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Research

How did we get here? The evolution of a polycentric system of groundwater governance

Ruth Langridge[1] and *Christopher K. Ansell*[2]

ABSTRACT. Polycentric systems are widespread globally and studied extensively, but cross-sectional studies are more prominent than longitudinal studies, and limited attention has been paid to how polycentric systems develop. We present an evolutionary framework to help identify the dynamic factors that shape polycentric system variations and that drive particular trajectories of polycentric formation. Building on prior work, we argue that polycentric institutions for resource management emerge out of spatially delimited conflicts over resource use and the externalities that they entail. Our perspective points to the characteristics and conditions of the resource itself as a starting point that crescively shapes landscape-level patterns of resource use. We illustrate this process through a case study of the evolution of a polycentric system in California's San Gabriel River Watershed. The study found a relationship between pronounced hydrologic linkages and stronger institutional linkages, suggesting that the physical characteristics of common-pool resources are one driver of subsequent institutional linkages. We also found that the impacts from resource use leads to both conflict and cooperation between basin users that shapes institutional formation and subsequent institutional interactions. This points to user impacts as a second important driver of polycentric formation over time. A better understanding of the evolutionary process of polycentric formation can illuminate opportunities to develop more cooperative relationships that support sustainable groundwater management.

Key Words: *evolutionary perspective; groundwater governance; institutional formation; polycentric system*

INTRODUCTION

The concept of polycentricity has played an important role in institutional analysis, with numerous scholars exploring the role of polycentric systems in the governance of common-pool resources (CPRs) and other social-ecological systems (SES). Whereas definitions of polycentricity vary, we adopt Carlyle and Gruby's (2017) succinct definition, which highlights two core attributes: (1) multiple, overlapping decision-making centers with some degree of autonomy; and (2) choosing to act in ways that take account of others through processes of cooperation, competition, conflict, and conflict resolution. In polycentric systems, each institution is seen as a component in a cross-border and cross-level management system that can potentially result in more robust and effective institutional as well as resource outcomes.

Building on the seminal work of Ostrom et al. (1961), research points to polycentric systems as enabling greater efficiency and effectiveness with a redundancy that can mitigate risk, reduce institutional failure, and increase adaptive capacity (da Silveira and Richards 2013, Carlisle and Gruby 2017). Because polycentric systems are composed of many units operating at different scales, they can improve the "institutional fit" between natural resources and their management regimes, a relationship that can increase learning and enhance resource sustainability (Ostrom 1990, Ostrom 1999, Agrawal 2001, Young 2002, Agrawal 2003, Heikkila 2004, Imperial 2005, Folke et al. 2007, Marshall 2009, Pahl-Wostl 2009, Cox et al. 2010, McGinnis and Walker 2010, Ostrom 2010, Schlager and Heikkila 2011, Aligica and Tarko 2012, Cole 2015, Carlisle and Gruby 2017, Pahl-Wostl 2017, Heikkila et al. 2018, Özerol et al. 2018, Cole et al. 2019, Lubell and Morrison 2021, Baldwin et al. 2023; G. R. Marshall, *unpublished manuscript*).

Challenges associated with polycentric systems include high transaction costs for reaching and enforcing agreements, unnecessary duplication of efforts (Imperial and Hennessey 1999, Kemper et al. 2005, Huitema et al. 2009, Mudliar and O'Brien 2021), and conflict between decision-making centers because of a "complexity of spatial patterning, multiple functional overlays, partial polity formation, and variable system coupling" (Skelcher 2005:102). Polycentric structures can be fragmented, conflictual, maladaptive, and weakly accountable (McGinnis and Walker 2010, Lieberman 2011, Pahl-Wostl and Knieper 2014, Biddle and Baehler 2019, Lubell et al. 2020, Morrison et al. 2023, Mudaliar 2023).

Polycentric systems are widespread globally and have been studied extensively, yet conceptual, methodological, and theoretical gaps remain in our understanding of these systems (Carlisle and Gruby 2018, Heikkila et al. 2018, Langridge and Ansell 2018, Berardo and Lubell 2019). Studies have focused largely on understanding overall system structure and the dynamic nature of interactions between decision-making centers (McGinnis 2011, Berardo and Lubell 2016, Morrison 2017, Carlisle and Gruby 2018, Biddle and Baehler 2019, Thiel et al. 2019, Thiel and Moser 2019, Ebel 2020, Weible et al. 2020). However, cross-sectional studies have been more prominent than longitudinal studies and relatively little attention has been paid to how polycentric systems develop in the first place. Yet, recent research is beginning to call attention to the importance of understanding the evolution of polycentricity over time (Morrison 2017, Carlisle and Gruby 2018, Biddle and Baehler 2019, Epstein et al. 2020, Baldwin et al. 2023, Morrison et al. 2023).

Elaborating an evolutionary perspective in greater detail is critical to identifying the dynamic factors that shape polycentric system variations and drive particular trajectories of polycentric formation. An evolutionary perspective can illuminate the different patterns of vertical and horizontal interaction that characterize polycentric systems and shape their degree of

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conflict and cooperation. Shedding light on opportunities for and constraints on cooperation that materialize as polycentric systems form can shape the possibility for sustainable CPR outcomes.

To develop these insights, we built on prior research and a case study of groundwater governance to contribute to our understanding of how polycentric systems for natural resource governance evolve. Based on a reading of the polycentricity literature and a case study of six Southern Californian groundwater basins in the San Gabriel River Watershed, we found that these systems evolve out of an interaction over time between the physical and ecological characteristics of the resource, and the legal and sociopolitical factors affecting resource use. The resulting problems that arise from overuse can engender conflict over who is responsible for mitigating negative impacts, as well as cooperative processes to control or protect the resource. This conflict and cooperation drive institutional formation and produce interactions between institutions that can affect access to, use of, and control over the resource. The process is iterative.

A framework for the evolution of polycentric environmental governance

In stressing the importance of resources, resource users, and governance institutions, our framework is broadly compatible with the Institutional Analysis and Development (IAD) and SES frameworks developed by Elinor Ostrom and colleagues (Ostrom 1990, Anderies et al. 2004, Ostrom et al. 2007, Ostrom 2007, Ostrom 2009, Ostrom and Cox 2010, McGinnis and Ostrom 2014, Cole et al. 2019, Epstein et al. 2020). In our view, polycentric systems arise from the landscape-level interactions of many action situations.

Prior research has contributed a number of useful ideas for thinking about the evolution of polycentric systems. Building on the Ostrom tradition, Stephan et al. stress that polycentric orders emerge and coalesce into systems as the components of the system come to “take each other into account” (2019:24-25). They also note that such systems often develop when there is an overarching body of rules that facilitates local organizing. Thiel and Moser go somewhat further and argue that “the emergence and functioning of polycentric systems” depends on overarching rules, social-problem characteristics, and community heterogeneity (2019:66). Research has also emphasized the importance of cross-scale interactions and linkages for the evolution of polycentricity (Andersson and Ostrom 2008, Biddle and Baehler 2019, Cáceres et al. 2022). Public policy also matters and contributes to “the frequency and magnitude of the evolution of a polycentric governance system through major policymaking venues” (Weible et al. 2020:27).

Recent research is also beginning to pay attention to the power dynamics endogenous to the evolution of polycentricity (Morrison et al. 2019, Mudliar 2021). This focus suggests that as polycentric institutions develop, different patterns of conflict, cooperation, and coordination are likely to appear and influence the overall effectiveness of the polycentric system. Building on this approach, Morrison et al. (2023) developed a building block approach to analyzing the evolution of polycentricity. They conceptualize these building blocks as constellations of actors, venues, issues, and relationships, and they create a three-mode network analysis amenable to capturing the development of these building blocks over time. As they demonstrate in an analysis of the polycentric governance of the Great Barrier Reef in Australia, this approach produces a systematic and fine-grained analysis of the evolution of polycentric institutions.

We build on this prior work but distinguish our own contribution as follows. Whereas it is critical to understand the institutional underpinnings of polycentricity, it is also important to remember its spatial and resource-exploitation dimensions. Polycentric institutions for resource management emerge out of the exploitation of certain natural resources for certain uses on a spatially delimited scale, for example the use of groundwater for agriculture in a particular watershed with multiple groundwater basins. Our approach suggests that these polycentric systems tend to arise out of the crescive institutionalization of this spatial-functional-exploitation nexus. Patterns of cooperation and conflict between institutions then emerge as this nexus changes, or expands, or creates impacts on a wider geographical scale, generating polycentric institutional arrangements. We acknowledge that polycentricity may also arise in a more centralized fashion, where a system becomes more polycentric as it responds to localized conflicts over resource use.

Our approach leads us to emphasize the physical character of the natural resource as an important starting point. The idea is not to start out in a state of nature, but to acknowledge that physical and ecological conditions establish basic patterns of interdependence for the usage of the resource at different scales that fundamentally shape how the resource is exploited and how resource users compete or cooperate to control, manage, and protect the resource. As resource users enter the picture, they begin to use and stake claims to the resource, with potential impacts on other users. The overarching rules of the legal system that can or do not require taking each other into account, as well as the sociopolitical mechanisms they have at their disposal for exploiting and staking claims to the resource, will also shape patterns of cooperation and conflict that arise among resources users as they attempt to address negative impacts. For example, with respect to water use, the exploitation of water by upstream users can impact the availability of water for downstream users. If upstream users claim legal rights to this water, they can exploit the resource without concern for downstream users. Thus, resource use and property rights can combine to shape collective action with respect to controlling and managing the resource. As upstream water use increases, downstream users may organize to defend their access to water. Upstream users may then organize to protect their own legal claims. Thus, as resource use intensifies, negative externalities can prompt conflict and/or cooperation to address unacceptable impacts. Institutions are formed to resolve these issues.

We identified both bottom-up and top-down pathways to the formation of polycentric systems. A bottom-up pathway suggests first that institutions will emerge from localized resource conflicts. The physical characteristics of the resource combine with the technological, legal, and sociopolitical environment of the resource users to shape the overlapping character of the institutions. For example, to control a resource, users often engage in collective action to enhance their access to the resource, to regulate their own joint use of the resource, or to ensure their access to the resource vis-à-vis other resource users. The evolution of polycentric systems is likely to result from exploitation impacts that result in some mixture of cooperative and conflictual collective action.

We anticipate iterative feedback effects from efforts to control, manage, and protect a resource, as the institutions created to address exploitation impacts become agents in subsequent conflicts. Successful collective action to control resource use in one action situation may produce a negative externality for other resource users, prompting them to organize (Stephan et al. 2019). McGinnis theorizes the interaction between different components of a polycentric system as a "network of adjacent action situations" (2011:51). As collective efforts to access or control resources multiply, as resource supplies become scarcer as the result of supply or demand factors, and as negative impacts to the resource and resource users increase, we expect landscape-level interactions between different control efforts to become more prominent, producing both conflict and cooperation between different collective control efforts.

Multiple factors may influence the process of conflict and cooperation. For example, in our study, the property-rights regime is fundamental to who uses groundwater and how it is used. However, community characteristics, social networks, available knowledge, local institutions, infrastructure, and the technology of resource exploitation may also be important, as suggested by the commons, co-management, and adaptive-governance literatures (Acheson 2003, Dietz et al. 2003, Olsson et al. 2006, Sandström et al. 2014).

The bottom-up emergence of polycentricity is only one possible pathway to the formation of polycentric systems. They may also develop via a top-down pathway through the actions and design of higher-level authorities with the power to shape institutional formation and management strategies (Blomquist and Schröder 2019). Carlisle and Gruby (2018), for example, show that the evolution of polycentric fisheries management in Palau shifted control away from local communities, and Brewer (2010) shows how federal involvement in local customary fishing arrangements led to a formalization of polycentricity. Thus, polycentricity can also evolve top-down through the actions of the state rather than bottom-up through the self-organizing action of local users.

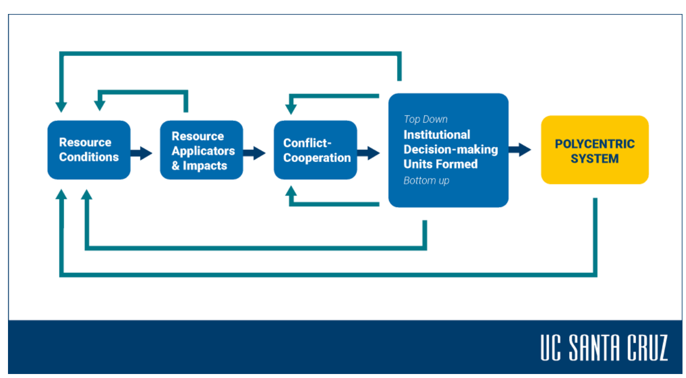
We theorized different possible mechanisms of top-down emergence. The first was the evolution of polycentricity by institutional layering. Morrison (2017) describes the polycentric management of Australia's Great Barrier Reef as developing through the state-directed creation of multiple policy venues for dealing with a variety of different environmental issues. Similarly, Weible et al. (2020) show that the State of Colorado's system for regulating oil and gas became increasingly polycentric as new policy venues and rules were gradually introduced, and Lubell and Robbins (2021) found that regional climate change governance began in centralized forums but became more decentered over time.

In addition to layering, top-down polycentric evolution may arise through policy design. Baldwin et al. (2016) and McCord et al. (2017), for instance, describe the top-down reform of Kenyan water governance to create a polycentric system of water governance. This reform occurred in the context of a trend toward state decentralization and a perception that the prior hierarchical management system had performed poorly. As with bottom-up processes, a wide range of factors may affect top-down policy-driven forms of polycentric evolution. The policy process literature has identified a wide range of mechanisms that are expected to influence policy change, including advocacy coalitions, epistemic communities, policy entrepreneurs, policy learning. focusing events, and venue shopping, to name just a few (for a broad overview, see Van der Heijden et al. 2021).

Whereas bottom-up and top-down pathways may be distinctive, they may also interact in complex ways to shape the precise structure and pattern of polycentricity over time. Acheson's (2003) study of the Maine lobster industry, for example, demonstrates how informal community-based action interacted with state and federal policy over time to produce successful fisheries management. Thiel et al. (2019) observe that the Kenyan water governance reforms were polycentric by design but depended on the bottom-up agency of local water users (see also Baldwin et al. 2016). In their study of wildfire governance in the western U.S., Kelly et al. (2019) observe that polycentric governance can be strengthened from the top-down and the bottom-up. Finally, in a study of polycentric irrigation governance in Japan, Sarker (2013) shows how national, state, and local governments provided support to a semi-autonomous federation of farmers, referring to this as "state-reinforced self-governance."

Figure 1 provides a schematic view of our perspective on the general evolutionary pathway of polycentric systems. The characteristics and conditions of the resource itself are the starting point for the analysis and will shape landscape-level patterns of resource use. Over time, resource exploitation often leads to problems of resource supply or quality that impact resource appropriation, with spillover effects on other connected or related uses. These impacts, in turn, create incentives for conflict or cooperation that can result in institutional formation, the dynamics of which may be mediated by a wide range of social, technological, and political factors. Polycentric arrangements can take place through bottom-up, top-down, or hybrid dynamics and will in turn generate institutional linkages and relationships over time that further shape the polycentric system. The process is iterative. Feedbacks can occur between resource conditions and resource users that can generate new conflicts and new cooperative processes, affecting institutional decision-making units, the overall structure of the polycentric system, and subsequent resource conditions. Illuminating this evolutionary process reveals relationships and feedbacks between system components that shape the specific nature of polycentric systems.

Fig. 1. Evolution of a polycentric system.



METHODS

We conducted a longitudinal study of the evolution of a polycentric governance system: the institutions governing groundwater basins in the San Gabriel River Watershed in Southern California. The study focused on groundwater because it is both a critical resource and a life-sustaining water-supply source for billions of people worldwide (Schlager et al. 1994, Giordano 2009, Siebert et al. 2010, Madani and Dinar 2012) and it plays an increasingly crucial role in mitigating resource scarcity, serving as an invaluable buffer against precipitation variability and water shortages during drought (FAO 2016, Langridge and Daniels 2017). Yet the institutional challenges in managing groundwater resource sustainably are significant (Lipson 1978, Mandani and Dinar 2012), with unsustainable depletion of groundwater now documented on both regional (Rodell et al. 2009) and global scales (Wada et al. 2010, Konikow 2011, Langridge and Van Schmidt 2020). Moreover, groundwater overdraft is projected to worsen under climate change (Famiglietti 2014, FAO 2016, Persad et al. 2020). Management of the groundwater basins in the San Gabriel River Watershed exemplifies many of the same governance challenges experienced elsewhere in the U.S. and around the globe (Schlager 2006, Theesfeld 2010, Megdal et al. 2015, Varady et al. 2016, Megdal et al. 2017). Understanding the institutional conditions that can improve groundwater governance is essential to sustaining this important resource and the people and environments that rely on it.

We use a qualitative case-study approach to increase insight into the conditions that shaped the development of a polycentric governance system in the San Gabriel Watershed. Earlier research illuminated the history of some of the groundwater institutions in this watershed (Lipson 1978, Blomquist 1992), and more recent reviews of some of the basins by Langridge provide additional information (Langridge et al. 2016). The large body of hydrologic and climatic data, technical and other administrative documents, and records available for this watershed, including websites for each adjudicated basin, permit a comprehensive analysis that draws on and expands this prior research. Langridge's prior work (Langridge et al. 2016) also provided contacts in each basin, and these were updated to identify additional key individuals including technical staff and stakeholders. Semi-structured interviews were conducted with a minimum of one individual for each basin over a two-year period to validate archival data and update material.

We first demonstrated how groundwater-management institutions in the San Gabriel Watershed can be characterized as a polycentric system using the criteria developed by Carlisle and Gruby (2017). We then used a modified backcasting methodology to illuminate how the polycentric system evolved. Backcasting has been defined in multiple ways and is generally used to envision a future condition and then understand how to get there (Quist 2007, Vergragt and Quist 2011, Bibri 2018). Robinson defines backcasting as a normative approach that works "backwards from a particular desired end point to the present in order to determine... what would be required to reach that point" (1990:823). However, it is also well suited to historical analysis. In our case, we defined a present condition, i.e., our dependent variable, which is a polycentric system, and then conducted research to evaluate how it came about, i.e., our independent variables. To aid our backcasting approach, we first elaborated on the data types in our framework categories (Table 1) and then charted, sorted, and evaluated this data to identify linkages and patterns and to draw inferences and relationships (Bibri 2020). As per Schröder (2018), we characterized the polycentric system as the institutions and access rules that regulate groundwater use and the scale at which these institutions and rules operate. We focused our attention on formal decision-making centers but acknowledge that other groups and institutions, e.g., the media, user associations, NGOs, etc., sometimes interact with these centers to affect decisions.

RESULTS

Groundwater institutions in California

Groundwater is critical to California, providing 40% of the state's water demand during average years, and up to 60% during drought years (see https://www.waterboards.ca.gov/water_issues/programs/groundwater/issue_supply.html). Importantly, the state has no permit system for groundwater withdrawals despite significant groundwater overdraft in many basins. The legal framework for governing groundwater in California determines access, use, and management of the resource. California's correlative legal doctrine specifies that each overlying property owner has a common right to the reasonable, beneficial use of the basin's supply, with priority over groundwater exporters and municipalities. This legal structure has led to frequent disputes, with groundwater users going to court to resolve disagreements. Where users wanted to settle competing water-rights claims, basins were sometimes adjudicated and the court appointed a Watermaster, defined as the institution to manage the basin in accordance with the court's judgment. In 2014 California passed the Sustainable Groundwater Management Act (SGMA) establishing mandatory groundwater-management rules for designated basins. Basins adjudicated prior to the passage of SGMA are exempt from SGMA requirements. The passage of Assembly Bill 1390 and Senate Bill 226 in 2015 provided some procedures for groundwater adjudications, including reporting specified basic information to the state. All the basins in our study were adjudicated prior to 2015.

Snapshot (2023) of a polycentric system: the San Gabriel River Watershed

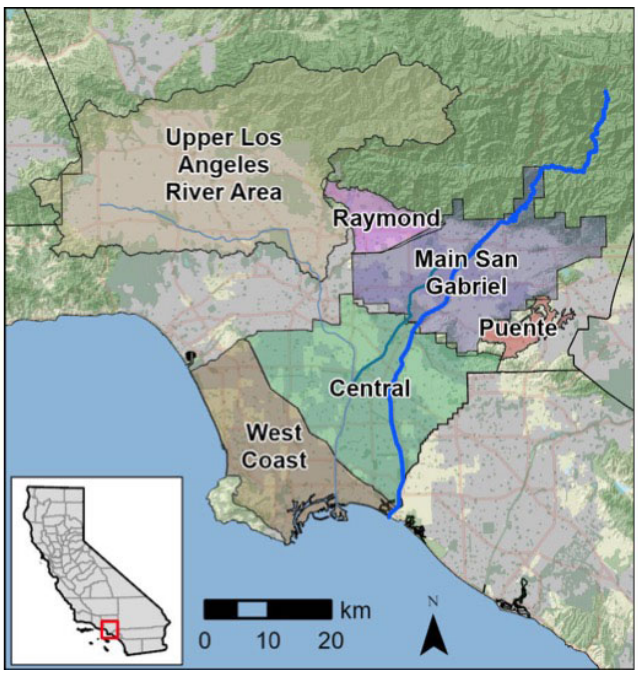
Located in the eastern portion of Los Angeles County in Southern California, the San Gabriel River Watershed covers an area of 640 square miles. With its source in the San Gabriel Mountains, the San Gabriel River flows roughly south for 58 miles over five groundwater basins (Fig. 2). We also considered a sixth basin in the Los Angeles River Watershed that was initially hydraulically connected to the San Gabriel River Watershed. At the time of our study in 2023, the groundwater governance system in the San Gabriel River Watershed met the two criteria of polycentricity defined by Carlisle and Gruby (2018): composed of (1) multiple, overlapping decision-making centers with some degree of autonomy that (2) choose to act in ways that take account of others through processes of cooperation, competition, conflict, and conflict resolution.

Each of the five groundwater basins in the San Gabriel River Watershed has been adjudicated as the result of conflicts within and between basins. As a result, the primary groundwater management institution in each basin is a court-appointed Watermaster who makes and enforces rules-in-use. Each

Table 1. Data categories.

Resource system unit-groundwater basin-subbasin	Actors: use and impacts	Conflictual and cooperative processes prior to institutional formation	Institutional formation	Institutional development
Physical connections with other basins or sub-basins; size and storage	Water use and users; water rights; location with respect to other users; undesirable impacts; resource dependency; land use Feedbacks	Individual conflicts and cooperative processes; shared financial and other projects Feedbacks	Main decision-making and other authorities; institutional mandate(s) Feedbacks	New linkages with decision-making units and shared financial and other projects and agreements Feedbacks

Fig. 2. San Gabriel River Watershed and linked groundwater basins. San Gabriel River: dark blue; Rio Honda: medium blue; Los Angeles River: light blue.



Watermaster has court-specified management requirements unique to its basin, but management actions in each basin also have implications for other Watermasters, because of the hydrologic connections between basins. In addition, basin management decisions are affected by other types of institutions, such as water districts and associations, which focus on water provision, information gathering, and strategy formation.

A snapshot summary of each basin in 2023 highlights some of the linkages between the governing institutions in each basin, providing support for our argument that the system is polycentric. Our results indicate that importing or exporting water between basins, sharing administrative processes, and collaborating on water management planning are the key areas of overlap for the Watermasters.

Raymond Basin underlies the northwesterly portion of the San Gabriel Valley and is located in Los Angeles County. In 2023 its Watermaster was the Raymond Basin Management (RBMB). With respect to its key linkages, a portion of the basin's groundwater production was exported for use in the adjacent Main San Gabriel Basin (MSGB) and there was some sharing of administrative services (Langridge et al. 2016; see also https://www.raymondbasin.org/about and https://www.arroyoseco.org/documents/TZ_MSC_20210511.pdf).

The Main San Gabriel Basin (MSGB) includes almost the entire valley floor of the San Gabriel Valley, with the exception of the Raymond and Puente Basins. The Watermaster is currently a court-appointed nine-person board composed of six producers and three municipal water districts. With respect to its key linkages, wells in MSGB provided potable water to the Central Basin; MSGB provided contract administrative services to RBMB; the Puente Watermaster measured annual flows between MSGB and Puente and reported them to the MSGB Watermaster; and there was tracking and conveyance of 98,000 acre-feet per year of water by MSGB to the Central and West Coast Basins (Langridge et al. 2016; see also https://www.watermaster.org/).

Puente Basin, a very small basin, has no barriers to groundwater movement between it and the much larger MSGB, but was adjudicated separately. The Watermaster is currently a three-person board, with one member nominated by the Rowland Water and Walnut Valley Water Districts, another nominated by City of Industry and the Industry Urban Development Agency (IUDA), and a third nominated by the first two members. With respect to its key linkages, the Puente Basin Watermaster measured the annual subsurface flows between Puente and MSGB and reported them to the MSGB (Langridge et al. 2016; see also https://puentebasin.com/).

Central Basin is located below MSGB. In 2023 the Watermaster was shared with the West Coast Basin and consisted of the Water Replenishment District of Southern California (WRD), a water-rights panel (Central Basin cities and water companies), and a storage panel (WRD and the water-rights panel; see also https://www.wrd.org/). With respect to its key linkages, an annual average water supply from MSGB is guaranteed, an amount that includes Puente Basin underflow (Langridge et al. 2016; see also https://www.wrd.org/).

West Coast Basin lies at the mouth of the San Gabriel River and extends to the northwest away from the river. In 2023 the Watermaster was shared with the Central Basin and consisted of an administrative panel (WRD), a water-rights panel (West Coast Basin cities and water companies), and a storage panel (WRD and the Water Rights Panel; see also https://www.wrd.org/). Its key linkages were the receipt of subsurface inflow from the Central Basin, and a guarantee of an annual average water supply from MSGB, which included Puente Basin underflow (Langridge et al. 2016; see also https://www.wrd.org/).

Upper Los Angeles River Area (ULARA) in the Los Angeles River Watershed was once hydrologically linked to the San Gabriel River Watershed. However, increasing urbanization resulted in the paving over of land where recharge would normally occur, eliminating the connection between the watersheds. Institutional linkages were minimal (Langridge et al. 2016).

How did we get here? The evolutionary process of polycentric formation

This section primarily draws on, and synthesizes material from, Lipson (1978), Blomquist (1992), Langridge et al. (2016), the Watermaster websites for each basin, and interviews with Watermasters in each basin.

Resource System

We begin by describing the physical resource system, including the size, storage, and hydrologic linkages between the six basins (Fig. 3). The San Gabriel River begins its journey to the ocean from the San Gabriel Mountains, the source of nearly all natural runoff. Precipitation in the basin varies, with the mountains in the north averaging about seven inches more annual precipitation (28.4 inches) than the valley floor (21.33 inches). The river bisects the Main San Gabriel Valley and surface runoff from the river and its tributary creeks provide a portion of recharge to the groundwater basins. The MSGB is hydrologically linked to the Raymond Basin that lies northwest of MSGB. Although the southeastern Raymond Fault separates the basins, groundwater can flow from the Raymond Basin across this boundary into the MSGB. On the south side of MSGB is Puente Basin; there are no hydrologic barriers between the two basins. The San Gabriel River then flows south through Whittier Narrows, which divide the upper and lower basins. It passes first through Central Basin and then through the West Coast Basin, which is located at the mouth of the San Gabriel River. Most of the Central Basin and all of the West Coast Basin are confined by relatively impermeable soils. The Central Basin receives its freshwater supply from MSGB through Whittier Narrows. The West Coast Basin generally receives natural freshwater replenishment from subsurface inflow from the Central Basin. As noted, the ULARA Basin to the northeast was once hydrologically linked to the Central Basin through the Los Angeles River system, but impervious land cover in the ULARA now blocks the natural recharge to the Central Basin.

Resource users and user generated impacts

Native Americans inhabited areas of the San Gabriel River Watershed region for millennia with no evidence of significant water development. Around 1770 Spanish settlers arrived and used groundwater, but irrigation was limited until the development of rancheros during Mexico's possession of California. After California statehood in 1850, westward migration increased, agriculture expanded, and orange groves proliferated.

In the Raymond Basin and the MSGB, municipal water providers became the primary pumpers in the 20th century, and users became very dependent on groundwater. In the Raymond Basin, the first wells were drilled for agriculture in 1881 and by 1913 withdrawals exceeded recharge. By 1920, the city of Pasadena was the San Gabriel Valley's dominant groundwater user, and it was concerned about having sufficient future groundwater supplies.

Fig. 3. Topographic map of the San Gabriel River Watershed region.

In the smaller Puente Basin, farming and ranching were the primary economies in the 1800s and the basin area was almost entirely dependent on groundwater. The Los Angeles Aqueduct enabled the two dominant water agencies to import surface water. By 1981 the region included significant industrial storage centers and golf courses. Over time, natural groundwater became polluted and unsuitable for potable use.

In the West Coast Basin, users were also primarily agricultural at the beginning of the 20th century. Oil discoveries touched off a huge development boom, shifting the water table's initial slope toward the coast to inland, and leading to saltwater impact on basin wells. Beginning in the 1920s there was rapid urbanization, and by the 1950s 90% of groundwater went to industrial and municipal use. Groundwater levels continued to drop, storage decreased, and saltwater intrusion increased. A second impact resulted from a falling water table that reduced inflow into the basin from the upper Central Basin. By 1957 accumulated overdraft was estimated at 832,000 acre-feet (AF).

In the Central Basin, agricultural areas also underwent rapid urbanization, with 23 cities formed by the 1970s. As the result of increased groundwater production, groundwater levels had dropped below sea level by 1950, with saltwater intrusion at the southern tip. By 1962 saltwater had proceeded more than three miles inland and the accumulated overdraft was about 1,000,000 AF. Fewer than 20 well owners, mostly cities and water companies, accounted for most of the groundwater production, and they were eager to get imported water to slow the overdraft.

In the ULARA, Glendale became known as the fastest growing city in the world. Over time, nearly the entire surface flow of the

Los Angeles River was diverted to the expanding urban area, prioritizing a need to tap groundwater, but reducing the linkages to the San Gabriel River basins.

In sum, users in every basin shifted from agriculture to urban development, but groundwater pumping continued with significant overdraft developing. Users were concerned about impacts that included future water shortages, saltwater intrusion, and industrial pollution.

From conflict and cooperation to institutional formation and development

As impacts to the six basins increased, each basin acknowledged the need for additional water supplies. Some cooperative processes ensued between basins to share water and to generate more water. As early as 1928 a new public organization, the Metropolitan Water District (MWD), was formed to secure funding for Colorado River water. Over time MWD became a major umbrella provider of imported water to local water districts and eventually developed cooperative programs with other Watermasters and water districts in the watershed. For example, it began a conjunctive use program with the Raymond Basin in 2002, and in 2016 it was a member of the Groundwater Coordinating Replenishment Group with the Raymond Basin Watermaster. MWD also coordinated with the MSGB Watermaster and others to develop a Mussel Control Plan. From 2010 to 2022 a project with MWD, called Pure Water Southern California, was proposed to provide cleaned and purified wastewater to recharge the West Coast, Central, and Main San Gabriel Basins through spreading facilities and injection wells.

Despite this cooperation, significant conflicts also occurred over who would have to pay for more expensive imported water and who would have to cut back on production. Initially, water associations and local water districts were formed. Both played roles in the management of groundwater through user input, information dissemination, and basin reports, and by securing imported water for their district customers, but they did not have the authority to resolve the conflicts over allocation rights and consequent costs, and eventually users opted to sue to adjudicate water rights. Watermasters were established in each basin as the governing institution with authority to mandate rules to comply with the court judgment.

Raymond Basin was the first basin in the watershed to be adjudicated. The basin's small size led to concerns regarding insufficient water for a growing population. The City of Pasadena realized it would have to both cut its production and import significantly more expensive Colorado River water. To resolve conflicts over who would have to cut production, and who would have to pay for imported water, Pasadena sued to adjudicate its groundwater rights in the basin (City of Pasadena v. City of Alhambra et al. 1937). The 1949 court judgment established rights, duties, and a basin-management plan. The California Division of Water Resources (DWR) was initially appointed as Watermaster but in 1984 the Watermaster evolved into the Raymond Basin Management Board (RBMB), with 10 members representing the 16 parties to the adjudication. Cooperative arrangements with other basins ensued over time and new rules and regulations were gradually adopted on water rights, storage accounts, and acceptable extractions. Raymond Basin (2002) and MSGB (2004) developed a significant cooperative arrangement, sharing an executive officer who served as Watermaster in both basins. Other staff were also shared, and the basins began cooperating in 2007 to seek federal funding and later to develop supply enhancement programs. In 2014 they jointly prepared the Salt and Nutrient Management Plan for each basin.

In the 1950s a conflict between watershed users over how much water would flow from the upper basins (Raymond, MSGB, and Puente) through Whittier Narrows to lower basin water users (West Coast and Central Basins) resulted in a lawsuit (Board of Water Commissioners of the City of Long Beach et al. v San Gabriel Valley Water Company et. al. 1959). A court settlement, referred to as the Long Beach Judgment, resolved the dispute with the lower basin users designated to receive a quantity of usable water annually from users upstream of Whittier Narrows. Water could be purchased if the natural flow was insufficient, with an obligation fund established between MSGB and CB to administer this.

Main San Gabriel Basin's upstream location, large size, and slower rate of urbanization resulted in problems becoming apparent later than they did in Raymond and the coastal basins. Early disputes were focused on the surface flows of the Main San Gabriel River. A collaborative effort between the City of Pasadena, the San Gabriel Valley Protective Association and various federal and local agencies was established to monitor those flows. But rapid urbanization and a dry period between 1945 to 1960 led to increased groundwater use that reduced flows to the Central Basin. Users considered importing water but conflicts ensued over the water source and who should pay the cost. Given the legal structure, it was also challenging for water managers in the upper watershed to satisfy obligations to the lower watershed as per the Long Beach Judgment without being able to govern basin groundwater users, so the basin was adjudicated with a final judgment in 1973. A court-appointed nine-person board of water producers and water districts serves as the Watermaster. As noted, cooperative projects have developed over time between MSGB and Raymond Basin and there is an interconnection pipeline between the spreading grounds in the Central Basin and the MSGB.

Puente was the last basin in the San Gabriel River Watershed to adjudicate. Although there are no barriers between it and MSGB, the users were concerned with overdraft and the cost of imported water needed to implement the Long Beach Judgment. In 1972 the two basins cooperatively established the Puente Narrows Agreement to govern subsurface outflow from Puente into the MSGB. But a desire to determine responsibility for outflows led to adjudication. The Watermaster was, and continues to be, a three-member board of users composed of two water districts and the City of Industry. Both basins have cooperated over time to develop local supplies. In 2017 a joint cooperative project between MSGB and Puente Basin established a Storage and Export Agreement between their respective Watermasters to study installation of a pipeline to move water supplies between Puente and MSGB.

In the lower watershed, the West Coast and Central Basins experienced significantly declining groundwater levels and increasing saltwater intrusion that led to their adjudication. Imported water was eventually insufficient to alleviate these problems and to resolve a conflict over who would have to curtail pumping. As a result, several users joined forces to adjudicate water rights in the West Coast Basin (California Service Water

Table 2. Hydrologic linkages.

Basin	Size	Storage	Hydrologic linkages
Raymond	40 mi²	1.4 m acre-feet (AF) 250,000 AF available	Water flows to Main San Gabriel Basin (MSGB)
Puente			No hydrologic barriers between Puente and MSGB
Main San Gabriel	167–255 mi²	8.6–10 m AF	Flow is from edges of basin to center and then SW to exit through Whittier Narrows to Central Basin
Central	277 mi²	13.8 m AF	Flow is from MSGB to West Coast Basin (WCB). Minimal links to Upper Los Angeles River Area (ULARA); some underflow from ULARA at LA Narrows and from MSGB at Whittier Narrows
West Coast	160 mi²	6.5 m AF	Underflow from Central Basin (CB) goes to WCB. WCB and CB links depend on water levels
ULARA			Minimal hydrologic linkages to CB

Company et al. v. City of Compton et al. 1961). In 1956 a conflict resulted in a lawsuit that incorporated 120 new users. The 1961 judgment designated the California Department of Water Resources as the Watermaster.

Central Basin groundwater production also continued in the 1950s, resulting in saltwater intrusion that had proceeded more than three miles inland. New programs of artificial replenishment and the importation of water were insufficient to overcome the basin's overdraft. Central Basin users then cooperated with West Coast Basin users to establish the Alamitos Barrier Project: injection wells at the southeastern tip of the Central Basin to prevent further saltwater intrusion into both basins. An additional proposed cooperative project was to impose a tax on the use of the basin to finance additional purchases of imported water. This led to users in both basins forming the WRD in 1959 to finance the purchase of replenishment water and to pay for a freshwater barrier to stop saltwater intrusion into both basins. The WRD could now raise funds for adjudication, but to avoid a long and costly conflict, Central Basin users put together a settlement stipulation that was accepted by the court in 1965. The California Department of Water Resources was designated as the governing institution Watermaster. In 1962 WRD began to administer the Montebello Forebay Groundwater Recharge Project.

The Watermasters for the West Coast and Central Basins evolved over time, and in 2013 and 2014 the WRD was designated as the administrative body for both. Both Watermasters consisted of a water-rights panel composed of water-rights holders in each basin, and a storage panel with WRD. These changes enhanced the ability of water-rights holders to provide greater input into decisions. In 2019 the WRD signed on for a regional recycled water program with the MWD, and in 2021 the WRD initiated a cooperative pilot recycled-water project, the Hyperion Water Reclamation Plant, to provide recycled water to West Coast and Central Basins.

Increased urbanization in the ULARA Basin led to the paving over of land where recharge normally occurred, eliminating the linkage between the San Gabriel Basins. As a result, there have been limited institutional linkages between the ULARA Watermaster and Watermasters in the San Gabriel River Watershed.

DISCUSSION AND CONCLUSION

Our framework describes a way to think about the dynamic processes involved in polycentric system formation. Our argument is that for social-ecological systems, institutional formation and linkages are shaped by the interaction over time between physical characteristics of the resource, its spatially delimited exploitation by resources users, and legal and sociopolitical factors that shape collective action and dispute resolution. Drawing on past research, we suggest that this evolution can occur bottom-up through local collective action, top-down through state-centered policy processes, via layering or design, or through some combination of these processes. Our case study indicates that polycentric formation in the San Gabriel River Watershed occurred primarily through bottom-up collective action shaped by the physical characteristics of the natural resource, which established localized and landscape-level interdependencies between groundwater users. Conflicts over who should pay the costs of addressing increasing impacts related to these interdependencies incentivized the formation of institutions to manage the basins. Cooperative processes between these institutions to address linked impacts also increased over time.

Our analysis calls attention to the significant resource connections in the San Gabriel River Watershed, with each groundwater basin hydrologically linked to at least one other basin in the watershed. Table 2 summarizes physical characteristics and hydrologic linkages between the groundwater basins. Basin size and storage were also important, because limited Raymond Basin water supplies were a factor in users choosing to adjudicate.

Unsurprisingly, we found that groundwater withdrawals by users generated resource impacts. The most prominent impacts were loss of storage and declining groundwater levels that resulted in subsequent water shortages and saltwater intrusion. We described the conflicts that ensued to determine who would be required to address these impacts under the legal system, which in turn resulted in the adjudication of water rights in each basin and the formation and evolution of Watermasters as the governing institution (Table 3). Institutional linkages are summarized in Table 4. The most common entailed importing or exporting water

Table 3. Watermasters.

Basin	Institutional evolution
Raymond	1949: California Division of Water Resources 1984: Raymond Basin Management Board of adjudication parties
Main San Gabriel Basin	1973: Nine person board of adjudication parties
Puente	1986: Three person board of users
West Coast & Central	1961, 1965: California Department of Water Resources 1959: Water Replacement District 2013, 2014: Three-panel Watermasters with linked administrative units

Table 4. Evolving institutional linkages.

Basin	Examples of evolving institutional linkages between basins
Raymond	With Main San Gabriel Basin (MSGB)
	2002, 2003: Same executive officer and share administrative services
	2003, 2006: Conjunctive use program with MWD
	2007: Seek funding and develop water enhancement programs
MSGB	With Central Basin (CB)
	1959: Long Beach Judgment: guarantee of annual water supply from MSGB
	1965: Payments to CB for a make-up obligation fund
	2002, 2003: Share administrative services
	With Puente
	1972: Puente Narrows Agreement: governs outflows from Puente to MSGB
	2017: Share administrative services
	With Raymond
	2007: Seek funding with MSGB; develop water enhancement programs
	2002, 2003: Share administrative services
Puente	With MSGB
	1972: Puente Narrows Agreement
	1986: Share administrative services
	2017: Storage and Export Agreement
West Coast (WCB) and Central	Between WCB and CB
	1950s–2005: Alamitos Barrier Project
	1959: Water Replenishment District of Southern California (WRD) to purchase water for both basins
	1962: Montebello Forebay Recharge Project administered by WRD
	2013, 2014: New Watermasters with shared administrative services
	2019: Regional recycled water program WRD with MWD
	2021: Hyperion water reclamation plant-share recycled water
	With MSGB
	1959: Long Beach Judgment: guarantee of annual water supply from MSGB
Upper Los Angeles River Area	Limited institutional linkages

between basins, sharing administrative processes, and collaborating on water management planning.

We observed two general patterns in the evolution of polycentricity. The first pattern is an association between pronounced hydrologic linkages between basins and stronger institutional linkages. For example, the hydrologic linkages between Raymond Basin and MSGB and between Puente and MSGB resulted in the cooperative agreements between their Watermasters, whereas the significant hydrologic linkages between West Coast and Central Basins incentivized joint governance processes exemplified by the 1959 formation of a WRD to obtain imported water for the two basins and the development of a joint Watermaster in 2013 and 2014. In contrast, the greatly reduced hydrologic connections between ULARA and San Gabriel basins were reflected in the limited institutional relationships between their Watermasters.

The second pattern is an association between impacts to users of the resource and institutional interactions. For example, saltwater intrusion in both the Central and West Coast Basins led to shared Watermaster responsibilities and shared institutional strategies to address user impacts. Another example is the MSGB and Puente agreement that determined how much water was required to flow from Puente to MSGB, and from the upper to the lower basins, to satisfy the Long Beach Judgment. In both cases the goals were to reduce negative impacts to the resource and consequently to users of the resource, and to achieve a more efficient and sustainable process: a positive outcome of a polycentric system. User impacts are frequent in the management of common-pool resources, suggesting that they are a second important driver of institutional interactions within a polycentric system.

In sum, our evolutionary perspective (Fig. 1) illuminates factors and conditions that drove institutional formation and institutional interactions over time, giving rise to a polycentric system of groundwater governance. As collective efforts to access and control the groundwater resource intensified, as resource supplies were reduced, and as negative impacts to the resource and resource users increased, we witnessed landscape-level conflict and cooperation between users that incentivized institutional formation and interactive development. Our findings suggest that the physical characteristics of a common-pool resource are a significant factor in the development of institutional relationships that form a polycentric system over time, and that user impacts are a key motivator of the conflictual and cooperative processes that result in institutional formation and institutional linkages. Past research points both to the strengths and weaknesses of polycentricity as a framework for managing common-pool resources, and empirical studies have called attention to the substantial diversity in the design and functioning of polycentric governance systems (Sovacool 2011, Heikkila et al. 2018). Our evolutionary perspective provides a useful longitudinal analysis of the formation of polycentric institutional characteristics and functions that can help to identify the diversity of conditions that contribute to the robustness of such systems.

As a common-pool resource, groundwater is critical for communities on both a local and global scale, and a better understanding of how a polycentric system of groundwater governance evolves can provide insights into the institutional relationships and decision-making that sustain the resource and the communities that rely on it. Future research can specifically address whether and how polycentric arrangements contribute to sustainable resource outcomes, and our proposed evolutionary framework may serve as a useful starting point for this investigation, both in other groundwater-dependent regions and for other common-pool resources, such as fisheries.

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Data Availability:

Data are available from the corresponding author.

LITERATURE CITED

Acheson, J. M. 2003. Capturing the commons: devising institutions to manage the Maine lobster industry. University Press of New England, Hanover, New Hampshire, USA. https://doi.org/10.2307/j.ctv1xx9c2c

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

Agrawal, A. 2003. Sustainable governance of common-pool resources: context, methods, and politics. Annual Review of Anthropology 32(1):243-262. https://doi.org/10.1146/annurev.anthro.32.061002.093112

Aligica, P. D., and V. Tarko. 2012. Polycentricity: from Polanyi to Ostrom, and beyond. Governance 25(2):237-262. https://doi.org/10.1111/j.1468-0491.2011.01550.x

Anderies, J. M., M. A. Janssen, and E. Ostrom. 2004. A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecology and Society 9(1):18. https://doi.org/10.5751/ES-00610-090118

Andersson, K. P., and E. Ostrom. 2008. Analyzing decentralized resource regimes from a polycentric perspective. Policy Sciences 41:71-93. https://doi.org/10.1007/s11077-007-9055-6

Baldwin, E., A. Thiel, M. McGinnis, and E. Kellner. 2023. Empirical research on polycentric governance: critical gaps and a framework for studying long-term change. Policy Studies Journal 00:1-30. https://doi.org/10.1111/psj.12518

Baldwin, E., C. Washington-Ottombre, J. Dell'Angelo, D. Cole, and T. Evans. 2016. Polycentric governance and irrigation reform in Kenya: polycentric water governance in Kenya. Governance 29 (2):207-225. https://doi.org/10.1111/gove.12160

Berardo, R., and M. Lubell. 2016. Understanding what shapes a polycentric governance system. Public Administration Review 76 (5):738-751. https://doi.org/10.1111/puar.12532

Berardo, R., and M. Lubell. 2019. The ecology of games as a theory of polycentricity: recent advances and future challenges. Policy Studies Journal 47(1):6-26. https://doi.org/10.1111/psj.12313

Bibri, S. E. 2018. Backcasting in futures studies: a synthesized scholarly and planning approach to strategic smart sustainable city development. European Journal of Futures Research 6 (13):1-27. https://doi.org/10.1186/s40309-018-0142-z

Bibri, S. E. 2020. A methodological framework for futures studies: integrating normative backcasting approaches and descriptive case study design for strategic data-driven smart sustainable city planning. Energy Inform 3:31. https://doi.org/10.1186/s42162-020-00133-5

Biddle, J. C., and K. J. Baehler. 2019. Breaking bad: when does polycentricity lead to maladaptation rather than adaptation? Environmental Policy and Governance 29(5):344-359. https://doi.org/10.1002/eet.1864

Blomquist, W. 1992. Dividing the waters: governing groundwater in Southern California. ICS Press, San Francisco, California, USA.

Blomquist, W., and J. Schröder. 2019. Seeing polycentrically: examining governance situations using a polycentricity lens. Pages 45-64 in A. Thiel, W. Blomquist, and D. Garrick, editors. Governing complexity: analyzing and applying polycentricity. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781108325721.003

Board of Water Commissioners of the City of Long Beach et al. v. San Gabriel Valley Water Company et. al. 1959.

Brewer, J. F. 2010. Polycentrism and flux in spatialized management: evidence from Maine's lobster fishery. Bulletin of Marine Science 86(2):278-302.

Cáceres, R., J. Pittman, M. Castrejón, and P. Deadman. 2022. The evolution of polycentric governance in the Galapagos small-scale fishing sector. Environmental Management 70:254–272. https://doi.org/10.1007/s00267-022-01666-z

California Service Water Company et al. v. City of Compton et al. 1961.

Carlisle, K. M., and R. L. Gruby. 2017. Polycentric systems of governance: a theoretical model for the commons. Policy Studies Journal 47(4):927-952. https://doi.org/10.1111/psj.12212

Carlisle, K. M., and R. L. Gruby. 2018. Why the path to polycentricity matters: evidence from fisheries governance in Palau. Environmental Policy and Governance 28(4):223-235. https://doi.org/10.1002/eet.1811

City of Pasadena v. City of Alhambra et al. 1937.

Cole, D. H. 2015. Advantages of a polycentric approach to climate change policy. Nature Climate Change 5(2):114-118. https://doi.org/10.1038/nclimate2490

Cole, D. H., G. Epstein, and M. D. McGinnis. 2019. The utility of combining the IAD and SES frameworks. Commons Journal 13(1):244-275. https://doi.org/10.18352/ijc.864

Cox, M., G. Arnold, and S. V. Tomás. 2010. A review of design principles for community-based natural resource management. Ecology and Society 15(4):38. https://doi.org/10.5751/ES-03704-150438

da Silveira, A. R., and K. S. Richards. 2013. The link between polycentrism and adaptive capacity in river basin governance systems: insights from the river Rhine and the Zhujiang (Pearl River) basin. Annals of the Association of American Geographers 103(2):319-329. https://doi.org/10.1080/00045608.-2013.754687

Dietz, T., E. Ostrom, and P. C. Stern. 2003. The struggle to govern the commons. Science 302:1907-1912. http://dx.doi.org/10.1126/science.1091015

Ebel, S. A. 2020. Moving beyond co-management: opportunities and limitations for enabling transitions to polycentric governance in Chile's territorial user rights in fisheries policy. International Journal of the Commons 14(1):278-295. https://doi.org/10.5334/ijc.998

Epstein, G., T. H. Morrison, A. Lien, G. G. Gurney, D. H. Cole, M. Delaroche, S. V. Tomas, N. Ban, and M. Cox. 2020. Advances in understanding the evolution of institutions in complex social-ecological systems. Current Opinion in Environmental Sustainability 44:58-66. https://doi.org/10.1016/j.cosust.2020.06.002

Famiglietti, J. S. 2014. The global groundwater crisis. Nature Climate Change 4(11):945-948. https://doi.org/10.1038/nclimate2425

Folke, C., L. Pritchard, Jr., F. Berkes, J. Colding, and U. Svedin. 2007. The problem of fit between ecosystems and institutions: ten years later. Ecology and Society 12(1):30. https://doi.org/10.5751/ES-02064-120130

Food and Agriculture Organization of the United Nations (FAO). 2016. Global diagnostic on groundwater governance. FAO, Rome, Italy.

Giordano, M. 2009. Global groundwater? Issues and solutions. Annual Review of Environment and Resources 34(1):153-178. https://doi.org/10.1146/annurev.environ.030308.100251

Heikkila, T. 2004. Institutional boundaries and common-pool resource management: a comparative analysis of water management programs in California. Journal of Policy Analysis and Management 23(1):97-117. https://doi.org/10.1002/pam.10181

Heikkila, T., S. Villamayor-Tomas, and D. Garrick. 2018. Bringing polycentric systems into focus for environmental governance. Environmental Policy and Governance 28 (4):207-211. https://doi.org/10.1002/eet.1809

Huitema, D., E. Mostert, W. Egas, S. Moellenkamp, C. Pahl-Wostl, and R. Yalcin. 2009. Adaptive water governance: assessing the institutional prescriptions of adaptive (co-)management from a governance perspective and defining a research agenda. Ecology and Society 14(1):26. https://doi.org/10.5751/ES-02827-140126

Imperial, M. T. 2005. Using collaboration as a governance strategy: lessons from six watershed management programs. Administration & Society 37(3):281-320. https://doi.org/10.1177/0095399705276111

Imperial, M. T., and T. Hennessey. 1999. Environmental governance in watersheds. Collaboration, public value, and accountability. Paper presented at the Twenty-First Annual Research Conference of the Association for Public Policy Analysis and Management, 4-6 November, 1999, Washington, D. C., USA.

Kelly, E. C., S. Charnley, and J. T. Pixley. 2019. Polycentric systems for wildfire governance in the western United States. Land Use Policy 89: 104214. https://doi.org/10.1016/j.landusepol.2019.104214

Kemper, K., A. Dinar, and W. Blomquist. 2005. Institutional and policy analysis of river basin management decentralization: the principle of managing water resources at the lowest appropriate level — when and why does it (not) work in practice? World Bank, Washington, D.C., USA.

Konikow, L. F. 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. Geophysical Research Letters 38(17):L17401. https://doi.org/10.1029/2011GL048604

Langridge, R., and C. Ansell. 2018. Comparative analysis of institutions to govern the groundwater commons in California. Water Alternatives 11(3):481-510.

Langridge, R., A. Brown, K. Rudestam, and E. Conrad. 2016. An evaluation of California's adjudicated groundwater basins. University of California Santa Cruz, Santa Cruz, California, USA. https://www.waterboards.ca.gov/water_issues/programs/gmp/docs/resources/swrcb_012816.pdf

Langridge, R., and B. Daniels. 2017. Accounting for climate change and drought in implementing sustainable groundwater management. Water Resources Management 31(11):3287-3298. https://doi.org/10.1007/s11269-017-1607-8

Langridge, R., and Van Schmidt, N. D. 2020. Groundwater and drought resilience in the SGMA era. Society & Natural Resources 33(12):1530-1541. https://doi.org/10.1080/08941920.2020.1801923

Lieberman, E. S. 2011. The perils of polycentric governance of infectious disease in South Africa. Social Science & Medicine 73:676–84. https://doi.org/10.1016/j.socscimed.2011.06.012

Lipson, A. 1978. Efficient water use in California: the evolution of groundwater management in Southern California. RAND Corporation, Santa Monica, California, USA. https://www.rand.org/content/dam/rand/pubs/reports/2009/R2387.2.pdf

Lubell, M., J. Mewhirter, and R. Berardo. 2020. The origins of conflict in polycentric governance systems. Public Administration Review 80(2):222-233. https://doi.org/10.1111/puar.13159

Lubell, M., and T. H. Morrison. 2021. Institutional navigation for polycentric sustainability governance. Nature Sustainability 4:664-671. https://doi.org/10.1038/s41893-021-00707-5

Lubell, M., and M. Robbins. 2021. Adapting to sea-level rise: centralization or decentralization in polycentric governance systems? Policy Studies Journal 50:143-175. https://doi.org/10.1111/psj.12430

Madani, K., and A. Dinar. 2012. Non-cooperative institutions for sustainable common pool resource management: application to groundwater. Ecological Economics 74:34-45. https://doi.org/10.1016/j.ecolecon.2011.12.006

Marshall, G. R. 2009. Polycentricity, reciprocity, and farmer adoption of conservation practices under community-based governance. Ecological Economics 68(5):1507-1520. https://doi.org/10.1016/j.ecolecon.2008.10.008

McCord, P., J. Dell'Angelo, E. Baldwin, and T. Evans. 2017. Polycentric transformation in Kenyan water governance: a dynamic analysis of institutional and social-ecological change. Policy Studies Journal 45(4):633-658. https://doi.org/10.1111/psj.12168

McGinnis, M. D. 2011. Networks of adjacent action situations in polycentric governance: adjacent action situations. Policy Studies Journal 39:51-78. https://doi.org/10.1111/j.1541-0072.2010.00396.x

McGinnis, M. D., and E. Ostrom. 2014. Social-ecological system framework: initial changes and continuing challenges. Ecology and Society 19(2):30. https://doi.org/10.5751/ES-06387-190230

McGinnis, M. D., and J. M. Walker. 2010. Foundations of the Ostrom workshop: institutional analysis, polycentricity, and self-governance of the commons. Public Choice 143(3):293-301. https://doi.org/10.1007/s11127-010-9626-5

Megdal, S. B., A. K. Gerlak, R. G. Varady, and L. Y. Huang. 2015. Groundwater governance in the United States: common priorities and challenges. Groundwater 53(5):677-684. https://doi.org/10.1111/gwat.12294

Megdal, S. B., A. K. Gerlak, L. Y. Huang, N. Delano, R. G. Varady, and J. D. Petersen-Perlman. 2017. Innovative approaches to collaborative groundwater governance in the United States: case studies from three high-growth regions in the Sun Belt. Environmental Management 59(5):718-735. https://doi.org/10.1007/s00267-017-0830-7

Morrison, T. H. 2017. Evolving polycentric governance of the Great Barrier Reef. Proceedings of the National Academy of Sciences 114(15):E3013-E3021. https://doi.org/10.1073/pnas.1620830114

Morrison, T. H., W. N. Adger, K. Brown, M. C. Lemos, D. Huitema, J. Phelps, and T. P. Hughes. 2019. The black box of power in polycentric environmental governance. Global Environmental Change 57:101934. https://doi.org/10.1016/j.gloenvcha.2019.101934

Morrison, T. H., Ö. Bodin, G. S. Cumming, M. Lubell, R. Seppelt, T. Seppelt, and C. M. Weible. 2023. Building blocks of polycentric governance. Policy Studies Journal 51(3):475-499. https://doi.org/10.1111/psj.12492

Mudaliar, P. 2023. What matters for coordination? Examining overlaps and interactions in Lake Victoria's polycentric fisheries in Tanzania. Regional Environmental Change 23(4):136. https://doi.org/10.1007/s10113-023-02135-x

Mudliar, P. 2021. Polycentric to monocentric governance: power dynamics in Lake Victoria's fisheries. Environmental Policy and Governance 31(4):302-315. https://doi.org/10.1002/eet.1917

Mudliar, P., and L. O'Brien. 2021. Crowding-out lower-level authorities: interactions and transformations of higher and lower-level authorities in Kenya's polycentric fisheries. Environmental Science & Policy 118:27-35. https://doi.org/10.1016/j.envsci.2021.01.007

Olsson, P., L. H. Gunderson, S. R. Carpenter, P. Ryan, L. Lebel, C. Folke, and C. S. Holling. 2006. Shooting the rapids: navigating transitions to adaptive governance of social-ecological systems. Ecology and Society 11(1):18. https://doi.org/10.5751/ES-01595-110118

Ostrom, E. 1990. Governing the commons: the evolution of institutions for collective action. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9780511807763

Ostrom, E. 2007. A diagnostic approach for going beyond panaceas. Proceedings of the National Academy of Sciences 104 (39):15181-15187. https://doi.org/10.1073/pnas.0702288104

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325(5939):419-422. https://doi.org/10.1126/science.1172133

Ostrom, E. 2010. Beyond markets and states: polycentric governance of complex economic systems. American Economic Review 100(3):641-72. https://doi.org/10.1257/aer.100.3.6419

Ostrom, E., and M. Cox. 2010. Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. Environmental Conservation 37(4):451-463. https://doi.org/10.1017/S0376892910000834

Ostrom, E., M. A. Janssen, and J. M. Anderies. 2007. Going beyond panaceas. Proceedings of the National Academy of Sciences 104 (39):15176-15178. https://doi.org/10.1073/pnas.0701886104

Ostrom, V. 1999. Polycentricity (part 1). Pages 52-74 in M. D. McGinnis, editor. Polycentricity and local public economies. University of Michigan Press, Ann Arbor, Michigan, USA.

Ostrom, V., C. M. Tiebout, and R. Warren. 1961. The organization of government in metropolitan areas: a theoretical inquiry. American Political Science Review 55(4):831-842. https://doi.org/10.2307/1952530

Özerol, G., J. Vinke-de Kruijf, M. C. Brisbois, C. Casiano Flores, P. Deekshit, C. Girard, C. Knieper, S. J. Mirnezami, M. Ortega-Reig, P. Ranjan, et al. 2018. Comparative studies of water governance. Ecology and Society 23(4):43. https://doi.org/10.5751/ES-10548-230443

Pahl-Wostl, C. 2009. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environmental Change 19(3):354-365. https://doi.org/10.1016/j.gloenvcha.2009.06.001

Pahl-Wostl, C. 2017. An evolutionary perspective on water governance: from understanding to transformation. Water Resources Management 31(10):2917-2932. https://doi.org/10.1007/s11269-017-1727-1

Pahl-Wostl, C., and C. Knieper. 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. Global Environmental Change 29:139–154. https://doi.org/10.1016/j.gloenvcha.2014.09.003

Persad, G. G., D. L. Swain, C. Kouba, and J. P. Ortiz-Partida. 2020. Inter-model agreement on projected shifts in California hydroclimate characteristics critical to water management. Climatic Change 162(3):1493-1513. https://doi.org/10.1007/s10584-020-02882-4

Quist, J. 2007. Backcasting for a sustainable future: the impact after 10 years. Dissertation. Delft University of Technology, Delft, The Netherlands.

Robinson J. 1990. Futures under glass: a recipe for people who hate to predict. Futures 22(8):820-842. https://doi.org/10.1016/0016-3287(90)90018-D

Rodell, M., I. Velicogna, and J. S. Famiglietti. 2009. Satellite-based estimates of groundwater depletion in India. Nature 460 (7258):999-1002. https://doi.org/10.1038/nature08238

Sandström, A., B. Crona, and Ö. Bodin. 2014. Legitimacy in co-management: the impact of preexisting structures, social networks, and governance strategies. Environmental Policy and Governance 24(1):60-76. https://doi.org/10.1002/eet.1633

Sarker, A. 2013. The role of state-reinforced self-governance in averting the tragedy of the irrigation commons in Japan. Public Administration 91(3):727-743. http://dx.doi.org/10.1111/padm.12011

Schlager, E. 2006. Challenges of governing groundwater in U.S. western states. Hydrogeology 14(3):350-360. https://doi.org/10.1007/s10040-005-0012-1

Schlager, E., W. Blomquist, and S. Y. Tang. 1994. Mobile flows, storage, and self-organized institutions for governing common-pool resources. Land Economics 70(3):294-317. https://doi.org/10.2307/3146531

Schlager, E., and T. Heikkila. 2011. Left high and dry? Climate change, common-pool resource theory, and the adaptability of western water compacts. Public Administration Review 71 (3):461-470. https://doi.org/10.1111/j.1540-6210.2011.02367.x

Schröder, N. J. S. 2018. The lens of polycentricity: identifying polycentric governance systems illustrated through examples from the field of water governance. Environmental Policy and Governance 28(4):236-251. https://doi.org/10.1002/eet.1812

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann. 2010. Groundwater use for irrigation – a global inventory. Hydrology and Earth Systems Science 14:1863-1880. https://doi.org/10.5194/hess-14-1863-2010

Skelcher, C. 2005. Jurisdictional integrity, polycentrism, and the design of democratic governance. Governance 18(1):89-110. https://doi.org/10.1111/j.1468-0491.2004.00267.x

Sovacool, B. K. 2011. An international comparison of four polycentric approaches to climate and energy governance. Energy Policy 39:3832-3844. https://doi.org/10.1016/j.enpol.2011.04.014

Stephan, M., G. Marshall, and M. McGinnis. 2019. An introduction to polycentricity and governance. Pages 21-44 in A. Thiel, D. E. Garrick, and W. A. Blomquist, editors. Governing complexity: analyzing and applying polycentricity. Cambridge University Press, Cambridge, UK.

Theesfeld, I. 2010. Institutional challenges for national groundwater governance: policies and issues. Groundwater 48 (1):131-142. https://doi.org/10.1111/j.1745-6584.2009.00624.x

Thiel, A., and C. Moser. 2019. Foundational aspects of polycentric governance. Pages 65-90 in A. Thiel, D. E. Garrick, and W. A. Blomquist, editors. Governing complexity: analyzing and applying polycentricity. Cambridge University Press, Cambridge, UK.

Thiel, A., R. Pacheco-Vega, and E. Baldwin. 2019. Evolutionary institutional change and performance in polycentric governance. Pages 91-110 in A.Thiel, W. A. Blomquist, and D. Garrick, editors. Governing complexity: analyzing and applying polycentricity. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781108325721.005

Van der Heijden, J., J. Kuhlmann, E. Lindquist, and A. Wellstead. 2021. Have policy process scholars embraced causal mechanisms? A review of five popular frameworks. Public Policy and Administration 36(2):163-186. https://doi.org/10.1177/0952076718814894

Varady, R. G., A. A. Zuniga-Teran, A. K. Gerlak, and S. B. Megdal. 2016. Modes and approaches of groundwater governance: a survey of lessons learned from selected cases across the globe. Water 8(10):417. https://doi.org/10.3390/w8100417

Vergragt, P. J., and J. Quist. 2011. Backcasting for sustainability: introduction to the special issue. Technological Forecasting and Social Change 78(5):747-755. https://doi.org/10.1016/j.techfore.2011.03.010

Wada, Y., L. P. Van Beek, C. M. Van Kempen, J. W. Reckman, S. Vasak, and M. F. Bierkens. 2010. Global depletion of groundwater resources. Geophysical Research Letters 37(20). https://doi.org/10.1029/2010GL044571

Weible, C. M., J. Yordy, T. Heikkila, H. Yi, R. Berardo, J. Kagan, and C. Chen. 2020. Portraying the structure and evolution of polycentricity via policymaking venues. International Journal of the Commons 14(1):680-691. https://doi.org/10.5334/ijc.1021

Young, O. R. 2002. The institutional dimensions of environmental change: fit, interplay, and scale. MIT Press, Cambridge, Massachusetts, USA. https://doi.org/10.7551/mitpress/3807.001.0001