frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 04 October 2022
DOI 10.3389/fenvs.2022.958597



OPEN ACCESS

EDITED BY
Giangiacomo Bravo,
Linnaeus University, Sweden

REVIEWED BY
Abigail Sullivan,
Boston University, United States
Anders Forsman,
Linnaeus University, Sweden
Saba Siddiki,
Syracuse University, United States

*CORRESPONDENCE
Jonathon R. Loos,
jonathon.loos@gmail.com

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management,
a section of the journal Frontiers in Environmental Science

RECEIVED 31 May 2022
ACCEPTED 30 August 2022
PUBLISHED 04 October 2022

CITATION
Loos JR, Andersson K, Bulger S, Cody KC, Cox M, Gebben A and Smith SM (2022), Individual to collective adaptation through incremental change in Colorado groundwater governance. *Front. Environ. Sci.* 10:958597.
doi: 10.3389/fenvs.2022.958597



# Individual to collective adaptation through incremental change in Colorado groundwater governance

Jonathon R. Loos[1]*, Krister Andersson[2], Shauna Bulger[1], Kelsey C. Cody[3], Michael Cox[1], Alexander Gebben[4] and Steven M. Smith[4]

[1]Department of Environmental Studies, Dartmouth College, Hanover, NH, United States, [2]Institute of Behavioral Science, University of Colorado, Boulder, CO, United States, [3]Earth and Space Sciences Department, Santa Rosa Junior College, Santa Rosa, CA, United States, [4]Department of Economics and Business, Colorado School of Mines, Golden, CO, United States

Designing adaptive institutions for achieving sustainable groundwater use is a central challenge to local and state governments. This challenge is exacerbated by the growing impacts and uncertainty of climate change on water resources. Calls to reform water governance systems are often made in the context of these challenges, and reform efforts increasingly emphasize the need for solutions that are locally designed and administered. Such reforms often require fundamental institutional change that is difficult to achieve amid the myriad forces that stabilize and reproduce existing institutional structures and functions. In practice, governance change is instead overwhelmingly incremental and tends to be punctuated by periods of adjustment in response to social or environmental shocks and disturbances. We present a comparative study of four major Colorado river basins and examine how each has evolved distinct arrangements of groundwater governance in response to regulatory and drought disturbances over the past century. We interrogate concepts of path-dependence and apply a historical lens to understand why locally designed institutions for self-regulation emerge in some Colorado groundwater basins but not in others. We uncover a pattern of collective action by groundwater users that first seeks to oppose state regulation, followed by acceptance and efforts to comply, and eventual attempts to get ahead of state regulation by enacting local institutions for self-regulation. We report these findings and discuss the insights they offer for understanding how adaptive natural resources institutions are shaped through time by the constraints and opportunities of path-dependence and local contexts.

KEYWORDS

**institutions, adaptation, governance, groundwater, path-dependence**

## Introduction

Irrigation is responsible for forty-four percent of freshwater use in the United States, 80 percent of which occurs in semi-arid western states (Dieter et al., 2018). Watersheds in the western U.S. are sustained by snowmelt fed streams and groundwater aquifers that are tightly coupled to fluctuations in annual precipitation. Rules governing the use of surface water in these basins emerged a century or more ago when knowledge of the hydrologic connection between surface and groundwater resources was limited or ignored (Jones and Cech 2020). In many states, such as Colorado, this led to rapid expansion of groundwater use even where surface waters were fully appropriated. Today surface and groundwater resources are overallocated in many watersheds and water scarcity has become an existential threat to many communities (Taylor et al., 2013; Megdal et al., 2017; Cody, 2019). Policy interventions for attaining sustainable water use exist along a gradient from top-down, state-imposed regulatory structures to locally designed arrangements that enact self-regulation among water users (Moelle and Closas 2019a). Rational choice institutional theory and studies of common pool resource governance suggest that institutions designed and implemented by water users themselves are likely to achieve better congruence with local social and environmental conditions than are top-down regulations alone, often achieving higher levels of compliance, equity, and self-sustained outcomes (Ostrom, 1990; Agrawal, 2001). However, supplying local institutions requires users to act collectively and is quite challenging and costly to achieve amid common pool resources (Ayres et al., 2018).

Water resources operate in dynamic and diffuse ways across landscapes that often encompass numerous user groups and levels of government. Central government authorities are often envisioned as having an important role in overcoming the challenge of scale and facilitating watershed-scale governance through centralized regulatory structures that set technical standards, collect and dispense knowledge, and monitor and sanction users to maintain water quality and quantity across a watershed (Lankford and Hepworth 2010). In practice, however, water governance is likely to reflect a mix of state-driven and locally-defined institutions, as articulated by a broad body of work on polycentric governance and co-management (Molle and Closas 2019b; Ostrom 2009; Pahl-Wostl and Knieper 2014). While this institutional layering may improve the capacity of governments to confront complex problems, the process of institutionalization is usually highly stabilizing. Over time, path-dependence and self-reinforcing mechanisms may generate institutional inertia and result in institutions that are highly resistant to change (Pierson 2000; Beyer 2010). These system properties are desirable for creating the necessary certainty to secure long-term commitments from stakeholders but come at the loss of plasticity needed to respond and adapt to exogenous shocks and shifting socio-ecological conditions (Barnett et al., 2015). This creates a problem where longstanding institutions must grapple with fundamental changes to the resource systems they govern (Kates et al., 2012). For instance, facing a starkly more arid climate than in the Eastern U.S. the prior appropriation doctrine emerged though a bottom-up process in the arid West that was eventually codified to promote agricultural development (Leonard & Libecap 2019). The doctrine has governed surface waters of Colorado since 1876, but was forced to reconcile with widespread groundwater use that fundamentally challenged systems of surface water appropriation a century later. Hydroclimatic change poses a similarly vexing challenge to water governance institutions that are designed to resist fundamental change (Libecap, 2011).

Governmental failures to halt the depletion of groundwater commons are often attributed to a lack of administrative capacity or political willingness to enact necessary groundwater regulations. However, as Molle and Closas (2019b) remind us, "groundwater governance is thick with politics" that play out among actors, organizations, and communities with various and overlapping identities, interests, and levels of power. These highly granular dimensions of groundwater politics are largely illegible to complex state governments and this is likely to play a role in the failure of many government interventions (Molle and Closas 2019b). In response to the shortcomings of state governments there is growing interest in the critical role of local institutions in achieving adaptive water governance amid complex multilevel governance systems (Sharma-Wallace et al., 2018; Garcia et al., 2019). Empowering water users to self-regulate has been proposed as a tricky but promising solution to the groundwater commons challenge (Rouillard et al., 2021). Self-regulation, or self-governance, is envisioned as the devolution of allocation, monitoring, and policing responsibilities to groundwater user groups, but where central governmental authorities retain power to mediate conflicts or impose more stringent regulations as needed. Self-governance within groundwater commons requires collective action that is difficult to initiate where it has not historically existed, even when prompted by state governments (Cody 2019; Perez-Quesada and Hendricks 2021). Even with the many "carrots" of self-governance in sight, developing new self-governance arrangements under the weight of long-standing institutions (e.g. prior appropriation) is a challenging endeavor and likely to follow a complex evolutionary path that is not empirically documented in many contexts.

Institutions and policy tend to change incrementally over time as periods of stability punctuated by windows of abrupt change (Boushey 2012). Policy shifts can occur in response to new problems, adjustments to power constellations among actors and organizations, alterations in dominant discourses, or changes to resource systems (North 1990; Arts et al., 2006). Bursts of large or rapid change may occur in response to acute shocks, such as drought, which has shown to be an effective

10.3389/fenvs.2022.958597

catalyst for water policy change in semi-arid agricultural regions (Berbel and Esteban 2019). Even when motivated by highly salient water scarcity pressures, the feasibility of fundamental or transformative change within water governance is constrained by the events of the past. Path dependence dynamics emerge as institutions become stabilized by mechanisms of increasing returns and self-reinforcing processes that narrow the scope of possible future decisions (Pierson 2000; Beyer 2010). In water governance systems these dynamics emerge through complementary configurations of water users, organizations, policies, and infrastructure that become embedded across multiple levels of society and install high costs for change (Geels and Kemp 2007). Path dependence effects are theorized to be particularly influential within long-lived common pool resource systems facing pressure to change (Heinmiller 2009). While path-dependence may constrain the range of possible change it does not prohibit it. A framework for analyzing path dependent institutional change within the context of groundwater commons was developed by Cody (2019) to examine the emergence of self-regulation among irrigators in Colorado's San Luis Valley. The occurrence of self-regulation within the San Luis Valley was lauded as a remarkable success that reduced water use by a third and offers a possible model for other groundwater commons to achieve sustainable groundwater appropriation (Smith et al., 2017). Self-regulation among groundwater users was found to have propagated through a series of social and institutional conditioning factors over time (e.g. techno-institutional complementarities, broader governance arrangements), and ultimately enacted in response to a severe drought (Cody 2019). A path-dependence analytical framework provides a macro-level perspective of the series of social and environmental shocks and institutional responses that prompted collective action and generated unique governance arrangements among irrigators in the San Luis Valley.

In this paper, we expand upon the work of Cody (2019) to consider four economically significant groundwater basins in Colorado to understand how each has developed unique local arrangements of groundwater governance.

Our analysis is focused upon four Colorado river basins on the eastern side of the continental divide: the South Platte Basin (SPB), Republican River Basin (RRB), Arkansas Basin (AKB), and Rio Grande Basin (RGB). Each basin includes fully appropriated surface water and groundwater that support significant production agriculture and have varying degrees of urbanization. Embedded in the same state governance and facing similar shocks, we focus on local attributes and histories to try and understand what led to distinct responses among stakeholders. Our analysis is temporally bound beginning with a severe statewide drought in the 1950s that prompted expanded groundwater use, which continues to the present.

Just as groundwater governance is thick with politics, it is also thick with history. Comparative historical studies of common-pool resource governance often examine the past to explain the nature of local institutions at a snapshot in time using theories predictive of successful common property regimes (Johnson 2004). Achieving an appropriate methodological balance between building contextual specificity and universal theorizing requires a pragmatic empirical approach, as discussed by Johnson (2004), and a careful consideration of history. We attempt to achieve this balance by centering our research framework around a close attention to history within each basin. We build depth into our understanding of how the evolution of groundwater governance in each basin has been mediated by both basin-specific events and characteristics, and the statewide regulatory landscape. We view institutional change as a mixed formal-informal process of bricolage, whereby long-standing local institutions (both formal and informal) are incrementally adjusted over time by actors and organizations to conserve what works and amend what does not (Merrey and Cook 2012). This framing helps reveal how institutional arrangements are deeply embedded within local socio-ecological context but also entangled with the actions of higher-level governments.

## Study systems

The surface waters of Colorado have been governed by principles of Prior Appropriation since the mid-19th century. Prior appropriation is often referred to as "first in use, first in right," and operates by assigning water rights in the order in which water was first appropriated for a beneficial use in a watershed. Senior water rights are those that were first allocated in the basin and must be fulfilled prior to junior rights during times of shortage. Each water right is transferable within a basin. The system of Prior Appropriation was initially established to govern the use of Colorado's surface waters at the time of state formation in 1876. Prior Appropriation was amended to include groundwater in 1969 following the expansion and overextraction of groundwater and subsequent injury to senior surface water users and failure to meet surface flow deliveries to several downstream states required by interstate river compacts. The state has since sought to reign-in groundwater appropriation to sustainable levels that protect senior surface water users and uphold interstate compact obligations. The nature of surface-groundwater dynamics–both hydrologically and socially – varies across Colorado's river basins as does the historical, cultural, political, and economic context of each basin. Irrigators in each basin often hold multiple positions, using both surface water and groundwater at different times, and holding rights senior to some users but junior to others. This prohibits a one size fits all approach to achieving sustainable groundwater governance across the state. A brief summary of the four study basins follows.

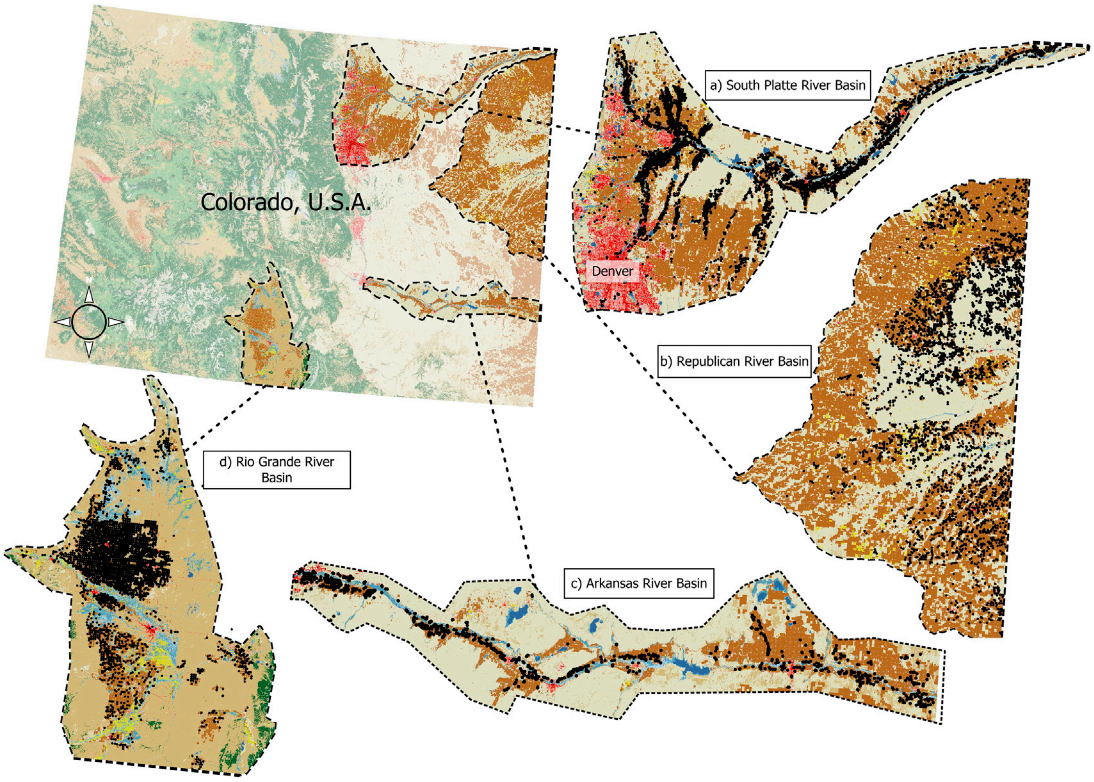


FIGURE 1
A map of the four study basins across Colorado, U.S.A. Black dots indicate the distribution of active groundwater wells across each basin as of 2015. Each basin has been enlarged to show detail and are not to scale with one another.

The South Platte River flows from the Rocky Mountains east through the Front Range and High Plains regions covering 22,00 square miles that are home to 85% of Colorado's population and its largest urban centers and economic production zones (Figure 1A). South Platte surface flows supply an average of 1.4 million acre-feet of water annually that are supplemented by about 400,000 acre-feet of imported (transmountain) water from the west side of the Rocky Mountains. Annual surface water diversions total around 4 million acre-feet, and the basin's alluvial aquifer supports around 500,000 acre-feet of groundwater withdrawals annually. The South Platte basin (SPB) supports the greatest value of agricultural production and the highest concentration of agricultural lands with 810,000 irrigated acres that receive 76% of the basin's water diversions. Agricultural production and irrigated acreage has begun to shrink in the SPB due to urbanization and population growth which puts high demand on limited water resources. The South Platte River Compact requires Colorado to supply a minimum flow of water to the neighboring state of Nebraska since 1922.

The Republican River Basin (RRB) is located in Colorado's Northern High Plains and flows east into Kansas and Nebraska (Figure 1B). It supports an estimated 600,000 acres of irrigated land and produces billions of dollars in agricultural revenue each year. The RRB is home to 92,000 Coloradans distributed across small towns and rural communities. Agriculture is the largest industry in the RRB and is largely dependent on groundwater because surface waters are confined by narrow valleys that are challenging to appropriate. The RRB is nested within the SPB and overlays a large portion of the Ogallala Aquifer. The Republican River compact requires Colorado to supply a minimum flow of water to the neighboring state of Nebraska since 1943.

The Arkansas River basin (AKB) flows from the Rocky Mountains east to the Great Plains and drains over 28,000 square miles making it the largest river basin in Colorado (Figure 1C). The AKB has the third largest agricultural water demand in the state with 428,000 irrigated acres, and includes the urban areas of Colorado Springs and Pueblo in the upper and middle reaches of the basin. This study focuses on the Lower Arkansas Valley where most of the basin's irrigated agriculture occurs in the drainage area below the City of Pueblo. Groundwater use is predominantly comprised of alluvial aquifers along the stream. The Arkansas River Compact requires Colorado to supply a minimum flow of water to the neighboring state of Kansas since 1949.

The Rio Grande basin (RGB) flows from the San Juan mountains and through the San Luis Valley in south-central Colorado (Figure 1D). The RGB covers about 8,000 square miles that are home to 50,000 people and supports a vibrant agricultural community in a high mountain desert. The RGB is supplied by surface flows and supports Colorado's largest wetland ecosystem. The RGB also encompasses two aquifers, one that is connected to surface waters and a confined aquifer that does not contribute to surface flows of the River. Surface flows and groundwater withdrawals together support around 515,000 irrigated acres in the RGB. The Rio Grande River Compact requires Colorado to supply a minimum base flow of water to downstream states of New Mexico and Texas since 1938.

## Materials and methods

Our comparative study methods are threefold. First, we constructed a timeline of events in each study basin from the 1950s to the present time, focusing on events that affected the appropriation of groundwater or the administration of water regulation in the basin (e.g. droughts, new regulations). Our theoretical approach is drawn from Cody (2019), which employed a framework for evaluating path-dependence of institutional change by constructing sequences of disturbance-response events within common pool resource systems across time and examining the factors and feedbacks that condition how resource users behave. Using this framework, we traced the biophysical and social disturbance events in each basin from the 1950s to present time (e.g. drought, water transfers, new policies). Within those timelines we tracked how local users responded to each disturbance event and categorized each as individual or collective level responses. This approach allows us to study where and when groundwater users act collectively in ways that lead toward or away from self-governance arrangements over time in a path-dependent manner. We consider the influence of several basin variables and institutional conditioning factors to explain the resulting patterns in actor behavior.

We hypothesize that several attributes of groundwater user communities and resource systems are influential in convincing groundwater users to forgo maximizing their individual interests in support of collective interests. We expect that groundwater users are more likely to agree to collective action in basins where groundwater is perceived to be scarce, users tend to live in common communities, users know and trust one another, users have strong knowledge of groundwater dynamics, users are highly dependent on groundwater resources, and where local users have experience working together to defend their interests. These concepts are grounded within common-pool resource governance theory and informed by recent empirical work within Colorado river basins (MacIlroy and Holm 2021; Ostrom 1990). We developed a set of variables to assess these factors within our study basins. They include; the salience of water scarcity, the spatial distribution of groundwater users, social capital among users, knowledge of watershed dynamics, user dependence on groundwater, and former experience in defending local interests. These variables are described in Table 1 and were evaluated using archival data and interviews. Categorical rankings were developed and described for each variable to convey high and low levels of each and to make them comparable across basins (Table 1).

Whether users ultimately achieve collective outcomes in response to disturbance events is influenced by a set of institutional conditioning factors. We adopt those conditioning factors from Cody (2019) and they include; transaction costs, techno-institutional complementarities, vested interests, broader governance arrangements, and relative prices. These factors condition the direct and indirect costs, politics, and ease of altering water appropriation practices, enacting new agreements, and ultimately developing local self-governance institutions. These variables are grounded within institutional economic and path dependence theory developed in part by North (1990) and operationalized by Heinmiller (2009). We observed and documented these conditioning factors at work within each basin and analyzed how they interacted with community attributes and basin biophysical variables to influence water user behavior in our disturbance-response timelines for each basin.

Disturbance-response patterns were constructed using public records and archival data that included legal briefs and court cases, hydrologic and climatic data, water rights and well-administration records, crop and agricultural production data, demographic and census data, and watershed management reports from across the study period. These sources were reviewed to collect information on the development of surface and groundwater commons, socioeconomic and market conditions, changes in policy and governance, the occurrence of droughts, the behavior of water users, and the evolution of the discourse and management surrounding water in each study basin. These datasets were used to construct a timeline of the appropriation and regulation of groundwater in each basin across the study period.

Our data collection also included interviews with key-informants in each basin that were identified as actors with professional roles and responsibilities in the administration of groundwater regulations or with significant involvement in the appropriation of water resources individually or through organizational affiliation. A similar set of actors were sought out for each basin and included; state agency personnel, managers from water conservation districts, managers of groundwater user associations, and other individuals demonstrating high levels of engagement with groundwater

TABLE 1 We hypothesize that several attributes of groundwater user communities and resource systems are influential in convincing irrigators to respond to disturbances collectively instead of individually. Variables are evaluated using multiple data sources and interviews, and described for each basin during the 1970s when Colorado began to efforts to regulate groundwater use.

| | Salience of Resource Scarcity | Spatial Distribution of Users | Former Experience in Defending local interests | Knowledge of Resource Dynamics | Social Capital Among Users | Dependence on Groundwater |
|---|---|---|---|---|---|---|
| **Description** | Awareness of resource scarcity elevates collective threats and influences consensus on problems and solutions. | Proximity of users to one another influences perceptions of the commons, community cohesion, and collective interests. | Previous experiences may prime users and local institutions for coordination and engagement to defend local interests, reduce transaction costs. | Knowedge of surface-groundwater dynamics reduces uncertainty and conflict and informs effective solutions. | Strength of relationships among users and regulatory actors influences trust and quality of communication among stakeholders and may prime for local solutions. | Dependence on groundwater relates to the strength of vested interests in continued groundwater access, may incentivize self-governance. |
| **South Platte (SPB)** | Moderate - over appropriated basin, competition with municipal users, sensitive to drought | Clustered | **Low** - powerful vested interests in front range region secured water imports, primary water conflict between surface and groundwater users | **High** - first litigation charging injury to surface water from well pumping in 1893 | **Moderate** - complex canal and reservoir networks connnect up and downstream users, conservation district convened 1969 | **Low** - many surface reservoirs and transbasin diversions, many irrigators have access to surface and groundwater |
| **Republican (RRB)** | Low - limited surface water availability | Diffuse | **Low** - few water conflicts prior to 1990s. | **Low** - groundwater basin established in 1970s, connection to surface water and downstream states unclear until 1990s. | **Low** - small communities are widely dispersed, low trust of state agencies | **High** - no surface reservoirs or transbasin diversions, most irrigators dependent on wells |
| **Arkansas (AKB)** | High - over appropriated basin, interstate compact, water export threats, competition with municipal users, sensitive to drought | Clustered | **High** - history of fighting water export threats, groundwater user associations formed early in response to interstate compact litigation | **Moderate** - early well expansion and alluvial nature of the basin developed informal understanding of groundwater dynamics | **Moderate** - complex canal and reservoir networks connnect up and downstream users | **Low** - moderate surface reservoirs, threat of transbasin diversions, many irrigators have access to surface and groundwater |
| **Rio Grande (RGB)** | High- over appropriated basin, interstate compact, water export threats, sensitive to drought | Dense | **Moderate** - interstate compact litigation in 1966 prompted formation of the RGB conservation district | **High** - interstate compact litigation in 1966 due to well-pumping led to scrutiny of groundwater-surface water connection | **High** - cohesive farming community with shared interests in groundwater use, early formation of conservation district enhanced social capital development | **High** - few surface reservoirs, threat of transbasin diversions, most irrigators dependent on wells, interstate compact enforcement |

topics in a basin, in addition to statewide government actors. Sixteen interviews were completed in total involving at least three actors from each basin and several actors involved with governance of one or more basins. Interview questions sought to characterize community and basin variables, understand institutional conditioning factors, explore emergent patterns in each basin, and probe dimensions of our research questions broadly. We used a subset of standard questions for all interviews while other questions were tailored to prompt elaboration or fill specific empirical gaps. Interviews were transcribed and coded for content analysis across five themes; basin and resource variables, community attributes, collective action, groundwater use, regulatory compliance efforts, and non-regulatory adaptation efforts. Statements in each interview were tagged with one or more codes indicating the content or implication of the statement for our analysis, we used 23 unique codes across the five thematic areas. We analyzed interview data by organizing statements by theme, by basin, or by examining the co-occurrence of codes. Interview data was considered together with other datasets to construct disturbance-response timelines and to interpret the influence of basin variables and institutional conditioning factors in each basin.

## Results

We report our results in the following section, beginning with each basin's response to the 1950s drought. Disturbance response timelines for each basin are presented in Figures 1–4. Colorado

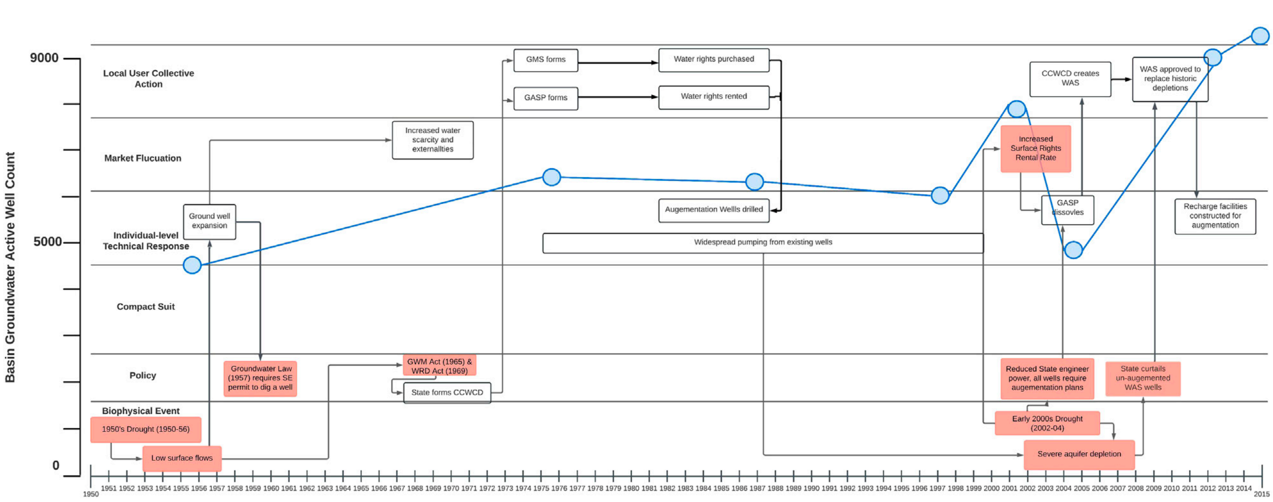


**FIGURE 2**
A historical timeline of disturbance and response event sequences affecting groundwater appropriation in the South Platte Basin from the 1950s to present, with the estimated number of active high-capacity groundwater wells depicted through time on the *y*-axis. Groundwater well data is estimated based on Colorado state records.

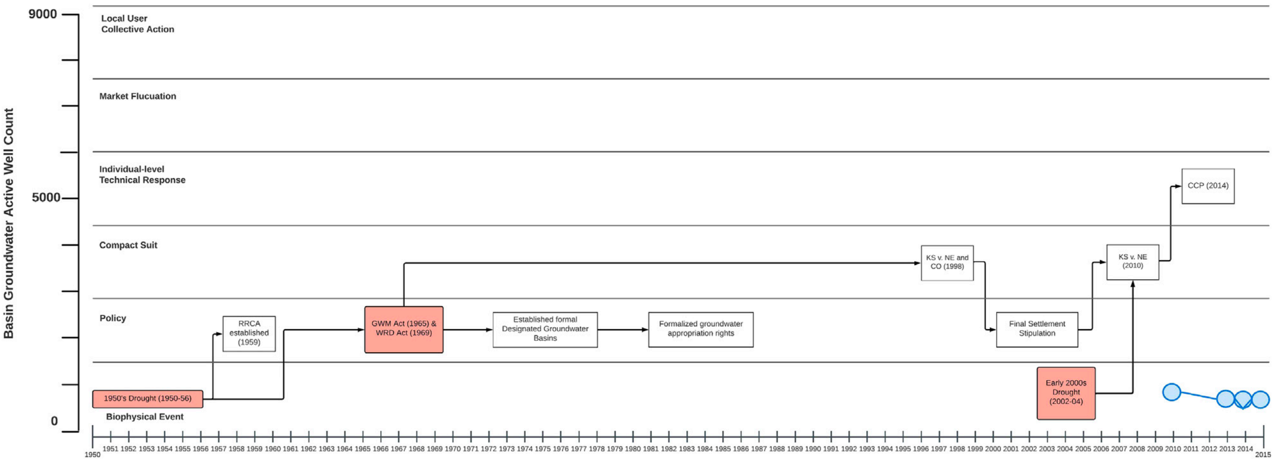


**FIGURE 3**
A historical timeline of disturbance and response event sequences affecting groundwater appropriation in the Republican River Basin from the 1950s to present, with the estimated number of active high-capacity groundwater wells depicted through time on the *y*-axis. Groundwater well data is estimated based on Colorado state records.

irrigators began supplementing their water supplies with groundwater by the turn of the 20th century. Early groundwater use was relegated to irrigators who could reach shallow aquifers and who had the capacity to construct wells. Court rulings in 1893 deemed groundwater extraction to not be a threat to senior surface water rights and groundwater use continued without formal regulation (Cech, 2010). A series of significant statewide droughts in the 1930s and again in the 1950s rattled water users across the state and exposed the uncertainty and scarcity of surface water supplies being used to support growing farming economies and communities. In contrast to surface water, groundwater became increasingly accessible through new drilling technology and offered a convenient and on-demand source of irrigation water. Groundwater well construction and pumping grew at a rapid pace in response, putting into motion a century-long pathway of competition for

10.3389/fenvs.2022.958597

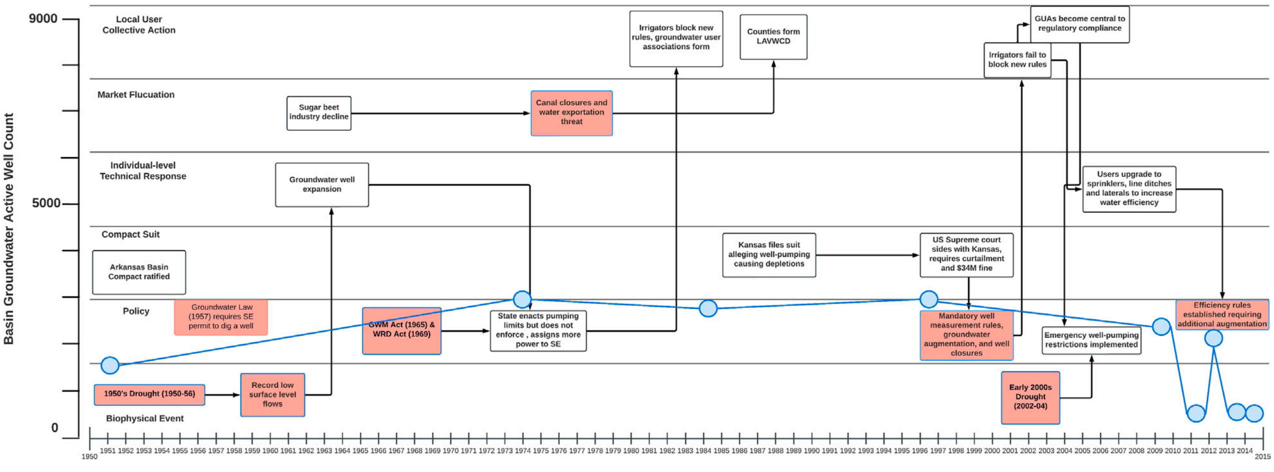


FIGURE 4
A historical timeline of disturbance and response event sequences affecting groundwater appropriation in the Arkansas River Basin from the 1950s to present, with the estimated number of active high-capacity groundwater wells depicted through time on the *y*-axis. Groundwater well data is estimated based on Colorado state records.

limited water and attempts to reconcile groundwater use with Colorado's system of prior appropriation.

## 1950s: drought

The South Platte Basin saw the earliest expansion of groundwater wells and irrigation. At least 1,200 new wells were drilled in the Basin during the early 1950s drought and groundwater extraction began to far exceed surface water recharge rates. The basin already had a complex network of reservoirs and diversions to support surface water supply to farmers and cities. An increase in wells and decreasing marginal pumping costs coupled with an uptake of new groundwater-dependent sprinkler technology shifted the ratio of irrigation away from surface water towards a greater dependence on groundwater. Groundwater In concert with these shifts was a conversion of agricultural land to support Denver's urban growth that led to an overall reduction in the number of surface water diversions in the Basin.

The Republican River Basin had little surface water use and limited groundwater well access by the 1950s drought and agriculture communities felt immense strain. The Basin's population declined while agriculture expanded during this time as new wells were drilled that could support irrigated farming in areas far from the river channel. Downstream water users began to feel the effects of groundwater pumping and as a result, Colorado, Kansas, and Nebraska formed the Republican River Compact Administration in 1959 to oversee the equitable distribution of water between states and mitigate future interstate conflicts.

Record low surface and groundwater levels in the Arkansas River Basin throughout the 1950s led to a decade-long decline in agricultural production. Even municipal drinking water sources were reportedly desperately low (Nace and Pluhowski, USGS 1965) and hundreds of new groundwater wells were constructed in response. Drought conditions coupled with national agricultural surpluses initiated the contraction of sugar beet farming in the Basin (Wiener et al., 2016), prompting the first major agriculture-to-urban water sale in 1955. Growing Front Range cities and declining sugar production shifted the relative price of surface water and made the Arkansas a target for inter-basin water purchases. Dependence on groundwater for irrigation grew in the ensuing years as surface flows were sold and groundwater remained largely unregulated.

Drought and severe water shortages led to the closure of one third of the farms in the Rio Grande Basin in the 1950s. Over 1,500 new groundwater wells were drilled by the irrigators that persisted, primarily among junior surface water right holders that sought to reduce their vulnerability to surface water scarcity. Expansion of groundwater access also enabled new irrigators without surface water rights to begin farming in the basin. Surface water in the Basin was already being targeted for out of basin transfers to by this time, adding additional pressure to increase dependence on groundwater in the basin.

The 1950s set the drought of record for all four Colorado basins and signaled that all surface water users were vulnerable during times of water scarcity. Irrigators across all four basins responded to the drought largely through individual technological responses that sought to reduce reliance on surface water by expanding access to

10.3389/fenvs.2022.958597

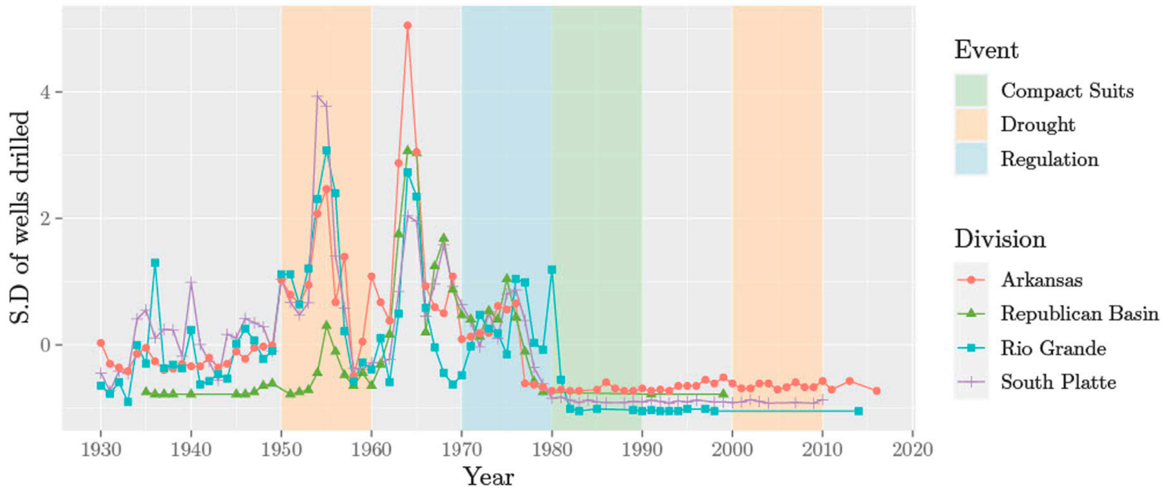


FIGURE 5
The number of new groundwater wells drilled per year in each basin across time for all four study basins. New wells are indicated on the $y$-axis using the standard deviation of new wells drilled per year in that basin to more clearly indicate relative annual change in new wells. Groundwater well data is estimated based on Colorado state records.

groundwater, especially among junior surface water right holders. Groundwater was perceived to be readily abundant and remained unregulated by the state, incentivizing the expansion of wells and growing reliance on groundwater among irrigators, especially as new pumping technology and complementary irrigation methods emerged (e.g. center pivot sprinkler systems) and more lands became accessible to irrigation.

## 1960s–70s: early attempts to regulate groundwater

The impact of rapidly increasing groundwater pumping in the 1950s and 60s was soon felt by surface water users across Colorado and in downstream states (Figure 5). Alarmed by injuries to senior surface water users and potential interstate water compact violations, the Colorado legislature passed two laws in 1969 to bring unrestrained groundwater pumping under control; the Groundwater Appropriation Act, and the Water Rights Administration and Determination Act. Together these acts required that groundwater be administered in accordance with the priority system of appropriation and set standards for administering well regulations, including requiring junior users to replace their groundwater depletions with "augmentation" water. Facing the threat of heavy-handed regulation by the State irrigators across Colorado began organizing into groundwater user associations. Groundwater user associations served as collective action organizations through which members could consolidate their power and resources to secure augmentation water or even push back against state regulation.

Two primary groundwater user associations emerged in the South Platte Basin (SPB) with differing organizational structure and strategies for securing augmentation water to support member pumping. One was formed as a private non-profit company (Groundwater Association of the South Platte, GASP) and the other organized as a subdistrict of the Central Colorado Water Conservation District (Groundwater Management Subdistrict, GMS), irrigators were free to join either. Both associations implemented volumetric pumping fees, or taxes, to fund the costs of leasing or purchasing augmentation water from other users in the basin. GASP utilized a low annual pumping fee to fund agreements with individual water owners to lease or borrow water each year. GMS implemented much higher pumping taxes to purchase augmentation water and construct infrastructure to store water year to year, this secured long-term commitments from GMS members whereas GASP membership fluctuated yearly. These arrangements worked to keep wells pumping and surface water users convinced that senior rights would be protected as the SPB went into its wettest period on record during the 1980s.

Statewide regulations were administered differently in the Republican River Basin (RRB) where groundwater was not yet established as being linked to surface flows and the latter are scarce. A modified version of prior appropriation was established that entitled senior wells priority water usage under conditions of shortage. The State also formalized the creation of Designated Basins within the RRB that are comanaged between farmers and local officials. DBs work within broader state governance arrangements to create their own rules of localized governance.

TABLE 2 Each post dummy is on or after the indicated year. Each break point was identified using the procedure of (Bai and Perron, 2003) minimizing BIC score. The control in each model is all years prior to the first break point.

| | | | Log Wells Drilled | | |
|---|---|---|---|---|---|
| | Rio Grande | | South Platte | | Arkansas |
| Year | 0.02 | | 0.006 | | 0.039*** |
| | −0.012 | | −0.011 | | −0.01 |
| Post 1949 | | | | | 0.099 |
| | | | | | -0.319 |
| Post 1956 | −0.261 | | | | |
| | −0.373 | | | | |
| Post 1957 | | | −0.057 | | |
| | | | −0.323 | | |
| Post 1968 | | | 0.093 | | |
| | | | −0.319 | | |
| Post 1976 | | | | | −1.181*** |
| | | | | | −0.327 |
| Post 1979 | | | | −3.779*** | |
| | | | −0.333 | | |
| Post 1981 | | −3.996*** | | | |
| | −0.38 | | | | |
| Post 1993 | | | | | −3.436*** |
| | | | | | −0.341 |
| Constant | −34.294 | | −6.097 | | −72.067*** |
| | −23.669 | | −21.167 | | −19.087 |
| N | 65 | | 76 | | 83 |
| R-squared | 0.795 | | 0.863 | | 0.791 |
| Adj. R-squared | 0.785 | | 0.855 | | 0.78 |
| Residual Std. Error | 0.740 (df = 61) | | 0.694 (df = 71) | | 0.723 (df = 78) |
| F Statistic | 78.993*** (df = 3; 61) | | 111.907*** (df = 4; 71) | | 73.719*** (df = 4; 78) |

***p < .01; **p < .05; *p < .1 Each Post dummy is one on or after the indicated year. Each break point was identfied using the procedure of Bai & Perron 2003 minimizing BIC score. The control in each model is all years prior to the first break point.

Groundwater levels in the Arkansas Basin (AKB) became depleted to the point that the state engineer deemed it necessary to enact further restrictions in the AKB. In addition to the new statewide regulations, the state curtailed pumping of groundwater wells in the AKB to 3 days per week. Groundwater users organized to successfully litigate and block the state's pumping restrictions, however. In response, the Colorado legislature assigned greater regulatory authority to the state engineer to enable curtailment of groundwater pumping in the future. Groundwater user associations gained membership in anticipation of future groundwater augmentation requirements. Meanwhile all six major sugar beet factories closed by 1979 prompting the closure of the AKB's largest supplying and most senior surface water ditch, the Rocky Ford Ditch.

Widespread groundwater use in the Rio Grande Basin (RGB) began to harm senior surface water users locally and in downstream states of New Mexico and Texas, leading to a compact violation suit against Colorado in 1966. In response the state created the Rio Grande Water Conservation District (RGWCD) to organize irrigators and defend local interests, Colorado then issued new rules regulating well use in the RGB. Groundwater users perceived the state's attempt to regulate groundwater as a threat to their interests and organized, through the RGWCD, to litigate against the state in 1975 to defeat further groundwater regulation. Interestingly, the state-formed RGWCD provided a forum for irrigators to develop relationships, organize information and resources, and act collectively to protect their interests and oppose state regulation. Their efforts were successful and in 1984 court verdicts protected existing well-users from regulation but barred any new wells. As Cody (2019) discuss, the influence of strong vested interests and reduced costs of organizing through the RGWCD empowered irrigators to protect status quo groundwater use in the RGB, enabling them to continue overexploiting groundwater resources whereas groundwater users in other Colorado basins were beginning to be reigned-in by the state.

Colorado's early efforts to regulate groundwater progressed differently across all four basins. Instead of responding individually to perturbation as in the past (e.g. by drilling wells), irrigators began to organize to protect their interests. Groundwater user associations (GUAs) emerged as organizations for irrigators to build relationships and leverage collective resources to resist regulation or seek out pathways to comply. Efforts to resist regulation were the most successful in the AKB and RGB where irrigators successfully blocked some well-pumping restrictions, and the RGB managed to avoid any state regulation of already existing groundwater wells. The influence of varying community and resource attributes on each basin's response to regulation becomes visible during this time (Table 1) resulting in distinct arrangements of water users, organizations, and coalitions of vested interests. This period marks the divergence of path dependencies among basins that would have long-term implications for the governance of each basin's groundwater commons (Table 2).

## 1980s–2000s: compact suits and another drought

Facing interstate compact violations in multiple basins and ongoing injury to senior surface water rights, largely due to groundwater extraction, the State of Colorado sought to further regulate groundwater appropriation. The State strengthened its groundwater regulation enforcement powers, imposed well measurement rules, and required all high-capacity wells (generally all irrigation, municipal, and industrial source wells) to submit augmentation plans demonstrating replacement water for current and future depletions in the time and place of use. Coinciding with this time was another severe statewide drought in the early 2000s that caused record low flows in numerous basins. In response to this drought the state passed the Colorado Water for the 21st Century Act to establish forums in each basin for water users, resource managers, experts, and public officials to regularly convene to discuss and encourage "locally driven collaborative solutions to water supply challenges" (Colorado House Bill 05-1177). These forums were called Basin Roundtables and were established in 2006, the RGB roundtable was the earliest to come online.

Stricter groundwater augmentation requirements had large consequences for groundwater users in the SPB. Senior surface water users faced severe water shortages in 2002 and pushed for greater scrutiny of groundwater pumping, eventually winning litigation that prompted stricter augmentation requirements for groundwater use in the basin. These policy changes coupled with drought sent the cost of augmentation water soaring and made the GASP model of annual augmentation agreements infeasible, prompting the organization to dissolve in 2006 (Waskom et al., 2014). Former GASP members were left without augmentation water plans and were prohibited from groundwater pumping; an estimated 1000 wells were shut-off in response. Changes in the legal landscape of groundwater appropriation sent the transaction costs involved in groundwater irrigation soaring. Irrigators could no longer join GUAs annually as needed, and even those irrigators enrolled in long-term GUA's faced rising costs of securing augmentation water. In 2009 CCWCD formed another user association (Well Augmentation Subdistrict, WAS) intended to provide membership for former GASP members in need of augmentation water to begin pumping again. However, all WAS members were prohibited from groundwater pumping until 2013 when augmentation plans could be approved and pumping was only allowed to proceed at limited capacity until historic depletions were resolved. Tightening regulatory requirements, large scale well curtailments, and increasing competition with municipalities prompted many irrigators to realize they "really didn't have the groundwater they thought they had for many decades" (SPB informant). High levels of expertise and creativity were needed for irrigators to meet new augmentation requirements as the SPB was moving towards a complex and tightly controlled system.

The RRB continued to face minimal pressure from surface water users, municipal water interests, and export threats, but it was tangled in an interstate water conflict with Kansas and Nebraska. A suit by Kansas in 1998 claimed that groundwater users in the RRB were overdrawing from waters protected by the interstate compact, although whether groundwater was under jurisdiction of the compact was still unclear. Under the Final Settlement Stipulation, the U.S. Supreme Court ruled that groundwater must be included in the appropriation agreements for the Republican River Compact among states, establishing that Colorado was out of compliance with compact obligations. In partnership with the Republican River Compact Association, the Colorado legislature also established the Republican River Water Conservation District in 2004 to develop strategies with basin stakeholders to reduce groundwater use. Meanwhile drought conditions from 2003–2006 further accentuated groundwater scarcity challenges. To work towards necessary pumping reductions, the water conservation district formulated a plan to purchase and retire 25,000 irrigated acres through voluntary agreements and to construct a pipeline to replenish surface flows at the Kansas state line. Unlike irrigators in other basins, RRB irrigators were widely dispersed across small communities making the costs of organizing high, even with the state formation of a water conservation district. Furthermore, groundwater had long been perceived as abundant among irrigators in the RRB, thus the motivation to organize to protect groundwater use remained lower among well-users than in other basins.

The 1980s in the AKB began with the closure of several major surface water ditches followed by the largest out of basin water sales, leading to a loss of 68,000 irrigated acres from the basin. In 1985 Kansas filed suit against Colorado for violating interstate compact terms due to excessive groundwater well pumping by AKB irrigators. Facing a loss in the Supreme

Court, Colorado required wells in the AKB be metered and monitored by the state, and strengthened the state's enforcement powers to fine irrigators that violated water rules and harmed the interstate compact or senior users. Well-users again attempted to block these new rules through the courts but this time failed. Facing compliance with stricter water augmentation requirements, irrigators became increasingly dependent on groundwater user associations to secure and finance sources of augmentation water. Feeling the strain of increased regulatory pressure on groundwater and the looming threat of further out of basin water transfers, AKB counties elected to create a water conservancy district with a mission to conserve and retain water within the basin to protect the future viability of AKB communities. During the extreme drought of the early 2000s groundwater pumping in the AKB was restricted to 60% of historical levels in 2002, and further reduced to 20% and then 0% in 2003. Curtailments were successful in avoiding harm to senior appropriators and demonstrated that groundwater user associations could effectively organize groundwater irrigators to comply with state regulations. Furthermore, these outcomes helped build consensus that well-metering was necessary to ensure equity in groundwater regulation. Unlike RGB irrigators, AKB well-users were unable to resist heavy-handed state regulation because they represented a small proportion of water users in the basin, the alluvial nature of the AKB made injury to surface waters highly salient, and there was tough competition with municipal users for groundwater.

RGB groundwater irrigators had thus far escaped state regulation and continued to maximize individual interests rather than work to protect collective interests in a sustainable aquifer. The 2000s drought rivaled the severity of the 1950s, kicking-off a decade-long period of record low flows and snowpack that led to a 41% reduction in irrigated acreage compared to 1997 levels (Cody 2019). In 2006 the RGB Basin Roundtable was established and leveraged the most state funding to support roundtable activities, soon becoming a place for irrigators to build relationships and trust, share information, and build a collective understanding of groundwater overexploitation. Drought and unregulated pumping had taken a severe toll on groundwater resources and reduced aquifer levels by 1 million acre-feet by the mid-2000s; groundwater scarcity suddenly became highly salient in the RGB (Cody 2019). Irrigators began organizing to identify a local solution, and in 2006 they formed a Special Groundwater District through a ballot measure that gained 60% approval of irrigators in the Subdistrict and was approved by the Courts. The Subdistrict included 671 irrigators and over 3000 wells and was established to design and implement a water management plan, alternative to regulations imposed by the state engineer, that would recover and maintain groundwater levels in the unconfined aquifer, protect senior surface water users, and avoid interference with Colorado's obligations under the Rio Grande Compact (Paddock 2020). The Subdistrict designed a system of self-regulation using market-based tools to incentivize reduced groundwater use by compensating farmers to fallow or retire land and installed a per-acre pumping fee on groundwater usage beyond their sustainable allotment (i.e. an over-pumping fee). The plan was approved in 2012 and the following year saw a 30% reduction in overall groundwater pumping within the Subdistrict (Smith et al., 2017). Cody (2019) attributes the emergence of Subdistrict 1's effort to self-regulate groundwater to numerous factors including strong vested interests in long-term viability of groundwater irrigation, broader governance arrangements (e.g. Basin Roundtable, federal programs to subsidize fallowed lands), and reduced transaction costs from high levels of social capital, communication, local leadership, and salience of resource dynamics and scarcity within a well-defined aquifer.

The 2000s drought was a shock to all four basins that revealed how each was progressing along distinct regulatory pathways mediated by local context and unique arrangements of water users and organizations.

## Current arrangements

Today groundwater in Colorado is understood to be a finite resource with varying levels of connection to surface water, and groundwater users in most basins have been brought into systems of prior appropriation. Complex systems of water sharing and coordination among farmers, municipalities, and commercial users have emerged to supply augmentation water and keep non-senior users in business. Groundwater usage is measured and generates highly detailed knowledge of surface and groundwater dynamics that supports monitoring but also empowers groundwater users with data on their own water usage. Groundwater scarcity and state government regulation have molded varying arrangements that fall along a spectrum from top-down regulatory interventions to bottom-up efforts to self-govern groundwater use. These variations are conditioned by unique socio-ecological and historical contexts in each basin and generated through path-dependent institutional evolution. Here we report those current arrangements in each basin and discuss the variables that conditioned them.

In the SPB a sense of equilibrium has emerged that encourages users to coordinate their water use while regulatory requirements protect senior rights and recover historic groundwater depletions. "Wells operate as insurance against drought," described one informant, so that surface users may lean on wells during times of scarcity and those without surface water are intimately tied to the hydrologic cycle. Instead of just pumping more individually, as they historically did, well-users must make up for any depletions they cause to senior users. Well-curtailments in the 2000s prompted a loss of many irrigators that were solely dependent on groundwater, and remaining irrigators were nudged towards acting collectively to form new augmentation groups. Informants described this as a time of experimentation by well-owners to find a path forward to continue operating. Farmers worked closely with technical experts and legal professional to form organizations and secure augmentation plans approved by the state. Today groundwater allocations are scaled by irrigator dependence on groundwater, and water users are described as highly dependent on each other. For instance, the basin's largest groundwater user association relies on effluent water from multiple municipalities to support its members' augmentation plans. This emergent network of water users and water sharing relies on high levels of data, high levels of communication and coordination, and imparts high transaction costs because of the diversity of water users involved and strong competition with non-agricultural water uses. Purely bottom-up efforts to self-govern groundwater use were unable to emerge here without the cohesion and trust that comes from smaller groups of more homogenous irrigators, as in the RGB, especially with high-value alternative water users available to purchase water.

The history of groundwater appropriation in the RRB is abbreviated compared to other Colorado basins and marked by much different aquifer resource dynamics. Operating in a designated groundwater basin, groundwater users have groundwater rights in the fashion of the prior appropriation doctrine. RRB water users faced little water conflict until interstate compact litigation in 1998 prompted a dramatic reconfiguration of the regulatory landscape. Whereas users had historically perceived groundwater as abundantly available and not within the scope of interstate agreements, users were forced to recognize that groundwater was limited and over-appropriated. The RRB conservation district sought to reduce irrigated acreage by enormous measures. The basin was successful in retiring 30,000 acres of irrigated lands but then asked to retire 25,000 more, posing an existential threat to many farming communities. Water districts and populations are highly dispersed across the RRB and made of tight-knit communities that remain strongly opposed to regulations (Shepler et al., 2019). The RRB's basin roundtable has been slow to generate relationships and consensus among irrigators than in other basins, and only a few local leaders emerged. Groundwater users are described as having low morale around the prospect of addressing water challenges, suggesting that resource scarcity is highly salient but that it may not be perceived as salvageable. Groundwater management districts are funding limited and politically resistant to raising taxes or installing pumping fees to support local institutions or develop solutions. Whereas the RRB has high levels of social capital within communities, few competing uses for water, and homogenous user groups, users remain highly dispersed across a groundwater commons that is tapped by multiple states and faces seemingly insurmountable sustainability challenges. These conditions resist the emergence of self-governance among groundwater users.

Groundwater user associations have become central to complying with regulations in the AKB, as they have in the SPB. Unlike the SPB, however, agriculture in the AKB makes up less than 10% of total economic productivity in the farming region of the basin. Vested interests in agriculture command less relative power than in other basins and have leveraged less robust regulatory protections for irrigators. AKB irrigators organized to protect their interests and achieved early success in defeating state attempts to curtail well pumping in the 1970s, but those successes were short lived once the state enhanced its own authority and sharply restricted AKB well pumping during the 2000s drought. The alluvial nature of the basin results in tight coupling between groundwater use and surface water availability, making groundwater extraction a direct threat to surface water users within the basin. Furthermore, the semi-arid landscape and complex hydrology of the basin makes predicting annual water supply challenging and well-pumping allocations are often reduced within the year. Meanwhile AKB counties organized their water conservation district to prioritize protecting the basin from interbasin transfers, or “buy and dry” schemes that continue to be proposed, effectively framing water transfers as the dominant external threat to the basin instead of groundwater depletion or new regulation. Today groundwater users in the AKB are strictly limited in their annual allocations. Groundwater user associations are described as convenors of different water user groups and critical to keeping users in business, informed, and in compliance with groundwater regulations. However, situated amid larger vested interests in a severely water-limited basin facing highly salient external threats (i.e. water transfers), conditions were ultimately not highly supportive of self-governance among groundwater users.

The RGB remains the only basin with irrigators carrying out collective self-governance and has shown mixed levels of success that continues to be tested by drought. Today the RGB is organized into seven water management subdistricts with subdistrict 1 including the greatest number of wells (3481 wells in 2020), while all other subdistricts each include less than 500 wells. In 2020, half of subdistricts were in compliance with aquifer recovery and sustainability plans while several others were still working to secure state government approved solutions. Subdistrict one continues to implement self-imposed over-pumping fees and conservation programs to meet groundwater extraction reductions and sustainability standards, and two other districts implemented similar market-based systems beginning in 2018. Subdistrict 1's self-regulation showed success at increasing aquifer levels and

10.3389/fenvs.2022.958597

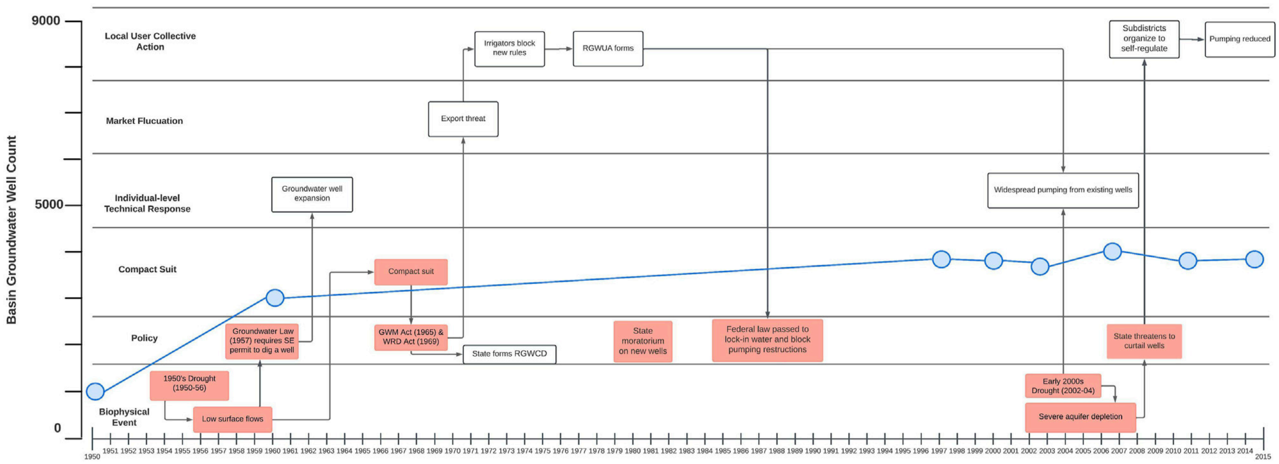


**FIGURE 6**
A historical timeline of disturbance and response event sequences affecting groundwater appropriation in the Rio Grande Basin from the 1950s to present, with the estimated number of active high-capacity groundwater wells depicted through time on the *y*-axis. Groundwater well data is estimated based on Colorado state records.

reducing groundwater extraction by irrigators in the few years following implementation (Smith et al., 2017). Subdistrict 1 has continued to calibrate it's market-based regulatory approach and has raised pumping fees multiple times since then. However, a 2018 drought coupled with low snowpack reversed previous gains in recovering aquifer levels and prompted an increase of pumping fees to $150 per acre foot, a 333% increase from initial fees of $45 in 2012. The RGB remains in a long-term drought that has stalled aquifer recovery since 2019 and prompted subdistrict 1 to consider further increasing over-pumping fees to $500 per acre foot (Waggoner 2021). Subdistrict 1's experiment in collective self-governance has been described as "an extremely high-stakes game of sustainable-farming "Survivor."" in local newspapers, and uncertainty around the long-term success of the program remains high (Waggoner 2021). As in other study basins, sustainable aquifer management standards for the RGB were established using 1978 conditions which don't account for long-running droughts of recent decades and water managers wonder whether those standards can be achieved under current and future aquifer conditions.

## Discussion

Our research has sought to understand why groundwater governance has emerged and evolved differently across several Colorado groundwater basins, and the role of collective action in directing those changes. In this study we uncovered three forms of collective action among groundwater users in response to state government attempts to regulate them. In some cases, these efforts are aimed at resisting groundwater regulation to protect local interests, while in others they sought to reduce the individual burden of complying with newly imposed regulations. In one unique case, irrigators acted collectively to self-regulate their groundwater use. We posit that these collective efforts reflect a predictable sequence of collective action phases that groundwater users move through in response to state efforts to regulate groundwater.

## Collective resistance, collective compliance, and collective solutions

The first phase is a collective resistance to new state interventions. In these cases groundwater users organized to protect their shared interests in groundwater resources from the external threat of regulation. For instance, irrigators in both the RGB and AKB had success in defeating the state's early attempts to regulate groundwater. In both cases, irrigators' collective efforts were enabled by the networks and social capital generated in part within forums convened by the state government. Users also resisted regulation in the SPB and RRB but were distributed across less cohesive groups with lower levels of coordination. As state regulations were eventually imposed in the SPB, RRB, and AKB irrigators pivoted from collective resistance towards collective efforts to comply with new regulations. These efforts are observable in response to requirements for irrigators to replace their groundwater usage with augmentation water that is challenging for irrigators to secure and finance individually. Groundwater user associations emerged as a bottom-up effort to collectively seek out, contract, and finance sources of augmentation water. Associations reduce the transaction costs for securing augmentation water by individual groundwater users and have become critical for most well-users to continue pumping. Key informants often described how membership in a groundwater user association is required to obtain augmentation water, however memberships tend to be limited and closed, creating a backlog of irrigators waiting to gain access to augmentation water. Thus, user associations have become an informal administrator in the groundwater regulatory process. User associations also act as a conduit for irrigators to coordinate and advocate for shared interests with the state government. For instance, associations in the AKB were key for stakeholders to gain compromise in negotiating new efficiency rules for irrigation technology in 2011 (Macllroy and Holms 2021).

Thirdly, we observe irrigators acting collectively to get ahead of state regulation by enacting local groundwater governance schemes. RGB irrigators offer the only successful example of this effort to date in the form of subdistrict one. Irrigators in the RGB are highly dependent on groundwater, benefit from high social capital in tight-knit communities, have a high level of knowledge over groundwater dynamics in their basin, and a long history of defending their water interests from regulatory and export threats. Taking all four basins together, we observe a pattern of slow and incremental adjustments that move open access, semi-regulated groundwater commons into the yoke of state regulatory institutions, in this case Colorado's doctrine of Prior Appropriation. While groundwater regulation is intended to improve groundwater sustainability and the adaptive capacity of groundwater dependent communities, users tend to perceive government attempts to get them there as an external threat to their individual interests. This likely reflects a central challenge to generating adaptive local institutions in other contexts.

Our observed patterns in collective action present a tension between individual and collective adaptation efforts. Prior to regulation, groundwater wells offered an individual-level, technical adaptation to drought. Drilling a well could offset an irrigator's vulnerability to surface water scarcity at only the cost of drilling and pumping. A wave of new well construction occurred across Colorado groundwater basins in response to the 1950s drought as irrigators sought to reduce their vulnerability to water shortage (Figure 6). Irrigator investments in well technology and ensuing network effects increased their dependence on groundwater and incentivized continued and expanded groundwater use. Irrigators began down a path that would come with high costs to reverse (Beyer 2010). As groundwater resources were eventually acknowledged to be finite and facing over extraction, groundwater users had become locked into arrangements that maximized individual-level interests at detriment to the commons. Through direct intervention, or simply the threat of intervention, the state government moved groundwater users away from these historic arrangements and prompted users to work collectively to continue pumping.

Our findings confirm what has been posited by other work - that path dependence dynamics can be highly influential on collective action within common pool resource governance systems, especially where governance is shifting from apportioning resource flows (e.g. through Prior Appropriation) towards conserving resource stocks (e.g. sustaining groundwater levels) (Heinmiller 2009). The expansion of groundwater irrigation in Colorado during the 20th century set into motion path dependencies including sunk costs on technology and equipment, vested interests in continued groundwater access, network effects among users and local governments, and informal contracts that together exerted immense inertia that opposed efforts to reform groundwater governance beginning in the 1960s. Much of the responsibility to overcome those forces was left to groundwater users and local jurisdictions, and the incremental pace at which they did differed across our study basins.

We find that droughts and regulatory shock events worked to mediate the pace of institutional change, prompting both individual and collective adaptation efforts. Early droughts enhanced the salience of surface water scarcity among irrigators and encouraged individual-level responses - drilling of new wells and increased reliance on groundwater to reduce vulnerability to surface water shortages. Later droughts resulted in water shortages among surface and groundwater users, and exacerbated conflicts among surface and groundwater user groups. These pressures were coupled with tightening groundwater regulations by the state government in response to interstate compact violations, which together drove irrigators to act collectively to resist, comply, or preempt further top-down regulation. Droughts have been shown to play a catalyzing role in driving water governance away from crisis-based responses to water shortages towards proactive risk-based water management, usually by central governments (Berbel and Esteban 2019). Our findings are generally congruent with this pattern but are unique in documenting user-driven efforts to develop drought-adapted institutions with varying levels of top-down pressure from state government. We observed user-driven schemes that include water sharing arrangements facilitated by local groundwater associations, scaled water allocations, rotational fallowing programs, and in one case a locally implemented pumping fee.

Our study contributes unique perspectives on the role of central government in directing transitions towards sustainable groundwater management. In other settings, such as California, the state government has taken on the dominant role in driving the evolution of groundwater governance through statewide mandates and top-down design of new local institutions (e.g. groundwater management districts) (Dennis et al., 2020). In California's case, the state government took responsibility for overcoming the inertia and feedback effects of historical path-dependent policies to reorient the State's groundwater governance towards sustainable goals. This differs from our study of Colorado where we find that the state government applied differing levels of pressure to reform groundwater governance across basins, and that local users held the primary responsibility for overcoming the resistance of path-dependence to pivot away from historical arrangements. The state government's initial attempt to regulate groundwater through rigid statewide policies in the 1960s was largely defeated. In response, the government redirected its focus towards remedying injuries to interstate compacts and senior surface water users, and this offered a defensible vehicle for applying regulatory scrutiny across groundwater basins. The level of state government intervention in local groundwater governance shifted over time as some basins organized collectively to resist regulation, or to implement self-regulation, while others failed to demonstrate meaningful reductions in groundwater use without state government intervention (e.g. well shutdowns in the SPB). Instead of supplying entirely new local groundwater governance frameworks, Colorado relied on the long-standing institutional structures of Prior Appropriation, historically used to govern surface water, to guide local groundwater users into preexisting arrangements. The state setup the institutional end-goal and users were given responsibility for getting themselves there. Users faced a scenario of "self-regulate or be regulated."

Our results depict how Colorado groundwater users work collectively in several ways to respond to, or enact, new groundwater governance policies. We show how users worked collectively to move along a pathway from resistance, to compliance, to self-imposed groundwater governance solutions. These findings may provide useful perspective to groundwater users grappling with various dimensions of the groundwater governance transition pathway. Understanding the histories and patterns of other basins may help users apply hard-learned lessons without the cost of trial-and-error approaches already born elsewhere. While we show how the long-standing, statewide legal framework of Prior Appropriation has been used to integrate groundwater into Colorado's water governance system, a common statewide approach for administering those rules is unlikely to be successful. Users and managers should consider the influence of historic path-dependencies at work within a basin to best define the scope of what policy tools are possible and achievable in unique local contexts. In doing so state government actors can better target resources and interventions towards helping local users and managers overcome the inertia of historic arrangements.

Our study suggests that local users are likely to be highly engaged with designing and implementing groundwater governance solutions, and that trust and working relationships take time to develop among local users and state actors. Local leadership and social capital among users are important to creating consensus about the nature of the problems they face and the need for collective action to address them. These factors seem critical for ensuring users perceive efforts to create adaptive common pool governance systems as mutually beneficial instead of as a threat to their individual interests. These insights can help guide effective strategies for engagement among managers and users.

The strength of our comparative study stems from our mixed-methods approach to carrying out a longitudinal analysis across four study units. We selected study basins that offer a semi-natural experimental design and enable us to distinguish among the influence of statewide and basin-specific variables in directing path-dependent evolution of groundwater governance. We draw from a large body of archival research, personal interviews, and groundwater records that together lend depth and richness to our findings. Our findings are limited by any gaps within historical records and databases. Our study would be improved by a greater degree of in-person observations and engagement with stakeholders that would improve our understanding of influential leaders and social capital at work within each basin. The predictive power of our findings for the future are limited to the patterns of the past and the external validity of our study could be improved by comparing findings to future research in Colorado's Western Slope, or groundwater basins in other states.

## Conclusion

Over the past century Colorado has sought to bring semi-regulated groundwater commons across the state into systems of state governance. We sought to understand how the state's four most significant agricultural basins evolved into unique arrangements of groundwater governance today. Initiated by severe drought in the 1950s, each basin's arrangements have emerged through both bottom-up and top-down processes of trial and error in response to drought, interstate water disputes, and local socio-economic trends. Our study basins began to diverge onto unique governance paths during the 1970s as groundwater users sought to collectively resist state government regulation with varying levels of success. The evolution of groundwater governance in each basin has since been influenced by path-dependence effects and mediated by local basin and community contextual factors (e.g. alluvial dynamics, salience of resource scarcity) that condition basin users towards or away from achieving collective self-governance solutions. We show how users worked collectively to move along a pathway from resistance, to compliance, to self-imposed groundwater governance solutions. These findings are useful for thinking about adaptation at the individual versus collective scale in groundwater commons, and the role of central governments in overcoming the inertia of historic governance arrangements to redirect common pool resource systems towards more adaptive and sustainable forms. Understanding the histories and patterns of groundwater development and regulation across various contexts may help groundwater users and mangers apply hard-learned lessons without undue trial-and-error. The example of collective self-regulation documented in Colorado's Rio Grande Basin offers valuable insights and tests theories of self-governance, however, these same solutions should not be expected in all contexts. Achieving adaptive groundwater governance solutions will require careful consideration of history, path-dependencies, and local contextual variables. The critical role of trust and working relationships among users and managers cannot be overlooked in this process so that outcomes feel less like a game of survival among users under heavy handed government authority, and more like a collective effort towards mutual well-being.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Ethics statement

The studies involving human participants were reviewed and approved by Office of Research Integrity at University of Colorado Boulder. The patients/participants provided their written informed consent to participate in this study.

## Author contributions

JL served as lead author on this paper. All other authors carried out research in support of this paper, and contributed expertise, guidance, and review.

## Funding

This research is funded by the U.S. Department of Agriculture, National Institute of Food and Agriculture, grant #67023-29421, "Innovative Governance of Scarce Surface Water and Groundwater for Irrigation of Production Agriculture in Southwestern United States." This research is also funded by doctoral student assistantships from the Guarini School of Graduate and Advanced Studies at Dartmouth College.

## Acknowledgments

This research was made possible by the collective contributions of authors at the Colorado School of Mines, Dartmouth College, Santa Rosa Junior College, and University of Colorado Boulder.

## Conflict of interest

The reviewer S.S declared a past co-authorship with the author M.C to the handling editor.

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.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## References

Agrawal, A. (2001). Common property institutions and sustainable governance of resources. *World Dev.* 29 (10), 1649–1672. doi:10.1016/S0305-750X(01)00063-8

Arts, B., Leroy, P., and Van Tatenhove, J. (2006). Political modernisation and policy arrangements: A framework for understanding environmental policy change. *Public organiz. Rev.* 6, 93–106. doi:10.1007/s11115-006-0001-4

Ayres, A. B., Edwards, E. C., and Libecap, G. D. (2018). How transaction costs obstruct collective action: The case of California's groundwater. *J. Env. Econ. Manag.* 91, 46–65. doi:10.1016/j.jeem.2018.07.001

Bai, J., and Perron, P. (2003). Computation and analysis of multiple structural change models. *J. Appl. Economet.* 18 (1), 1–22. doi:10.1002/jae.659

Barnett, J., Evans, L. S., Gross, C., Kiem, A. S., Kingsford, R. T., Palutikof, J. P., et al. (2015). From barriers to limits to climate change adaptation: Path dependency and the speed of change. *Ecol. Soc.* 20 (3), art5. doi:10.5751/ES-07698-200305

Berbel, J., and Esteban, E. (2019). Droughts as a catalyst for water policy change. Analysis of Spain, Australia (MDB), and California. *Glob. Environ. Change* 58, 101969. doi:10.1016/j.gloenvcha.2019.101969

Beyer, J. (2010). The same or not the same - on the variety of mechanisms of path dependence. *Int. J. Soc. Sci.* 15, 1–11. doi:10.5281/zenodo.1333470

Boushey, G. (2012). Punctuated equilibrium theory and the diffusion of innovations. *Policy Stud. J.* 40 (1), 127–146. doi:10.1111/j.1541-0072.2011.00437.x

Cech, T. (2010). Surface water and groundwater interaction, management, and conflict in colorado: Alarming trends for the 21st century. *Environ. Pract.* 12 (4), 304–315. doi:10.1017/S1466046610000463

Cody, K. (2019). The evolution of norms and their influence on performance among self-governing irrigation systems in the Southwestern United States. *Int. J. Commons* 13 (1), 578–608. doi:10.18352/ijc.910

Dennis, E. M., Blomquist, W., Milman, A., and Moran, T. (2020). Path dependence, evolution of a mandate and the road to statewide sustainable groundwater management. *Soc. Nat. Resour.* 33 (12), 1542–1554. doi:10.1080/08941920.2020.1772926

Dieter, C. A., Maupin, M. A., Caldwell, R. R., Harris, M. A., Ivahnenko, T. I., Lovelace, J. K., et al. (2018). *Water availability and use science program: Estimated use of water in the United States in 2015. Circular 1441*. United States Geological Survey, 71. doi:10.3133/cir1441

García, M. M., Hileman, J., Bodin, O., Nilsson, A., and Jacobi, P. R. (2019). The unique role of municipalities in integrated watershed governance arrangements: A new research frontier. *Ecol. Soc.* 24 (1), art28. Available at: https://www.jstor.org/stable/26796927 (Accessed: February 4, 2022). doi:10.5751/es-10793-240128

Geels, F. W., and Kemp, R. (2007). Dynamics in socio-technical systems: Typology of change processes and contrasting case studies. *Technol. Soc.* 29 (4), 441–455. doi:10.1016/j.techsoc.2007.08.009

Heinmiller, T. (2009). Path dependency and collective action in common pool governance. *Int. J. Commons* 3 (1), 131–147. doi:10.18352/ijc.79

Johnson, C. (2004). Uncommon ground: The "poverty of history" in common property discourse. *Dev. Change* 35 (3), 407–434. doi:10.1111/j.1467-7660.2004.00359.x

Jones, A., and Cech, T. (2020). *The South platte well crisis and beyond: Evolving alluvial groundwater regulation*. Denver, CO: University of Denver Law School. Available at: https://heinonline.org/HOL/P?h=hein.journals/udenwr22&i=191.

Kates, R. W., Travis, W. R., and Wilbanks, T. J. (2012). Transformational adaptation when incremental adaptations to climate change are insufficient. *Proc. Natl. Acad. Sci. U. S. A.* 109 (19), 7156–7161. doi:10.1073/pnas.1115521109

Lankford, B., and Hepworth, N. (2010). The cathedral and the bazaar: Monocentric and polycentric river basin management. *Water Altern.* 3 (1), 82–101.

Leonard, B., and Libecap, G. D. (2019). Collective action by contract: Prior appropriation and the development of irrigation in the western United States. *J. Law Econ.* 62 (1), 67–115. doi:10.1086/700934

Libecap, G. D. (2011). Institutional path dependence in climate adaptation: Coman's "some unsettled problems of irrigation". *Am. Econ. Rev.* 101 (1), 64–80. doi:10.1257/aer.101.1.64

MacIlroy, K., and Holm, H. (2021). *Lessons learned from Colorado experiences with interstate compact administration*. Grand Junction, CO: Ruth Powell Hutchins Water Center at Colorado Mesa University, 26. Available at: https://www.coloradomesa.edu/water-center/compact-stories.html (Accessed March 31, 2022).

Megdal, S. B., Gerlak, A. K., Huang, L. Y., Delano, N., Varady, R. G., and Petersen-Perlman, J. D. (2017). Innovative approaches to collaborative groundwater governance in the United States: Case studies from three high-growth regions in the sun belt. *Environ. Manag.* 59 (5), 718–735. doi:10.1007/s00267-017-0830-7

Merrey, D., J., and Cook, S. (2012). Fostering institutional creativity at multiple levels: Towards facilitated institutional bricolage. *Water Altern.* 5 (1), 1–19.

Molle, F., and Closas, A. (2019a). Comanagement of groundwater: A review. *Wiley Interdiscip. Rev. Water* 7, 1–19. doi:10.1002/wat2.1394

Molle, F., and Closas, A. (2019b). Why is state-centered groundwater governance largely ineffective? A review. *Wiley Interdiscip. Rev. Water* 7, 1–17. doi:10.1002/wat2.1395

North, D. C. (1990). *Institutions, institutional change, and economic performance*. Cambridge, MA: Cambridge University Press The political economy of institutions and decisions.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. doi:10.1126/science.1172133

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge, MA: Cambridge University Press.

Paddock, W. A. (2020). *Implementation of integrated surface and groundwater administration under the 1969 act in the Rio Grande basin, water division No. 3*. Denver, CO: University of Denver Law School, 89. Available at: https://heinonline.org/HOL/P?h=hein.journals/udenwr22&i=277.

Pahl-Wostl, C., and Knieper, C. (2014). The capacity of water governance to deal with the climate change adaptation challenge: Using fuzzy set Qualitative Comparative Analysis to distinguish between polycentric, fragmented and centralized regimes. *Glob. Environ. Change* 29, 139–154. doi:10.1016/j.gloenvcha.2014.09.003

Perez-Quesada, G., and Hendricks, N. P. (2021). Lessons from local governance and collective action efforts to manage irrigation withdrawals in Kansas. *Agric. Water Manag.* 247, 106736. doi:10.1016/j.agwat.2021.106736

Pierson, P. (2000). Increasing returns, path dependence, and the study of politics. *Am. Polit. Sci. Rev.* 94 (2), 251–267. doi:10.2307/2586011

Rouillard, J., Babbitt, C., Pulido-Velazquez, M., and Rinaudo, J. (2021). Transitioning out of open access: A closer look at institutions for management of groundwater rights in France, California, and Spain. *Water Resour. Res.* 57 (4), e2020WR028951. doi:10.1029/2020WR028951

Sharma-Wallace, L., Velarde, S. J., and Wreford, A. (2018). Adaptive governance good practice: Show me the evidence. *J. Environ. Manag.* 222, 174–184. doi:10.1016/j.jenvman.2018.05.067

Shepler, R., Suter, J. F., Manning, D. T., and Goemans, C. (2019). Private actions and preferences for coordinated groundwater conservation in Colorado's Republican River basin. *J. Am. Water Resour. Assoc.* 55 (3), 657–669. doi:10.1111/1752-1688.12741

Smith, S. M., Andersson, K., Cody, K. C., Cox, M., and Ficklin, D. (2017). Responding to a groundwater crisis: The effects of self-imposed economic incentives. *J. Assoc. Environ. Resour. Econ.* 4 (4), 985–1023. doi:10.1086/692610

Taylor, R. G., Scanlon, B., Doll, P., Rodell, M., van Beek, R., Wada, Y., et al. (2013). Ground water and climate change. *Nat. Clim. Chang.* 3 (4), 322–329. doi:10.1038/nclimate1744

Waggoner, P. (2021). Subdistrict No. 1 considering increasing over-pumping fees. Available at: https://www.mineralcountyminer.com/article/subdistrict-no-1-considering-increasing-over-pumping-fees (Accessed August 8, 2022).

Waskom, R., et al. (2014). *Colorado water: South platte groundwater*. Fort Collins, CO: Colorado State University Water Center, 44. Available at: https://watercenter.colostate.edu/colorado-water-archive/.

Wiener, J. D., Pulwarty, R. S., and Ware, D. (2016). Bite without bark: How the socioeconomic context of the 1950s U.S. drought minimized responses to a multiyear extreme climate event. *Weather Clim. Extrem.* 11, 80–94. doi:10.1016/j.wace.2015.11.007