2019; Mudliar, 2021).

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 objectives, and power in the policy-making process (Kashwan et al., 2019). The power to make decisions for CRB governance is granted to actors, in part, by formalized policy and rules (Kenney, 1995). Water governance rules and actors' roles and positions are laid out by formal rules in policy documents such as the 1922 CRC (Kenney, 1995). Power dynamics within and across institutional levels for CRB water governance are reflected by the administration of governance rules by actors with differing granted authorities and positions within the institutional structure. Further, between Federal and State level actors there are power imbalances, where those at the Federal level have more, and concentrated, power to shape CRB governance than State and lower-level actors (Kenney, 1995; Molle, 2008). Within the actor-centered power approach, power is conceptualized as stemming from structural power, such as social structures based on rules, where the rules are a source of power for actors to leverage to empower themselves to achieve their objectives (Krott et al., 2014). Formal rules can grant power to any given water governance actor (Coccia, 2018; Levi, 1990). Power in the policy-making process is often referred to as political power. An actor's amount of political power can be conceptualized by studying their participation in water governance. The more power an actor has, the more they are able to participate which reflects asymmetries in power (Molle, 2008; Wilder and Ingram, 2016). One example of powerful actors shaping the policy-making process can be seen in the early 1920s when CRB water governance decision-makers used their power to "selectively use the available science as a tool to sell their projects and vision for the river's future" instead of taking the hydrologic scientists, who brought the best available streamflow estimates to the decision-makers, seriously and considering the actual streamflow for development (Kuhn and Fleck, 2019, p. 5).

3 Water governance of the Colorado River Basin

Tribal and Indigenous peoples have lived and prospered within the Colorado River Basin and managed the Colorado River water since time immemorial (Hundley, 2009; Kuhn and Fleck, 2019; Wescoat, 2023). Indigenous communities have rights to their historic lands, waters, and use and access to natural resources as the original peoples and stewards of the land in the CRB. These rights were formalized with the colonization of the river in the 1908 Supreme Court ruling for the *Winters v. United States* case which grants Tribes water rights based on when their reservation (i.e., non-ancestral land they were forcibly moved to) was created by the federal government (Bark and Jacobs, 2009; Formisano, 2021; McKenna and Supreme Court of the United States, 1908). Today, several of these water rights remain unsettled or have just recently been adjudicated. First proposed in 1994, the negotiations for settling the Hopi Tribe, Navajo Nation, and San Juan Southern Paiute Tribe water rights claims, which include claims to the Upper and Lower CRB, remain unsettled. The last notable progress for these settlements was in May 2024, when the Hopi Tribe, Navajo Nation, and San Juan Southern Paiute Tribe approved the proposed Northeastern Arizona Indian Water Rights Settlement but await settlement ratification via Congress (Arizona Superior Court, 2024).

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 CRC was crafted by the seven Basin States (Arizona (AZ), California (CA), Nevada (NV), New Mexico (NM), Colorado (CO), Utah (UT), and Wyoming (WY)) and the Federal Government which 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 (MX) (Owen, 2018), despite the exclusion of MX and Native America Tribes in the creation and signing of the 1922 CRC (Méndez-Barrientos et al., 2024) Further, the water rights and governance of the CRB were set "… within a settler-colonial context… based on expropriation, unequal access, and injustice" (Méndez-Barrientos et al., 2024, p. 192). 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 Basin States and authorized splitting the LB's 7.5 MAF of Colorado River 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 and 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 water to MX in normal flow years, marking the first time MX had a formally identified role in managing Colorado River 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 (UCRC) 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 1940s. 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 a 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 Colorado River 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 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 Basin States for 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 9 years for Colorado River 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 Colorado River management and ways future tribal water resource development could influence CRB operations. Additionally, Tribal Nations have been significantly excluded from water governance and programs over the last century although they hold rights to 25–30% of the Colorado River's historic flow (Karambelkar and Gerlak, 2020; Méndez-Barrientos et al., 2024). There are 182 Federally Recognized Tribes and several state-recognized Tribes and Tribes seeking federal or state recognition in the Southwest, yet recognitional justice is lacking as there are inequities in water distribution both historically and in present times (Bureau of Indian Affairs, 2017; Elias et al., 2023; Indian Affairs Bureau, 2020).

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 Basin States to consider all water users, beyond junior rights holders, as having a stake in keeping the 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 Colorado River water delivery (Schlageter, 2021). In 2022, as water shortage conditions continued, a Tier 2a shortage was declared, which cut the 2023

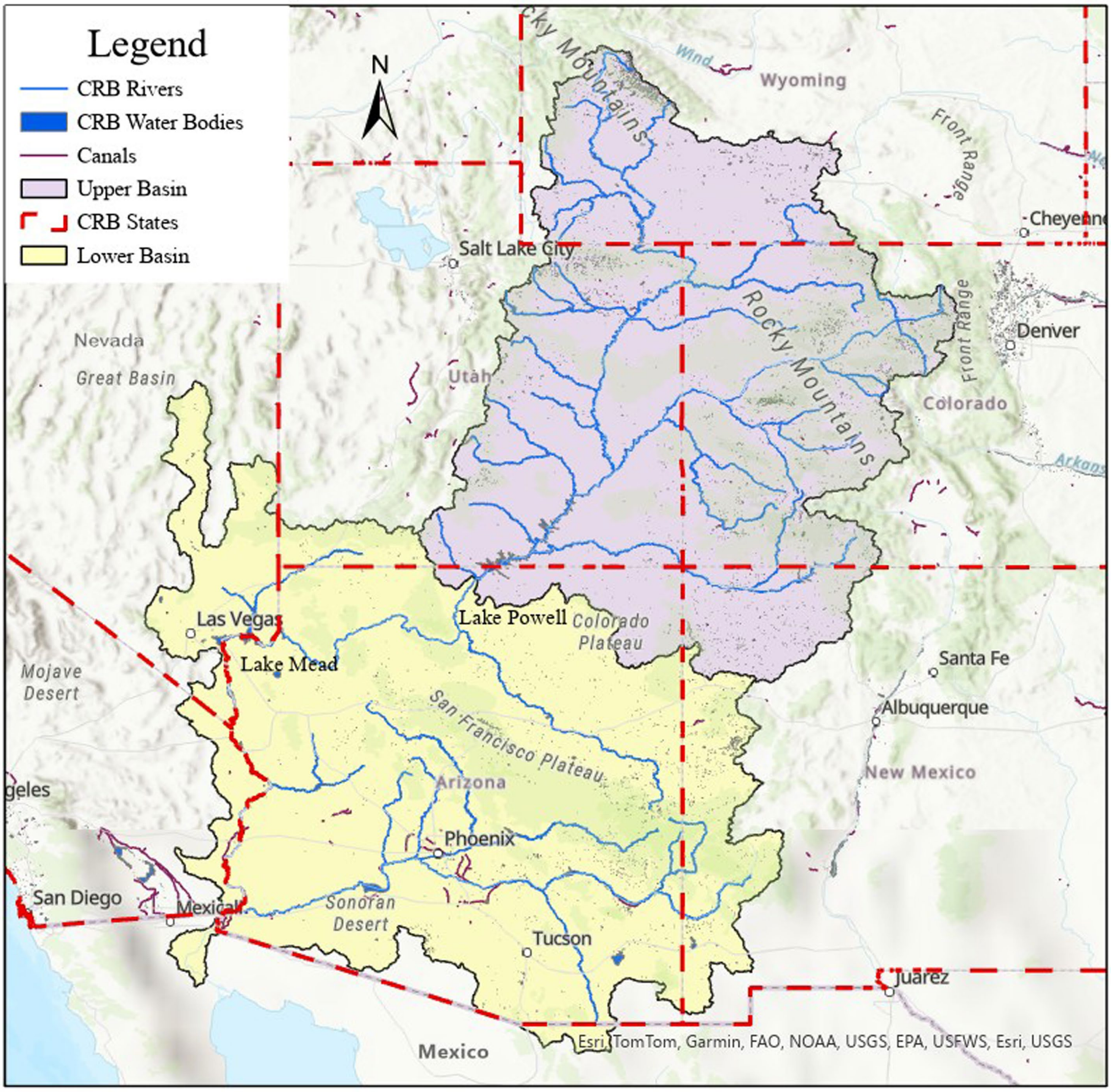

FIGURE 2
Case study location, Colorado River Basin, U.S.

Colorado River supply for AZ, NV, and MX. The USBR further demanded in 2023 that water use be cut an additional 2–4 MAF by the Basin States and Tribes reliant on the Colorado River (Stern, 2023).

Presently, tensions are elevated about CRB's water governance amidst an uncertain climate and water supply (Gerlak et al., 2021; Karambelkar and Gerlak, 2020; Sullivan et al., 2019). In part, some tensions result from differing goals between the UB and LB (e.g., 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 <17.5 MAF early western water decision-makers assumed (Kuhn and Fleck, 2019). While water governance management strategies and water action responsibilities have changed over time, we do not fully know how those changes have shaped water management actions and actors' roles. Our research describes changes in rules-in-form over a 100-year period and analyzes these changes in the context of the case history.

4 Methods

For this analysis, we examined written rules for governing the physical supply of water in the CRB (Ostrom, 2011). To identify rules that guide governance decisions, we use a systematic approach 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. Then, we used content analysis to determine how internal decision-making processes are expressed in formal documents (Bernard et al., 2016; Bowen, 2009).

TABLE 1 Colorado River water governance document selection.

Document	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

Next, we characterized each rule based on spatial scale and whether the rule grants or constrains authority based on rule issuer and target. This information is used to map the institutional structure using social network analysis. Lastly, the results are interpreted in the context of the case history presented in Section 6.

4.1 Data and rule selection

To understand the evolution of the water governance structure, we analyzed documented rules and agreements in formal, written water management documents for the American Southwest from 1922 to 2022. This analysis only considered formal documents with legal or regulatory standing regarding Colorado River Basin water governance. The resulting set of documents are called the "Law of the River" documents (Sullivan et al., 2017; Wescoat, 2023). Next, 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 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, stock, accumulat*, groundwater bank*, aquifer storage
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

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., 2013b; Wiek and Larson, 2012). From the literature, we identified four main domains associated with water system management: water supply, storage, movement, and use activities (Garcia et al., 2019; Mirumachi et al., 2021; Wiek and Larson, 2012). Next, we 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 addresses at least one CRB water management domain.

We conducted content analysis using codes derived from theory and prior knowledge of water governance and institutions (Akamani and Wilson, 2011; Mirumachi et al., 2021). We inductively coded the rules based on the identified keywords informed by existing water governance scholarship (Table 2). To better understand and document the institutional arrangements, we characterized the rule level, spatial scale, issuer, and target of each rule without mutual exclusion. The three rule levels (constitutional, collective-choice, and operational) defined within the IAD Framework were utilized to assign levels to the rules based on what the rule choice process was discussed. Next, to understand the network of actors, we 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. The first two authors used consensus coding to reach intercoder agreement (Cascio et al., 2019; Hill et al., 1997).

4.2 Network analysis

We constructed a directed network based on the rule characterizations above using the igraph package (Gabor and Nepusz, 2006) in R. Directed networks indicate the flow of information, or in our case, rule direction from the issuer to the target. To test our hypothesis that the distribution of authority changes over time and is split as the network size increases, we 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, we calculated the measure of in-and out-degree centrality and betweenness centrality (Friemel, 2017; Jones and White, 2021; Olivier, 2019). To clarify, we counted the rule issuer and target separately by 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 the 1956 Colorado River Storage Project Act to the highest amount of 40 in the 2007 Interim Guidelines (Figure 3b). While the Millenium Drought began in 2000, the significant increase in rules via the 2007 Interim Guidelines indicates a delayed, but robust policy response. Additionally, no formal rules have been rescinded and as a result, the rules are layered upon each other. This is an important finding because, while new rules have been added, the initial water management activities and responsibilities have been maintained over the long term. Through this analysis, we found that through lock-in effects rules have, as anticipated, stayed in place and shaped subsequent rules-in-form over time across the CRB (Bardach, 2006).

The number of rules by rule level and water management action type were calculated from the extracted and coded rules (Figure 3a). Of the extracted rules, operational rules are the most common and constitutional level rules are the least common. To further investigate rule levels, we examined the occurrence of each rule level by document (Figure 3b). As the documents were developed over time, this allowed us to parse out the timing and context of additions of rules by level. Operational level rules are most common and are found in each document. Collective choice rules are the second most prevalent and constitutional rules are least prevalent. Such findings demonstrate that policy change in the CRB has been at the operational level, signaling that the focus of change has been on further specifying how practical decisions are made. Further, the focus of change has not been on the way decisions are made although there have been some collective-choice level rule additions, indicating that the way policy is made is evolving but at a slower pace. There are only two constitutional level rules, one in the 1922 CRC and the second in the 1948 UCBR (Figure 3b) which is surprising as both documents set up major governance structures. The lack of change is of note because many new actors are added over time and part of the job of constitutional level rules is to specify actor roles in lower-level rules. As constitutional level rules occurred least, this signals that there are informal processes for selecting decision-makers or that these are out of scope given our selection criteria.

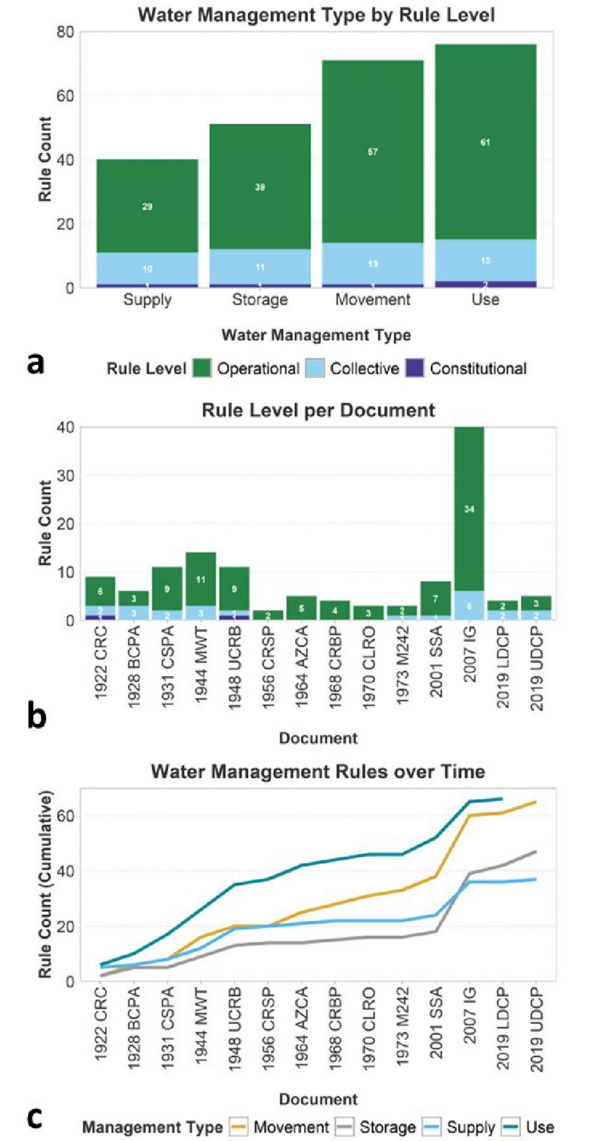

FIGURE 3
(a) Rule level per water management type; (b) rule level count per document; (c) cumulative water management rules over time.

We 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, we 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. Also, rules regarding water use and movement actions occurred most often in the documents. Water movement rules are tied for least prevalent in 1922 to the second most prevalent in 2019 (Figure 3c). This makes sense as the period of water allocation and infrastructure development paved the way for moving water and aided in the expansion of rules regarding the physical dispersion of CRB water. Notably, storage rules were the least prevalent until 2007 when the coordinated operations between Lake Mead and Lake Powell, as well as the use of storage by individual water users, became important strategies to cope with drought (Figure 3c). This increase in prevalence is in alignment with the water governance period of demand management under variable hydrology starting in the mid-1990s as well as the current water management period focused on drought. Water supply rules start as second most prevalent in 1922 and fall to least prevalent in 2007 although the 2007 Interim Guidelines were set for drought management (Figure 3c). Despite the 2019 DCPs, also established for drought management, currently, water supply rules are least prevalent even though the CRB has historically struggled with water supplies and overallocation. This may be due to the doctrine of prior appropriation driving priority water rights in the West and challenging changes to allocations of water supplies.

5.2 Water governance network

Figures 4a–d illustrate the water governance network in 1922, 1948, 1973, and 2019, respectively. The circular nodes represent actors while the arrows represent and indicate the rule direction between the rule issuer and target. The color-coding in Figures 4a–d aligns with the governance level of the actors as listed in Table 3. 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 changed 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. Rules can be used to impose authority (i.e., rule issuers exert their power over rule issuees) and grant authority (i.e., rule issuers their power to give new powers to rule issuees) (Coccia, 2018; Kenney, 1995; Levi, 1990; Molle, 2008). Both of these processes are reflected in Figures 4a–d which show changes in the distribution of authority over time as the network grows, as more actors have authority granted to them via formal rules, they can issue rules to other actors. The growth of the network in the number of actors and rules aligns with the governance period starting in the mid-1990s with a focus on expanding the criteria for decision-making and actors formally included as decision-makers.

Different processes, rule issuing and targeting, are dominant at different governance levels (Bodin and Crona, 2009). Table 3 shows the total amount of rules issued by and targeted at actors at the same governance level throughout all 14 documents analyzed. A significant portion of the rules are issued, and thus originate, at the national level (Table 3). Rule targets at the national level delegate rule implementation to lower levels of governance, most frequently (51) to the sub-state level. The second most rules are issued at the sub-basin level (Table 3). This makes sense because as actors, the UB and LB receive rules from actors at the national level and then make specific operational rules for states and sub-state actors. The distribution of rules in the sub-basins is possible via state members' voluntary agreement permitting both basins the power to issue rules. Sub-state actors are the most targeted by the rules (Table 3). As 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 (e.g., national) have more authority and use this authority to issue rules than actors with lower levels of governance (e.g., sub-state).

By looking at the top five actors for each metric, we found that the distribution of authority does not significantly change over time due to a lack of alteration to responsibilities for water management actions. Tables 4–6 are breakdowns of the top five actors' centrality measurements at each time snapshot. The U.S. is the main rule target, indicated via high in-degree values (Table 4), thus the U.S. plays a major role in responding to rules. The actors with high in-degree values are less consistent as only the U.S. and BS remained in the top five from 1948 to 2019 (Table 4). The SOI dominates the network over time as the entity that issues the most rules, as indicated by high out-degree values from 1948 onward (Table 5). From 1948 on, there are a small number of actors, SOI, IBWC, USBR, and UCRC, who consistently have high out-degree metric values indicating they issue the most rules. Actors that act as intermediaries have high betweenness values. There is less consistency in the top five actors with the highest betweenness metric values. From 1948 to 2019 the UB and USBR are the only actors that remain in the top five. In the case of the highest betweenness value per time snapshot, the USBR, UB, and SOI are indicated as the top intermediaries (Table 6), but we know that multiple intermediaries receive rules and then make specific operational rules for other entities (i.e., states and water suppliers). Considering betweenness is a representation of actors that serve as links by receiving and issuing rules, it makes sense that when the network is smaller and simpler fewer actors have a linking role. Betweenness, in this case, may be a measure of the increasing complexity of the network and institutional structure over time. We found that the actors who are rule issuers and targets do not vary widely. The same cohort of actors, the CRB, USBR, U.S., SOI, and UB (Tables 4–6), have the highest centrality values over time, indicating the bureaucratic hierarchy has remained because actors in positions of power in the water governance network have been maintained over the last 100 years.

6 Discussion

In our combined spatial, temporal, and network analyses covering the past century, we observed how Colorado River Basin water governance has been influenced by the legacy of policy. We present a 100-year temporal analysis, drawing on formal documents and rules that shape CRB water governance by integrating case history, institutional analysis, and social network analysis. We found that the rules have evolved water management strategies over time, shifted the emphasis of various water management actions, and changed the distribution of authority across actors and levels. The rules span multiple scales from sub-state to national, indicating the multi-level governance system structure that is characteristic of Colorado River Basin water governance.

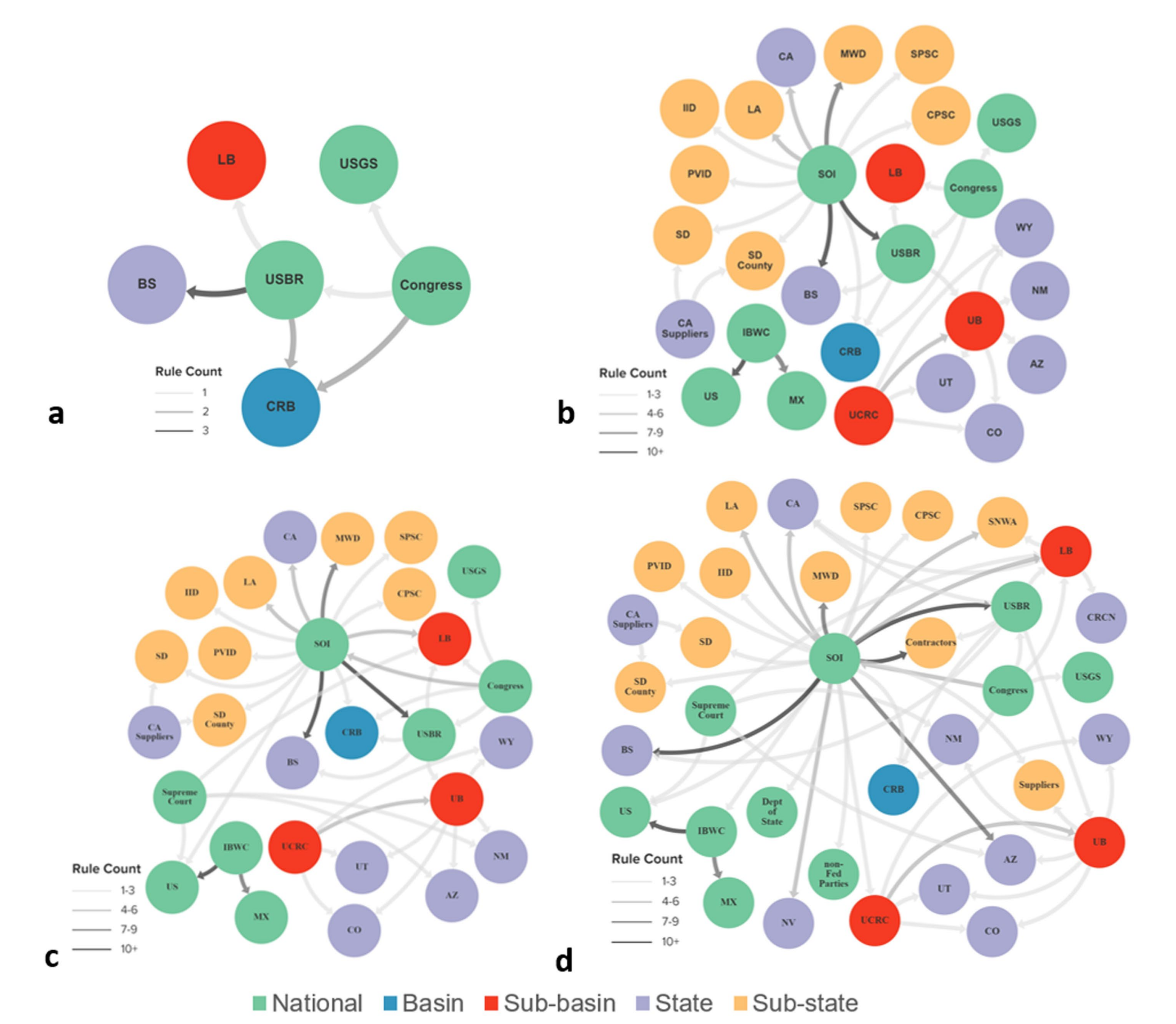

FIGURE 4
Network diagram snapshots (a) 1922; (b) 1948; (c) 1973; (d) 2019.

In the institutional analysis, we found that water system dynamics persist over time with the layering of rules (Figure 3c), consistent with other water management studies (Elshafei et al., 2014; Gleick, 2003; Pulwarty et al., 2005). The maintenance of the original rules via the addition of rules that have created layers within the water governance institutions and the actor network is evidence of path dependency (Lewis and Steinmo, 2012; Peters, 2019). The layering of new rules has permitted CRB water governance to remain viable through new operating conditions and infrastructure integrations as seen in the case history. However, 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 – and the BS's difficulty in meeting it – gives an example of the challenge of negotiating new rules in the context of 100 years of history and the evolution of water governance in the CRB. Our findings that approaches 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 and Lubell, 2018; Olivier et al., 2020; Vano et al., 2014; York et al., 2020).

Over the last century, change has occurred, but we found that the path dependency of institutions has played a role in the magnitude of change to water management. The persistence of original decisions is evidence that path dependency has shaped how water governance has changed. Other studies of path dependency and water policy have similar findings (Anderson et al., 2018; Ingram and Fraser, 2017; Marshall and Alexandra, 2016). Although we observed the addition of operational and collective choice rules throughout the period, observation rules are more prevalent (Figures 3a,b). This indicates that rulemaking has focused on operations but that some shifts in the way decisions are made have been made throughout the past 100 years.

We observe only one additional constitutional level rule after the CRC indicating that the processes for selecting decision-makers are informal, and/or constitutional level rules are not captured within our selection criteria scope.

Despite struggles with water overallocation since the early 1920s (Hundley, 2009; Kuhn and Fleck, 2019), there are few supply rules (Figure 3c), demonstrating how early allocation agreements endure even with changes over time. Water use rules are present in every document (Figure 3b). This may be because the pre-1920s doctrine of prior appropriation and the 1922 CRC set rules in alignment with the doctrine for beneficial use. These findings are in agreement with other study findings that water management in the CRB is path dependent and that rules have been shaped by early rules, particularly ones set via the 1922 CRC (Heinmiller, 2009; Loos et al., 2022; Turley, 2021). As a case in point, the overallocation since the inception of the 1922 CRC has not been addressed in the rules-in-form within the Law of the River documents.

TABLE 3 Rule issuers and targets by governance level with rule count totals.

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

As the challenges facing the CRB have evolved over the last century, so too has water governance and the structure of the actor network. Over time, actors across institutional levels and types of water management were added (Figures 4a–d). Overall, the central network structure remained stable without actor replacement or removal, only additions. As the actor network grew, the distribution of authority changed from a few central actors to many actors in the current large and complex network. Network growth is due in part to the mid-1990s and 2014 to 2018 expansion of criteria for actors formally included in the decision-making for natural and human uses of Colorado River water. Changes in the network reflect changing values as more attention was paid to diversity, equity, and inclusion as evidenced by the addition of new actors (Mexico, IWBC, etc.). Such network additions support our hypothesis that over time authority has been distributed across a growing number of actors.

Our analysis found that the key decision-making positions remained the same. The actors who issue rules lack significant change over the last century (Tables 4, 5). 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). Consistent with existing literature (Berggren, 2018a), the findings support our hypothesis that path dependency has shaped how water governance evolves and who is able to influence decisions.

In contrast to Olivier and Schlager (2021), we 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 incentivized to maintain the system and there is less space for experimentation and innovation between the rules. Thus, our finding that water management responsibilities also remained stable over time aligns with and empirically contributes to the literature on institutions and path dependency (Kessy, 2018; Marshall and Alexandra, 2016; Wilson, 2014). Our findings are in agreeance with other cases that have found that water resource governance does not significantly evolve, change, and shift over time as they are shaped by the path dependence set by the original governance structure (Möck et al., 2022; Pahl-Wostl, 2015; Tchiel et al., 2019).

TABLE 4 Top 5 actors in-degree value per snapshot year.

1922		1948		1973		2019	
Actor	Value	Actor	Value	Actor	Value	Actor	Value
CRB	4	US	13	US	17	US	19
BS	3	MX	9	MX	9	Contractors	15
USBR	1	CRB	7	CRB	8	USBR	14
USGS	1	BS	4	BS	6	BS	13
LB	1	MWD	4	LB	5	AZ	10

TABLE 5 Top 5 actors out-degree value per snapshot year.

1922		1948		1973		2019	
Actor	Value	Actor	Value	Actor	Value	Actor	Value
USBR	6	SOI	24	SOI	29	SOI	103
Congress	4	IBWC	22	IBWC	24	IBWC	24
		UCRC	9	Congress	11	Congress	11
		USBR	7	UCRC	9	UCRC	11
		UB	7	USBR	7	USBR	10

TABLE 6 Top 5 actors betweenness value per snapshot year.

1922	1948			1973		2019	
Actor	Value	Actor	Value	Actor	Value	Actor	Value
USBR	2	UB	17	UB	17	SOI	23
		USBR	14	USBR	12.2	UB	11.7
				SOI	10.8	LB	7.1
						UCRC	5.6
						USBR	4.5

Although the network has evolved with the addition of rules and actors and an increase in the number of connections between actors (Table 3 and Figures 4a–d), issues recur as there has been no major structural change or reform of 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 and Crona, 2009; Das et al., 2019). Due to the lack of major alteration, the water governance structure has not kept pace with an increasingly changing climate in the Anthropocene and is unable to respond sufficiently. Further, the current system for water governance does not fully address the context in which the CRB is operating, and management rules have not kept pace with the changing water system. Our case history details changing priorities and the increasing challenge of water scarcity. An improved understanding of current CRB governance and how it has evolved can help provide insight to inform the redesign of operating rules and fill the knowledge gap of how we have arrived at the critical water situation we are in today.

Our study is novel because we surpass 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 (Table 1) (Ingram et al., 1984; Wescoat, 2023). Additionally, our study goes beyond other institutional studies of the CRB 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, 2018b; Karambelkar, 2018; Sullivan et al., 2019; Turley et al., 2022).

It is important to note that other variables not examined in this study may influence the findings. For example, informal stakeholder groups referred to as shadow networks by Wutich et al. (2020) may influence decision-making via informal drivers and factors (e.g., unplanned interactions, social influence, social norms) and impact how decisions are made regarding resource management. Our study is limited as we only cover changes to water management strategies and responsibilities based on formal rules across high institutional levels. Informal rules and norms are not included in the data set or analysis, as a result, our study could be missing changes to water management influenced by informal rules across lower institutional levels. Thus, the full story of the deficiency of past water management and incremental changes amidst rapid climatic change has not been captured. To fill this gap, other studies could be conducted to understand how path dependency, adaptations, and informal rules have and have not contributed to sustainable water management in the CRB. Identifying the shortcomings of historic and legacy water governance may help inform more effective strategies for future adaptations.

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 we do not cover in this study but recognize as an important piece of the larger story of water in the West. To improve the understanding of how the CRB water system evolved, future analysis should take the larger history into account, especially with our increased understanding of the importance of Tribal perspectives and input.

Taken together the institutional analysis, social network analysis, and case history indicate a tension between path dependency, a changing environment, and shifting values. Through examining the case history we found that CRB water management has 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. The institutional analysis empirically demonstrates the path dependency of institutions over the century-long, and ongoing, water governance regime. We contribute to understanding the evolution of water governance in the CRB with our analysis where we found a layering of new rules without the removal of existing rules and an expanding network of actors over the last century. Expansion of the network demonstrates a shift in values to be more inclusive of actors within the water governance network. To build upon this scholarship, factors that may shape and influence decision-making, such as informal rules and norms as well as shadow networks, should be studied to help tell the larger story of how water governance has evolved in the CRB over time. Future research could apply our approach to other basins with histories of water policy and conduct cross-case comparisons with our study as well as existing studies to add to water governance knowledge and literature.

Data availability statement

The original contributions presented in the study are publicly available. This data can be found here: https://www.usbr.gov/lc/region/pao/lawofrvr.html.

Author contributions

KL: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. MG: Conceptualization, Funding acquisition, Project administration, Writing – review & editing. DW: Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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