How state-reinforced knowledge infrastructure influences adaptive urban water governance

ABSTRACT

Resilience and environmental governance scholars have long studied and debated the role of the state in driving or coordinating responses to the varied dimensions of adaptive governance. In this study, we empirically analyze how multilevel, state-reinforced institutional designs impact the adaptive governance of urban water systems by structuring information production and use. Specifically, we analyze the multilevel institutional designs of "knowledge infrastructure systems," defined as the rules and capacities within a system that allow actors to "produce, curate and communicate" information for governance. Drawing on a novel compilation of hydroclimatic data, media content, interviews, planning documents, and institutional designs, we empirically examine a typology of multi-level institutional arrangements in four U.S. urban water systems. Drawing from scholarship that considers the reflexivity of legal avenues and system performance, we conclude that state-reinforced rules governing the production and use of knowledge can clarify capacity-needs and support the efforts of managers responding to climate stressors through adaptive governance processes. They do so by formalizing planning types, timelines, and sanctions for noncompliance, while allowing local users and providers flexibility to innovate within these processes.

INTRODUCTION

Organisms, species, and societies all need accurate information about their environments to survive and adapt (Parr et al. 2022). In complex and highly dynamic socio-environmental systems, adaptation requires rapidly accumulating and processing information about system dynamics and feedbacks, as well as the ability to reflexively respond to such information via plausible expectations about the future (Anderies et al. 2019, Deslatte et al. 2024). In natural resource governance systems, doing this often requires adaptive approaches (Folke et al. 2005, Emerson and Gerlak 2014, Whaley and Weatherhead 2014, Craig et al. 2017) that support flexible, iterative, and malleable decision-making processes (Craig et al. 2017). However, scholars working across disciplinary fields lack a unified, consistent approach for determining what specific types of governmental institutions best support adaptive governance, given that the information for adequately managing yesterday's challenges may not be suited for those of today or tomorrow (Ostrom 2009, Folke et al. 2010, Schlager and Heikkila 2011, Anderies et al. 2013, Leslie et al. 2015).

In particular, resilience and environmental governance scholars have long studied and debated the role of the state in driving or coordinating adaptive governance (Ostrom 1990, Folke et al. 2010, Garmestani et al. 2019). In multilevel arrangements, the "state" refers to the constitution of formal authority to empower or constrain collective-action across levels of governance through the development of overarching rules, the provision of information or funding, or other pathways in which knowledge may be co-produced (Dietz et al. 2003, Sarr et al. 2021). Understanding how such “state-reinforced” governance arrangements (DeCaro et al. 2017) impact adaptive processes at other levels is therefore critical to designing governance institutions that can better support adequate responses (Ostrom 2009, Folke et al. 2010, Schlager and Heikkila 2011, Anderies et al. 2013, Leslie et al. 2015).

In this study, we empirically analyze how multilevel, state-reinforced designs impact the adaptive governance of urban water systems, primarily through their role in structuring information production and use. Urban water systems are an example of a heavily-engineered coupled infrastructure system (CIS) that depends on multiple types of information to preserve desired performance within some acceptable bounds (Anderies and Janssen 2013, Levin et al. 2022). Moreover, water systems are some of the first places where the impacts of climate change have been demonstrated (Schlager and Heikkila 2011, Garcia et al. 2022), prompting the need for rapid climate action. Just as many forms of “natural” and “hard” infrastructure in urban water systems (water sources, reservoirs, treatment plants, distribution systems) constrain the ability of managers to take such action, so too do multiple levels of “soft” infrastructure (laws, regulations, policies) that directly influence how water system governance happens.

Specifically, we analyze the multilevel institutional designs of “knowledge infrastructure systems,” defined as the rules and capacities within a system that allow actors to “produce, curate and communicate” information for governance (Anderies et al. 2019:5277). We posit that multilevel knowledge infrastructure influences urban water governance in several critical ways. For instance, water managers increasingly need to identify and plan for a menu of voluntary or mandatory water use restrictions and alternative supply sources to help ensure that variability in precipitation and streamflow does not impact the reliability of water deliveries. To do so, governmental entities at multiple levels (i.e., municipal, regional, state, national) may permit or require specific types of analysis or coordination by different actors (Craig et al. 2017), which influences the types of information decision makers at more localized levels, such as water utilities, have access to and, ultimately, the types of actions they take. Within this context, we ask the following research question: how does state-reinforced knowledge infrastructure influence adaptive governance processes in urban water supply systems?

Drawing on a novel compilation of hydroclimatic data, media content, interviews, planning documents, and institutional data, we empirically examine adaptive governance processes in a spectrum of multilevel institutional arrangements in four U.S. urban water coupled-infrastructure systems (UW-CISs), with a focus on the impact of their respective state-reinforced knowledge infrastructure. Drawing from scholarship that considers the reflexivity of legal avenues (DeCaro et al. 2017) and the performance of CISs (Anderies and Levin 2023), we conclude that state-reinforced rules governing the production and use of knowledge can clarify capacity-needs and support the efforts of managers responding to climate stressors through adaptive governance processes. They do so by formalizing planning types, timelines, and sanctions for noncompliance, while allowing local users and providers flexibility to innovate within these processes.

KNOWLEDGE INFRASTRUCTURE FOR DECISION MAKING IN SOCIO-ENVIRONMENTAL SYSTEMS

Scholars routinely observe that adaptive environmental governance requires striking a balance between the stability of governance institutions and the flexibility societies need in order to adjust flows of investments, resource outputs, and information (Moser and Ekstrom 2010, Chaffin et al. 2016, Craig et al. 2017, DeCaro et al. 2017, Garmestani et al. 2019). Anderies and colleagues (2019) contend that knowledge infrastructure plays a critical yet under-examined role in striking this balance (Anderies et al. 2013, Anderies et al. 2019). Knowledge infrastructure (KI) consists of the "knowledge types and knowledge mobilization strategies managers use" (Anderies et al. 2019:5281) in governance processes aimed at maintaining safe operating spaces. They work by supporting collective or group-based active inference processes (Friston 2010, Parr et al. 2022), wherein humans with contested welfare goals make predictions about current or future environmental conditions and attempt to update these prior predictions when encountering disconfirming information (Constant et al. 2022, Clark 2023). KI may be generated by universities, national, state, or local governmental agencies, media, community organizations, and other resource user groups, all of whom possess assets that allow information to be produced, curated, and distributed (Anderies et al. 2019).

Figure 1 conceptually depicts a knowledge infrastructure system for an exploited ecosystem, including four knowledge types (blue lines) identified by Anderies and colleagues (2019) as important for governance in social-ecological systems:

K1: Knowledge about or experience with the past, which requires infrastructure (people and sensors) capable of building longitudinal or time-series data as well as "institutional knowledge" of a system's capacities and weaknesses (Ives et al. 2003);

K2: Knowledge about the interactions of ecosystem dynamics, decision-making and exogenous drivers, which requires scientific expertise from climate and social/behavioral scientists (Tversky and Kahneman 1974, Walters 1997, Forrester et al. 2014);

K3: Knowledge about future events based on properties of uncertainty, which have typically been difficult to model with localized specificity because of high spatial variability of hydroclimatic variables and spatially coarse climate change projections (Hanna and Marqusee 2022, Stevenson et al. 2022, Wing et al. 2022); and

K4: Knowledge about resource use or appropriation, which requires ongoing monitoring or self-reporting (Cox et al. 2010, Anderies et al. 2019).

These various forms of knowledge, along with the contested objectives of policy actors, feed into group-based active inference processes (gray oval) regarding exploited ecosystems, wherein groups make predictions, take action, experience the outcomes of those actions, and potentially update their perceptions. The group-based inference processes support actions that feed back to reshape the dynamics of exploitation in the system and, therefore, the system state (Deslatte et al. 2024).

Many engineering-based approaches to modeling these systems depict the translation of information into action as an automatic, algorithmic-like function once measurements of some system characteristics reach a threshold (i.e., a closed-loop feedback controller, like a thermostat). However, these models largely ignore the "real world" political or institutional contexts through which a CIS translates different types of information and contested welfare goals into collective action (Anderies et al. 2019). This can be observed in practice when resource planners and managers in urban water systems face significant knowledge deficits and cognitive limitations (Herman et al. 2020, Tubridy et al. 2021, Garcia et al. 2022). In these cases, CISs are thought to rely predominantly on certain streams of knowledge within KI, such as K1, that are designed to translate high variability in input signals into nearly constant outputs.

When considering the impacts of climate change, however, managers must actively work to update their plans and predictions about future conditions as new types of information are made available (Parr et al. 2022, Clark 2023). In doing so, decision makers must also account for the dynamics or interactions between social and economic features (K2) and future uncertainties (K3) as climate change shifts hydroclimatic trends from historical, stationary patterns (Folke et al. 2010). Finally, all these stochastic- or experience-based approaches are premised on the ability to accurately monitor resource appropriation levels (K4), which is one of the core institutional "design principles" that Ostrom and colleagues identified for managing common-pool resources (Ostrom 1990, Cox et al. 2010). These knowledge types can be harder for public organizations to develop given the need for various forms of scientific expertise and the inherent, probabilistic uncertainty in downscaling global climate modeling with practical specificity to local infrastructure needs.

STATE-REINFORCED KNOWLEDGE INFRASTRUCTURE

Although often overlooked by adaptive governance scholars, one way higher-level governmental authorities influence lower-level adaptive governance is through the legal and institutional principles they promulgate (DeCaro et al. 2017), which enable or constrain various forms of knowledge. For instance, Craig et al. (2017) note that U.S. environmental laws are based on historical ecological conditions, which can create "the illusion of stability" because of faulty assumptions about the predictability and reversibility of ecological states (Craig et al. 2017). Because these laws provide high-level guidance for environmental governance across the multilevel system, they may undermine effective governance in the contemporary context by failing to account for the impacts and uncertainties of climate change, especially when they vary at smaller scales. At the same time, Garmestani and colleagues (2019) contend that, given advances in scientific understanding of social-ecological dynamics, even laws based on past conditions can provide "substantive flexibility and procedural discretion" by allowing lower-level administrators the capacity to promulgate new requirements, standards, or prohibitions, and roll back poorly performing ones (Garmestani et al. 2019). Thus, it is critical to not only understand what kinds of knowledge are constructed and mobilized by higher-level governmental institutions, but also how this differentially impacts adaptive governance processes at other levels. Here, we illustrate how examples of higher-level governmental institutions discussed by DeCaro et al. (2017), specifically reflexive law, legal sunsets, and legally binding authority and responsibility, have implications for enabling or constraining various types of knowledge throughout the multilevel system.

Reflexive law and legal sunsets

Reflexive law supports standards or procedures for decision making rather than static rules for appropriation (e.g., water allocation), while sunset provisions may require periodic planning and review of strategies or goals. As an example of reflexivity, U.S. community water systems regulated under the federal Safe Drinking Water Act (SDWA) are required to regulate more than 90 contaminants and monitor other non-regulated ones. Most contaminants are the product of various environmental, industrial, and/or agricultural interactions (K2), and regulating them depends upon being able to adequately monitor the distribution system and homes (K4). However, the U.S. Environmental Protection Agency (EPA) is allowed to take many factors into consideration in setting "feasible" enforceable standards for water systems, including the affordability of technology, available treatment techniques, the capacities of smaller systems, or other cost-factors, the net effect of which allows for broader peer engagement and reflection upon best practice, past experience, and available innovations (Tiemann 2014, Westling et al. 2019). Moreover, systems are required under the SDWA to maintain certified workforces, which can be an important source of institutional or historical knowledge of a system's performance and capacity (K1). Here, the EPA allows utilities to use online training and testing, extend deadlines for expiring operator certifications, and to rely on reciprocity in staffing from other jurisdictions to meet these requirements.

As an example of sunset provisions, a number of states require regularly updated regional or jurisdiction-level long-range water planning (Herman et al. 2020). Texas, for instance, updates its State Water Plan every five years to detail supplies, current demands, and projected needs across municipal, agricultural, and other users spread throughout 16 hydrologically diverse planning regions (K1 and K4). The required updates to such plans function as a sunset by prompting revaluation of current strategies and outcomes, as well as the potential introduction of new science or best practice. Both these legal design principles introduce flexibility, but require, at a minimum, supportive knowledge infrastructure that can mobilize diverse experiences and backgrounds in decision making (K1), aid in determining the boundaries and interaction effects between political, social, and ecosystem characteristics (K2), and monitoring of resource use (K4).

Legally binding authority and responsibility

Authority to decide on and implement policies locally as well as the assignment of responsibility for collectively resolving social dilemmas are critical within multilevel governance contexts. In the context of water management, both authority and responsibility can be shared or contested between multiple entities across scales and jurisdictions (Carlisle and Gruby 2018).

Critically, exercising effective legal authority over water systems can depend upon knowledge of other users' behavior, given the nature of the resource (groundwater aquifers and shared surface water sources) and the reality that urban water utilities are nested in broader, multilevel governance networks (K4; Huitema and Meijerink 2010, Garcia et al. 2019, Manny et al. 2022, Pahl-Wostl and Knieper 2023, Wiechman et al. 2024). Clear authority over water use can be further obfuscated by the variation in authority that water utilities have across states, which means that some nested political or institutional systems can appear rigid or nonresponsive to emerging challenges like climate change (Epstein et al. 2015, Chaffin et al. 2016, DeCaro et al. 2017). For instance, many state-level utility regulatory commissions make determinations about water system rates and long-range planning based on narrowly defined or ambiguous legal criteria like “reliability” or “reasonableness” determined solely from K1 and K4 knowledge types (Deslatte et al. 2024). Even the introduction of information pertaining to long-range resource sustainability (K2 and K3) can be challenged on the grounds that rate-structures supporting intergenerational equity goals may adversely impact current users (Teodoro 2010, Deslatte et al. 2022a).

Pertaining to legal responsibility, as previously noted, community water systems regulated under the SDWA are responsible for monitoring various water contaminants; however, water systems are also increasingly inheriting responsibility for resolving broader environmental problems. California water utilities, for instance, must now account for climate change impacts in their water management planning (K3).

The legal principles discussed above each introduce stability into multi-level adaptive governance processes by mobilizing knowledge types that support internal monitoring and enforcement of appropriation (K1 and K4) as well as conflict resolution (K2). However, given the need for flexibility in adaptive governance processes, especially in the context of urban water management under climate change, they may also constrain necessary action that requires new types of knowledge. Thus, we pay special attention to the presence and impact of these legal principles when empirically examining how state-reinforced KI impacts adaptive urban water governance processes. Our methods for doing so are described next.

METHODS

We focus on identifying relevant knowledge infrastructure in four U.S. urban water systems (Santa Rosa, CA; San Jose, CA; Phoenix, AZ; and Indianapolis, IN) by tracing the development of long-range water planning over a decadal period (approximately 2009–2021). Our cases were chosen as part of a broader research effort that involved identifying variation in hydroclimatic conditions and creating a six-category taxonomy of governance rules determining who is responsible for setting water rates and how they enter and exit their positions (see Deslatte et al. 2022b, for a detailed description of the case selection methodology). From an initial list of 40 candidate cases, we reduced the sample to 16 cases for analysis based on convenience and to achieve a geographically diverse set of cases. Depicted in Table 1, the case selection attempts to maximize differences along two dimensions: state-reinforced KI pertaining to climate planning and the degree of local autonomy vs. political accountability the urban water utility possesses to set water rates and infrastructure investments. This allows us to compare evidence from cases that vary along one of these dimensions but are similar on the other (e.g., high vs. low state-reinforcement, but similar local autonomy). The time period was chosen based on data availability and to allow enough time for observing iterative planning efforts as the utilities faced supply threats from drought, urbanization, or other environmental changes. The empirical analysis proceeds in two steps, following a methodology used by Garcia and colleagues (2019) based on the Institutional Analysis and Development (IAD) framework developed by Elinor Ostrom (2009).

Within-case synthesis

First, we conducted a within-case synthesis of hydrological, media, interview, and institutional data sources, rooted in the Treuer et al. (2017) method, to examine the relationship between multilevel state-enabling or state-constraining rules, biophysical and community contexts, and the combinations of knowledge used in water planning. This approach involved synthesizing changes to information mobilized via planning during the study period as a result of differences in the institutional designs for knowledge production and use, along with changes in hydrological streamflow, precipitation, and media time-series data. For each case, we identified data conforming to the IAD's categories of variables, depicted in Figure 2, representing relevant rules in use (laws, regulations governing water-supply planning), the biophysical characteristics (meteorology and hydrology), and the community attributes (public salience or attention to water issues; McGinnis 2011, Garcia et al. 2019). We synthesized these sources to create data-driven narratives for each case, which averaged approximately 2000 words in length and detailed the hydrological trends, governance context, the multilevel, state-enabling, or constraining rules in use and the combinations of knowledge that influenced planning efforts (Treuer et al. 2017). We used these narratives to investigate patterns in changes over time for each case. Data types and sources are reported in Table 2 and discussed in more detail below.

Biophysical conditions

To examine biophysical conditions, we identified periods of meteorological and hydrological droughts using precipitation and streamflow data, respectively. We obtained total monthly precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al. 2008), and computed the average for each basin that supplies water to the cities. Daily streamflow data were downloaded from the U.S. Geological Survey (USGS) using the R package dataRetrieval (DeCicco et al. 2024) and submitted to a completeness requirement to ensure data gaps did not bias results, with a maximum allowable gap of two days in any given year. Drought was defined as a period of abnormally dry weather sufficiently long enough to cause a serious hydrologic imbalance in a specific area (Blunden et al. 2023). Drought was characterized by an extended period of unusual precipitation or streamflow deficit in relation to the long-term average conditions, and it is usually quantified through two indexes: the Standardized Precipitation Index (SPI) for precipitation deficits and the Standardized Streamflow Index (SSI; Vicente-Serrano et al. 2012) for streamflow deficits. We calculated the SPI and SSI using a 2-year/24-month accumulation period (abbreviated as SPI-24 or SSI-24) because we considered it more relevant for water resource management, including reservoir management, groundwater recharge, and overall water supply planning.

Community attributes

To examine community attributes relevant to resource users, we examined news media from each city's newspaper of record to capture the public salience of water issues. We searched for relevant articles in U.S. Newsstream, a commonly used news database (Buntain et al. 2023). Our query located articles with a main subject of water within the study period (2008 and 2022). Articles were categorized by multiple main subjects; any articles about water in some capacity (e.g., water shortages, droughts, water conservation, water utility) were expected to be identified by the main subject of water. We then employed Structural Topic Modeling (STM) using the R package STM to identify the primary topics in each city's news article corpus across the study period and to assign news articles to a given topic and track how such topics change in prevalence over time.

Rules in use

To examine formal rules, we used the Institutional Grammar Tool (IGT) developed by Crawford and Ostrom (1995) to decompose the syntactic components of relevant institutional statements (rules) extracted from state statutes, local ordinances, and administrative code (Siddiki et al. 2022). We used these data to create institutional network diagrams depicting the formal actors (the attributes of institutional statements); the formal requirements (aims) for generating, curating, and mobilizing information in long-range water plans (objects); the permissible or obligatory nature of the effort (deontics); and the context (activation conditions/execution constraints) applied to them (for a full description of the methodology see Mesdaghi et al. 2022, Deslatte et al. 2023). This step produces a formal mapping of the state-reinforced activities likely to enable or constrain information flows (Anderies et al. 2019). We labeled these formal enablements or constraints institutional dependencies, consistent with recent IAD work, and empirically identified them through instances where the conditions for taking an action and the object of that action were dependent upon each other (Mesdaghi et al. 2022, Deslatte et al. 2023).

Planning processes and knowledge infrastructure

Finally, to identify the knowledge infrastructure used in our cases, we descriptively coded all available water management plans and interviews using a codebook developed by the authors to study iterative collective action situations. This step focused on identifying sources and methods of knowledge accumulation or use (K1–4) in planning documents, and was augmented by semi-structured interviews with utility managers from the four cases (N = 12). The interviews asked questions about types of information used in decision making, the role of the media, and water challenges utilities faced; they were transcribed and coded to detect patterns in data on these themes.

Data synthesis through cross-case comparison

In the second step of our methodology, we conducted cross-case comparisons of state-reinforced KI systems, which are the primary results presented below, based on the aforementioned legal principles. By systematically exploring the same metrics across multiple cases, we argue that we can extract a broader understanding of the state role in the adaptive governance of urban water systems.

RESULTS

Broadly, we found evidence across our cases that state-reinforcement of adaptive governance processes, or the lack thereof, played an important role in supporting or directing climate responses. We observed a similar, iterative pattern driven by distinct hydroclimatic changes, in which utilities attempted to first develop more comprehensive or accurate data on the state of the system (K1), the socioeconomic dynamics impacting it (K2), and improved monitoring of system exploitation (K4). Figure 3 displays precipitation deficits across the four cases over a roughly 100-year period, illustrating that all four cases experienced extreme hydroclimatic shifts during the study period. Additionally, we found that media attention during the period was generally responsive to water-rate increases, changes in governance, and use restrictions driven by these extreme events.

We also found that state-constraints on welfare goals appeared to restrict the ability of Indianapolis utility managers to incorporate knowledge about climate-driven uncertainties into planning (K3). Meanwhile, Phoenix, facing the potential for federal water allocation reductions from the Colorado River, attempted to develop a more diverse knowledge infrastructure in the absence of legal requirements or sunset provisions, tapping other governmental and university-based capacities. In the California cases, state-requirements for climate planning were imposed, along with legal sunsets (requirements for new planning), but these processes were flexible enough to allow for varied approaches to compliance.

From our within-case syntheses and cross-case comparisons presented below, we concluded that combinations of both high state-reinforcement and low political autonomy can support adaptive governance through knowledge-building, while overly constraining institutions hinder this effort. Low political autonomy appears to aid (rather than hinder) in responding to extreme events, but this finding is contingent on the presence of reflexive local rules for planning and investment. We begin by discussing and comparing cases of low state-reinforcement (Indianapolis and Phoenix) before moving to cases with high state-reinforcement (Santa Rosa and San Jose).

Low state-reinforcement: Indianapolis and Phoenix

Phoenix and Indianapolis present stark contrasts in two regards: they feature the most extreme hydroclimatic differences between cases, and they have distinct local institutional arrangements for governing water supplies. Indianapolis features a water utility overseen by a nonprofit trust (high local political autonomy) and has experienced its wettest decade on record in the 2010s; Phoenix has a municipally owned utility (low local autonomy) and has experienced a multi-decade drought. Both utilities operate in a multilevel system; however, formal state-reinforcing rules for climate-related governance are absent. We found the lack of state-reinforcing climate rules hindered the ability of Indianapolis to develop knowledge infrastructure that could aid in adaptive governance processes, but did not have the same effect in Phoenix because of both the extreme nature of its drought and the legal reflexivity present in the City's local planning processes.

Biophysical and community context

Indiana is a riparian water rights state, meaning most any water user may access water sources, and the state lacks any significant statewide or regional water supply or quality planning requirements. Situated within a borderline humid subtropical climate in the upper Midwestern U.S., the Indianapolis utility has extracted water from three reservoirs fed by the White River and its tributaries. Approximately 84% of its supply comes from surface water, with the remainder sourced from five groundwater stations. Generally since 2000, the water system has observed continuous wet spells and higher flows than usual, with the total annual precipitation consistently exceeding the long-term annual average. Figure 4, left, top, depicts the Geist reservoir in this system. In particular, the 2010s marked the wettest multi-year period on record. Despite this, Indianapolis experienced a summer drought in 2012, which threatened supplies and prompted local mandatory water restrictions on outdoor water use.

During the first half of the study period, media attention in Indianapolis focused on municipal water issues and water politics coinciding with the city's 2011 decision to transfer its debt-laden water utility to a public trust (detailed below; Fig. 4, left, bottom). Beginning in 2015, we observed a shift in attention to issues related to water quality and water governance as the utility repeatedly raised wastewater rates to comply with an EPA consent decree to reduce water pollution from its combined sewer system.

By contrast, Phoenix is located within the hottest desert region in North America. Facing depleting water resources, the Arizona Legislature adopted a comprehensive Groundwater Management Act in 1980, which established groundwater rights, conservation requirements, water supply assurance standards for subdivisions, and the creation of five regional Active Management Areas (AMA) for water planning and regulation throughout the state. The City of Phoenix's Water Services Department (WSD) is the largest utility within the Phoenix AMA. As a result, the Phoenix utility shifted its water use to primarily surface sources: the Salt and Verde River watersheds through canals managed by the Salt River Project (SRP), and the Colorado River through the Central Arizona Project (CAP). Like other western states, Arizona governs surface water use under the legal doctrine of prior appropriation, which gives priority rights to earliest users. Phoenix surface water rights were developed through a complex process of interstate and federal water rights negotiations and contracts, which divide Colorado River water between seven basin states.

Since the 1990s, the Colorado River Basin has experienced an unprecedented and prolonged drought, aggravated by an overallocation of resources and climate-driven reductions in snowpack (Fig. 4, right, top). Despite the long-term nature of the drought, media attention to water supply oscillated from a low point (2009–2013) to spikes in 2015, 2018, and 2020 coinciding with successive water-rate increases (Fig. 4, right, bottom); utility managers framed the need for these rate increases around the "uncertainties" of future hydroclimatic conditions and aging infrastructure (Deslatte et al 2023).

Governance processes and knowledge infrastructure

The City of Indianapolis transferred its water and wastewater utilities to Citizens Energy Group (CEG) in 2011, which is a public charitable trust whose directors (IND BOD) are appointed by a private Board of Trustees (IND BOT) that fills its own board vacancies (high local political autonomy). Figure 5 depicts the formal planning processes in Indiana (upper pane in blue), in which the Indiana Utility Regulatory Commission (IURC, coded as both an Indirect Object and Attribute using the IGT) oversees water supply planning. The diagrams depict networks linking the actions an actor or group may, must, or must not take, conditioned on other statements that illustrate dependencies, or the formal linkage between specific conditions for taking action and the receiver (object) of that action. We identified two important dependencies in Indianapolis (dotted lines). Exemplifying the lack of state-reinforcement, utilities are allowed, but not required, to develop Future Water Supply Plans (gray oval). However, the plans must be submitted to the IURC and are evaluated based on criteria (dependencies) such as whether they are "reasonable," "prudent," and "reliable." The plans also must address all anticipated costs, alternative sources and any impacted property rights. Water rate increases must also be consistent with these plans. Utilities "may" submit any Environmental Compliance Plans to the IURC necessary to comply with federal drinking water laws, but submitted plans must be evaluated based on whether they are the "least-cost," "efficient," and "economical" options. Interviewees noted CEG's unique governance arrangement insulated utility decision making from "partisan politics" and "the political calendar," [Interviewee IN03] which corresponds with the decline of media topics focused on water politics and municipal water during the study period.

However, throughout the study period, the absence of any state-reinforcing climate rules negatively impacted information across utilities, and was noted by multiple Indiana state agencies and advocacy organizations. Following the 2012 drought, the IURC reported that Indiana utilities lacked "basic data" on regional systems to modernize and integrate water management. In 2014, the Indiana Chamber of Commerce released a report calling for a state-level entity to provide "rules, models and data" for coordinating planning regionally between state agencies, utilities, and universities. In a 2015 survey conducted by the Indiana Finance Authority (IFA), Indiana's 20 largest water utilities (including CEG) uniformly reported they were not adequately replacing aging infrastructure, and the state's regulatory process for rate-setting precluded long-term sustainable planning.

Exemplifying this challenge, CEG in 2015 sought approval of a 22% water rate increase for infrastructure expansion, which was challenged by the Indiana Office of Utility Consumer Counselor and neighboring cities as unduly imposing greater cost-burden on current users compared to future ones. Ultimately, the request was reduced to 16% by the IURC. In the rate filings, CEG officials noted that the decision left the utility with insufficient revenues to maintain and expand infrastructure over its planning horizon. Subsequently, CEG produced an Integrated Water Resource Plan (IWRP) in 2020, which included data on peak-day water demand projections for a 50-year planning window (K4) and projected water supply, treatment, and transmission capacity (K1). The IWRP incorporated growth trend data from CEG's Operations Department for demand planning (K2). As of 2020, the IWRP concluded that additional capital projects would be required to meet forecasted demand because of population growth through 2070. For its analysis of source capacity, CEG relied on surface water yield modeling for the White River and Fall Creek systems based on historical rainfall data (K1). Groundwater yield was also based on historical production from its own well fields (K1). CEG is also required to prepare annual water-quality reports under the federal Clean Water Act (K1). But to date, the only comprehensive analysis of climate impacts on water supply in Central Indiana was conducted by IFA in 2021 (K3), concluding that climate-driven changes in water demand and supply could be expected but that the forecasts were inconsistent and lacked guidance for how utilities should respond.

By comparison, the City of Phoenix's WSD is overseen by a Director appointed by the City Manager, with policy-making authority vested with the elected Phoenix City Council (low local political autonomy). Although interviewees suggested this low autonomy was a hindrance to adaptive management of the utility, we observed iteratively improved knowledge infrastructure across all four types during the study period. Figure 5 depicts the formal Phoenix planning process (lower pane in red) and two institutional dependencies. The WSD Director, appointed by the City Manager, oversees development of the Drought Management Plan (gray oval), specifying the regulatory tools the City could use to reduce water use and enforce restrictions, which was codified into City ordinance and first developed in 1990. The ordinance specifies the Director will revise the plan only upon their determination that "conditions have changed" to necessitate an update, thus affording considerable flexibility. The ordinance also allows the Director to declare progressively restrictive water use reductions during shortage periods. To date, the city has never had to impose mandatory water restrictions.

Throughout the study period, WSD progressively sought to develop more accurate predictions about the long-term climate-driven drought impacts on their water supplies. This appears motivated by both the potential for reductions in Colorado water allocations and the challenge of convincing council members to support water-rate increases for climate adaptation. Interviewees noted the low political autonomy of the utility created "political challenges" in raising water rates to maintain or adapt physical infrastructure; council members "don't want it on their voting record," [Interviewee PH05]. Following the spike in media attention to water supply, we did observe increased attention to water politics (2020 2022; Fig. 4, right, bottom), possibly reflecting the worsening water shortage within the Colorado River Basin and initial actions taken in the Colorado River Basin to respond.

During the study period, WSD prepared and updated a Water Resource Plan (WRP) in 2011 and 2021, which is not required by existing law or city ordinance. The effort involved integrating supply and demand strategies into a framework, using research suggesting surface water shortages on the Colorado, Salt, and Verde River systems may last decades (K1,2). Because the "uncertainty of climate change may introduce a new normal in average annual surface water flows," this Shortage Response Framework introduced continuous supply- and demand-related monitoring of watersheds and reservoirs (K1) along with growth and usage trends (K4), as well as progressive stages of supply development actions and use restrictions. WSD also began voluntarily partnering with university-based researchers, federal agencies, and SRP and CAP staff to attempt to model climate-related impacts on river flows (K3). The initial effort involved downscaling various Global Climate Models (GCM) to generate more locally precise estimates of variability in precipitation and temperature. As of 2021, the results of the partnership were inconclusive, with WSD noting it was unable to translate climate impacts into reliable streamflow estimates. In its 2021 WRP update, WSD incorporated modeling of different supply-and-demand scenarios through 2070, to incorporate expected drier climate cycles (K3). The scenario planning determined supplies from the SRP will be "resilient" during the planning horizon, but Colorado River supplies would likely see reductions after 2026. Under the high-growth scenario, WSD would likely have to implement new water supply development projects and impose more stringent use restrictions for the first time.

High state-reinforcement: Santa Rosa and San Jose

Santa Rosa and San Jose feature similar hydroclimatic contexts (although different water source portfolios) and different levels of local political autonomy. Santa Rosa and San Jose are positioned on opposite ends of the San Francisco Bay area in northern California, with a semi-arid Mediterranean climate. Santa Rosa provides water through its municipal-owned Santa Rosa Water department (SRW), overseen by a City Council-appointed Board of Public Utilities (low local autonomy). The City of San Jose relies on the San Jose Water Company (SJWC), which is one of the largest investor-owned urban water systems in the U.S. and regulated by the California Public Utilities Commission (high local autonomy). Water utilities in California must update their planning every five years (sunsets). Since 2009, the state legislature has repeatedly increased the requirements for water supply- and demand-planning, including climate planning (authority and responsibility). We found these state-reinforced rules were reflexive enough to drive the development of more diverse knowledge infrastructure, particularly in Santa Rosa where utility managers operate with less local political autonomy.

Biophysical and community context

The Bay area, like most of California, suffered from a multi-year drought from 2007 to 2009 (deficit conditions in red in upper panes, Fig. 6). California then suffered from a more severe drought from approximately 2012 until 2017. Approximately 95% of Santa Rosa's water is from surface sources managed by the Sonoma County Water Agency (SCWA). The 2007–2009 drought resulted in a significant decline in reservoir storage that did not fully recover before the more severe drought began in 2012.

During the study period, media attention in Santa Rosa (Fig. 6, right, bottom) focused on water supply issues that peaked after prolonged drought periods, while water politics was predominantly the most salient issue from 2008 to 2015. Following the 2017 Tubbs fire, the most destructive in California history at the time, the media focus also shifted to water quality after the city discovered contamination from melted plastic water supply pipes.

Conversely, nearly 50% of San Jose's water is purchased from the Santa Clara Valley Water District (SCVWD), with the remainder drawn from nearby groundwater or surface water resources. Prior to the study period, SJWD had determined that in a multi-year drought, shortages of up to 20% could result, and both entities had explored various options to enhance supply reliability. During the 2012–2017 drought (Fig. 6, left, top), the amount of imported surface water available dramatically decreased. San Jose utilized groundwater to counteract the surface water deficit, and as a result, groundwater elevations exhibited a noticeable decline from 2013 to 2015. In 2015, SJWC had to implement a 20% mandatory reduction in urban water usage demand.

Similar to Santa Rosa, media attention in San Jose (Fig. 6, left, bottom) gradually shifted in focus from water politics to water infrastructure and water supply although municipal water coverage peaked in 2015 corresponding to the mandatory use restrictions. Media data for San Jose was not available for analysis from U.S. Newsstream before 2010 or after 2018, but leading up to this period, media attention to water infrastructure and water politics was on the rise as the investor-owned utility sought state regulatory approval for a series of water rate-increases.

Governance processes and knowledge infrastructure

Figure 7 depicts numerous institutional dependencies the California Legislature has placed on utilities' supply- and demand-planning following drought periods. For ease of interpretation, given the utilities are in the same state, we generalize both utilities as "suppliers" (attributes appearing four times in Fig. 7). SJWC, as an investor-owned utility (IOU) is also subject to additional regulatory requirements to base rates on its long-range plans and seek state approval for them (depicted in red). Unlike the previous cases, both California utilities were required to develop and update Urban Water Management Plans (UWMPs, central gray ovals) every five years (2010, 2015, and 2020 during our study period) under the state's Urban Water Management Act (adopted in 1983). Utilities must also coordinate or share information with surrounding water suppliers. Our analysis found these iterative plan updates (sunsets), regional information-sharing, and specified thresholds for determining supply sufficiency (reflexive law) required more complex information and expanded knowledge infrastructure.

In 2009, the California Legislature responded to a drought by requiring suppliers to set targets for achieving a statewide per capita urban water use decline of 20% by 2020. To meet that goal, the legislature allowed suppliers to use multiple methodologies but required that they: (1) determine base daily per capita water use (K4); (2) determine urban water use targets (K2); (3) compare urban water-use targets to 5-year baseline (K1); and (4) determine an interim urban water-use target. In their 2010 UWMPs, both utilities complied with the requirements and relied primarily on historical supplies from wholesalers and demand to assess water reliability under future drought scenarios (K3). This pattern of setting progressively more ambitious goals but allowing flexible means to achieve them illustrates state-reinforced reflexivity.

Between the 2010 and 2015 planning efforts, state lawmakers responded to worsening drought conditions by requiring suppliers to quantify distribution system water losses (K4); analyze artificial water uses (like fountains) as part of water shortage contingency planning (Fig. 7, lower gray oval); report on estimated water savings resulting from adopted codes, ordinances, or transportation and land use plans (K2,4); and estimate the energy used to extract or divert water supplies (K2). Water suppliers were allowed, but not required, to coordinate planning and reporting as part of a Regional Alliance.

Following the 2012–2017 drought, lawmakers required that suppliers account for hydrological variability attributable to climate change (K3); prepare a Drought Risk Assessment (DRA), considering water supply and demand under an assumption that the next five years (2021–2025) would experience drought that is hydrologically equivalent to the driest five consecutive years on record (K1); address seismic risk to water system facilities (K2); and report estimated energy use for water supply extraction, treatment, distribution, storage, conveyance, and other water uses (K1). Suppliers were required to include water loss audit reports covering the preceding five years (K4) and to report on their plan to meet water loss performance standards. Suppliers were also required to prepare a stand-alone shortage contingency plan.

In their 2020 UWMPs, both utilities relied on external data tools or studies to discuss future expected impacts of climate change. In interviews, both utilities noted that information-sharing with their water wholesalers was important for complying with climate-planning requirements:

"They've been doing a lot of work on climate adaptation and climate variability and how we would be impacted looking at various models. And so that's driven a lot of the work we're looking at as well," [SR01].

Santa Rosa reported that, based on impacts listed in the EPA's Climate Change Handbook for Regional Water Planning, the city's water supply was not vulnerable to climate change, but that demand was likely to be affected by increased extreme precipitation and heat. Its 2020 UWMP also anticipated drought conditions could result in reduction of surface water due to climatic conditions (K3). The utility noted that its wholesaler and eight other contractors intended to collaborate on a resilience study intended to "get us through various disasters and stress tests" [SR01]: "We're going to continue to have to look at solutions and continue to have to plan for scenarios that really we've never seen before."

Conversely, SJWC provided a cursory qualitative discussion of constraints and challenges that may affect both water supply and demand, noting their quantitative analyses for supply and demand are reliant on SCVWD input and modeling, which would increasingly require incorporation of climate change parameters. SJWC also noted that SCVWD had been preparing a Climate Change Action Plan, the findings of which would be used for its own future analyses. SJWC also deferred to SCVWD's information for a Drought Risk Assessment (DRA), which considers all of SCVWD's water supply sources, including imported water, local surface water storage, recycled water, and local groundwater. In acknowledging this reliance on external data sources analyses, SJWC interviewees noted their status as an IOU incentivized cost-efficiency initiatives and curtailed taking broader adaptive actions without the approval of both the SJWC board of directors and the state PUC: "We're sort of driven by our board" [SJ02].

To summarize our results, all four utilities largely focused on building and using knowledge about stationary, historic climate experience and resource exploitation (K1,4), while three cases began some initial efforts aimed at developing climate-system knowledge (K3). These knowledge-building efforts were largely responsive to state-directed planning requirements and sanctions (in the California cases) and constraints (Indianapolis). Our outlier case, Phoenix, featured a lack of state-reinforced climate rules, but also a looming threat of water allocation reductions (realized in 2022) and significant local reflexivity for developing climate-related knowledge.

DISCUSSION

Governmental authorities can enable or constrain the development and deployment of knowledge infrastructure in multilevel governance systems. The above results of our data synthesis for four cases demonstrate that they may do so through institutionalizing iterative data collection in long-range planning (via planning sunsets and reflexive knowledge-building), and providing legally defined authority and responsibility for adapting to environmental change. Several differences emerge between the cases based on these legal principles of adaptive governance.

Reflexive law

Reflexive environmental law has been defined as setting “legal floors, legal ceilings and intelligible principles” while incorporating flexibility to respond to complex dilemmas (Craig et al. 2017, DeCaro et al. 2017). The California cases display more reflexive institutional designs, which enabled knowledge development and use by setting multiple planning goals (e.g., 20% per capita use reductions) and processes (seismic risk, reliability assessments), but providing flexibility for achieving them. The Phoenix case illustrates similar information-gathering and development efforts, but did not rely on state requirements to do so; rather, the Phoenix WSD planning efforts appear driven by the interactions of rapid population growth, the formal authority placed with the WSD director, and the severity and duration of their drought. Conversely, the Indianapolis case displays a state-constraining legal framework in which water rate-setting and investment, and by extension, urban water planning, is limited by static cost-based evaluative criteria and case precedent. Together, these cases suggest that as climate change impacts urban water provision in numerous ways, reflexive institutions with incorporated flexibility can help utilities engage in more adaptive governance that better addresses uncertainty and non-linearity.

Legal sunsets

The design principle of legal sunsets allows for environmental policies or agreements to be periodically re-evaluated and modified (Gunderson et al. 2014, DeCaro et al. 2017). The institutional design of California’s Urban Water Management Plan process includes such sunsets, along with requiring that updates incorporate new information, progressively assess reliability under worsening drought conditions, and engage with “social, cultural and economically” diverse users. Moreover, California imposes an explicit sanction, denying eligibility for state water loans or grants, if plans are not updated. Phoenix and Indianapolis both have state-formalized planning processes but do not impose any conditions or timeframes for updating them, potentially reducing motivation to consistently explore and update information in the absence of major recognized stressors or shocks.

Legally binding authority

Institutional designs should define centers of authority that can legitimize the shared policy and implementation goals of resource providers and users (Ostrom 2010, Sarker 2013). Although all four cases operated in systems with authority distributed amongst water suppliers, wholesalers and regulatory agencies, Santa Rosa and Phoenix appeared to exercise greater ability to make decisions jointly with users and act on them, while San Jose and Indianapolis, despite greater local political autonomy as investor-owned or public-trust operations, were more constrained by state utility regulatory commissions. The formal constraints on rate-review and infrastructure investments by state-level regulatory commissions impacted the types of knowledge the utilities prioritized and mobilized to support long-range planning, potentially undermining proactive planning in cases that also lack state-enabling rules to incentivize it.

Responsibility

Last, institutional designs should provide definitions and assignment of responsibility for resolving environmental resource dilemmas (Sarker 2013, Wheeler 2013). Climate change is a global externality, but it is at the center of hydroclimatic changes impacting urban water planning. Here, California has a clear advantage in its state-reinforced design for water planning, given the progressively expansive, data-driven legislative directives for water suppliers to prepare for environmental changes. Although by the end of our study period suppliers were still just beginning to address recent state mandates to account for climate change-induced hydrological variability, the evidence suggests this formal responsibility, and the legal responsibility to share information and coordinate across suppliers, will lead to more sophisticated and locally precise climate modeling as a larger part of California water management planning. Although Phoenix has also made strides to account for climate change via collaborative arrangements with other entities, the efforts have been voluntary and informal thus far. Meanwhile, Indianapolis, which is witnessing an increase in precipitation but also seasonal droughts, has witnessed only piecemeal efforts to account for climate impacts on water supply and appears formally constrained from introducing other, potentially contested welfare goals (i.e., equity) into planning. The long-term responsibility for climate impacts remains unclear in this case.

CONCLUSION

Climate change poses significant challenges to the sustainability of urban water governance processes globally, which often require a central state role in planning, coordinating, and supporting responses. This article examines how state-reinforced knowledge infrastructure impacts adaptive governance processes in urban water systems. Across the four cases, we found a heavy reliance over the study period on knowledge about stationary, historic hydroclimatic experience and resource exploitation (K1,4), and a relative brevity of actionable knowledge about future climate impacts (K3). These KI appeared heavily responsive to state-directed planning requirements, sanctions, and constraints. New knowledge was developed and applied in response to progressively more detailed state guidance and requirements to assess system reliability during extreme events and other climate change impacts.

Ultimately, most systems designed for yesterday's environmental conditions will face increased vulnerability to shifting hydroclimatic means and extreme events. State-reinforced knowledge infrastructure can help clarify the authority, responsibility, capacity-needs, and decision processes of managers responding to climate stressors. They can do so by formalizing planning types, timelines, and sanctions for noncompliance, while allowing local users and providers flexibility to experiment or innovate through compliance-related processes. Given the variety of physical infrastructures that societies and communities must maintain, it is possible the processes of developing KI could be useful in understanding other areas of adaptive governance. But such extensions are beyond the scope of this study. Future research can build on this effort to further identify the configurations of knowledge infrastructure systems, why they are more or less-optimally developed and mobilized, and how they support adaptive environmental governance.

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your response will be hyperlinked to the article. To submit a response, follow this link. To read responses already accepted, follow this link.

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Use of Artificial Intelligence (AI) and AI-assisted Tools

None.

DATA AVAILABILITY

The data and code that support the findings of this study are available on request from the corresponding author, AMD. None of the data and code are publicly available because they contain information that could compromise the privacy of research participants. Ethical approval for this research study was granted by the University Nevada Reno and Indiana University.

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