

Understanding the Impact of Institutions on Climate-Adaptive Policy Designs: A Study of Collective Action Inference in Urban Water Systems

ABSTRACT

Feedback is ubiquitous in complex systems and critical to the process of designing public policies to solve problems such as climate adaptation. However, well-known cognitive and institutional constraints can impact information feedback processes, limiting a system's ability to incorporate feedback into policy designs. This study analyzes the role that institutions play in regulating feedback in coupled infrastructure systems (CIS) to support the development of climate-adaptive policies. Focusing on urban water systems, we ask: *how do multilevel institutions governing information processing influence urban water systems' climate-adaptive policy responses?* Using the CIS framework, we develop a theoretical argument for policy design based on the cognitive model of active inference. Drawing on hydrological, administrative, media, interview, and institutional data, we trace two urban water systems' policy design processes over a decade. We find that successive waves of state-level changes to water planning rules prompted more “exploratory” information processing during the study period. Moreover, an urban water utility's ownership type (public vs. investor-owned) influenced how expected climate impacts were incorporated into policy designs. These findings provide insight into how institutional arrangements shape policy designs and suggest ways such arrangements may be altered to enable adaptive responses in the face of environmental uncertainty.

1 Introduction

Complex societies increasingly rely on heavily engineered, coupled infrastructure systems (CISs) to provide drinking water, transit, flood mitigation, communications, energy, and other public goods. In these CISs, both the physical “hardware” (plants, pipes, sensors) and information-based “software” (policies, regulations, experience) interactively guide system responsiveness to change (Anderies and Janssen [2013](#)). When designing policies to govern these systems, managers and policymakers depend on accurate and timely information feedback about the state of current or emerging challenges (Anderies et al. [2007](#); Levin et al. [2022](#); Ostrom [2011](#)). However, cognitive and institutional constraints can both impact a system's ability to incorporate feedback into policy design processes, ultimately affecting a CIS's ability to adequately adapt to change (Baumgartner and Jones [2015](#); Workman [2015](#); Workman et al. [2009](#)). Thus, understanding the nexus between the rules controlling feedback and policy design in these systems can yield important insights for maintaining system responsiveness amidst dynamic change (Heikkila and Andersson [2018](#); Ostrom [2009a](#); Siddiki et al. [2019](#)).

This study analyzes the role rules (hereafter, “institutions”) play in regulating information feedback in CISs using the case of climate adaptation in urban water systems. Many urban water systems, both in the United States and elsewhere, are currently experiencing shifts in their mean hydroclimatic trends or regimes due to climate change, driving the gradual aridification of river

basins, as well as changes in the severity and frequency of extreme events, such as acute drought or flood-inducing rainfall (Swain et al. [2020](#); Cook et al. [2021](#)). Water providers need to adapt infrastructure to deal with the accelerating pace of these climatic changes. This can introduce considerable risk and uncertainty that policymakers and managers navigate through institutionalized pathways for reducing ambiguity (Deslatte et al. [2025](#)).

Institutions emerge among groups, communities, or societies (i.e., collectives) to create conformity, certainty, or stability (Anderies and Janssen [2013](#); DeCaro et al. [2017](#); McGinnis [2011](#); Ostrom [2010](#)). Multilevel institutions (e.g., state laws, local ordinances, community norms) can guide adaptation processes by enabling or constraining the actors involved, structuring the information to be developed or curated, or specifying the timelines, decision-making heuristics, or evaluative criteria used (Deslatte et al. [2025](#)). In an urban water context, the institutions that interact at multiple levels can lead to incremental adjustments and risk aversion (Deslatte et al. [2023](#)), due in part to the long life of urban water infrastructure—roughly 75 years—and the massive capital investments required to construct and maintain it. Thus, adapting to challenges such as climate change depends on understanding how institutions guide the collective processing of feedback—about past CIS conditions, interactions among CIS components, and uncertainties about the future—and channel it into responsive policy designs (Anderies et al. [2019](#)).

To advance this effort, we ask the following research question: *how do multilevel institutions governing information processing influence urban water systems' climate-adaptive policy responses?* Our theoretical argument draws from a cognitive science approach called active inference (Parr et al. [2022](#)), which we argue can aid in developing foundational models that account for both behavioral and structural features of collective action (Jones [2017](#); Ostrom [1998](#)). Fundamentally, active inference holds that all self-organizing systems (cells, human bodies, organizations) adhere to the free-energy principle from information physics, which holds that systems seek to minimize the energy they must exert to maintain successfully functioning within their environment. Adapted to collective action, we posit that actors within urban water systems behave in accordance with this principle as they seek to minimize uncertainty, or long-run surprise, through *epistemic-pragmatic information tradeoffs*. Institutional designs shape these tradeoffs as actors make and update predictions about their environments, designing more adaptive policy responses in order to reduce prediction errors (Ostrom [2009a](#)). We organize this analysis using the CIS framework, a sibling of the Institutional Analysis and Development (IAD) framework developed by Elinor Ostrom and colleagues (Ostrom [2009a](#)). The CIS framework organizes complex systems into resource users, providers, and coupled infrastructure components in order to model information, resource, and material feedback in CISs (Anderies and Janssen [2013](#)).

We focus on the empirical context of two Urban Water-CISs (UW-CISs) in California, US: one municipal utility and one investor-owned utility. Both feature heavily engineered physical infrastructures (pipes, treatment plants, storage) coupled to differing institutional designs that regulate their performance (Deslatte et al. [2024](#)). To analyze these formal, multilevel institutions, we use the Institutional Grammar Tool (IGT) (Crawford and Ostrom [1995](#)) to map boundary, information, and choice rules. Then, drawing on a range of hydrological, administrative, media, and interview data, we trace the two systems' policy design processes over a decade as they

respond to the enactment of state-level climate planning mandates, focusing on (1) the formal roles for policy designers (Siddiki et al. [2011](#)), (2) the types of information they gather, curate, or mobilize (Anderies et al. [2019](#)), and (3) the policy responses they design (Walker et al. [2023](#)).

We find that changes to the constitutional-level rules governing water planning (i.e., planning mandates) prompted a shift to more “epistemic” information-processing at the collective-choice level in both cases. These exploratory knowledge-building efforts were greater in the public utility compared to our investor-owned case, relative to incorporating expected climate impacts into policy designs. These findings offer insights into how multilevel institutions shape policy design efforts and suggest ways such arrangements may be altered to better enable adaptive responses in the face of environmental uncertainty. Moreover, constitutional-level information feedback rules can enable the flexible development and use of technical and scientific knowledge for policy designing.

2 Information Feedback, Surprise, and the Policy Design Process

Adaptive human and physical-infrastructure systems must, by definition, be flexible enough to meet the demands of a changing environment (Simon and Newell [1971](#)). One of the central challenges for policy scholars has been the need to develop models that capture how both *behavioral and structural features* of collective decision-making processes co-determine responses to environmental uncertainty (Jones [2017](#); Poteete et al. [2010](#)). Boundedly rational human decision-making suffers from well-understood constraints on information, time, and cognitive abilities, leading individuals to take mental shortcuts or “satisfice” in many decision-making contexts (Simon [1991](#)). For decades, institutional scholars have observed that structural variables like group size (Olson [2009](#)), the subtractability of a resource (Ostrom [1990](#)), group heterogeneity (Heckathorn [1993](#)), information availability (Constantinides and Barrett [2015](#)), and the potential to exit (Ostro et al. [1994](#)) also interact with these behavioral features, including via learning heuristics, trust, and reputations (Ostrom [2009b](#)). In other words, despite bounded rationality assumptions, humans in repeated choice situations have the capacity to behave in an adaptively rational way to collectively confront challenges.

While attempts to develop adaptively rational models have emerged (DeCaro et al. [2021](#); Jones [2017](#)), we argue that the concept of *active inference* can help motivate this effort. Active inference holds that all self-organizing behavior—including policy design—can be reduced to an effort by actors within a system to minimize uncertainty (hereafter ‘surprise’) about the external environment via updating *generative models*, which are the joint distribution of hidden (external) states, observations of these states, and control states, or available actions (Constant et al. [2022](#)). Critical to this parsimonious explanation is where actors draw the boundary between what is inside and outside of the ‘system’ being preserved (Parr et al. [2022](#)).

Specific to *policy designs*, we posit that actors attempt to minimize surprise by making predictions about both the current and expected observations produced via policies and then actively seeking information that supports these predictions—iteratively updating their generative model or shared beliefs about their environment (Deslatte [2022](#)). We call this process *collective action inference*, which, in this study context, highlights how policy designs rely on inference-based processes that aggregate individual information-processing efforts to minimize

group-level uncertainty. Critically, these inference efforts will be impacted by the *institutional designs* that structure the action situations in which they occur (Ostrom 2009b). Institutions guide policy design efforts when they determine who is inside a focal action situation, what evidence-gathering actions are available, or how information feedback is reconciled with prior expectations.

Figure 1 depicts this process as a nested actor-action situation feedback loop. Institutions function at multiple levels to regulate feedback and reduce long-run surprise or decline of collectives (Anderies and Janssen 2013; Deslatte 2022). They expand or reduce available information, actions, participants, evaluative criteria, and payoffs, which (1) create stable, predictable collective processes and (2) strengthen shared beliefs in action-outcome linkages (Mesdaghi et al. 2022; Ostrom 2009b; Sarr et al. 2021). The first blue loop features individual actors making predictions about environmental conditions, taking actions to gather new information, processing sensory outputs from the environment, and updating predictions about their situation. The arrows connecting the Actor (A) and Action Situation (AS) to y represent the nested levels of rules that may cumulatively activate or constrain evidence-gathering actions, while the arrows flowing from y back to A/AS reflect rules guiding the perception or interpretation of information feedback. Here, individual action is aimed at maximizing evidence for a generative model, while perception refers to reconciling error signals or discrepancies (e.g., Bayesian updating). Unlike rational choice theory, active inference assumes the optimization goal of the actor is to simply gather and interpret information which minimizes surprise and thus enables moving to more “sustainable” states that delay the entropic decline of the system (Parr et al. 2022).

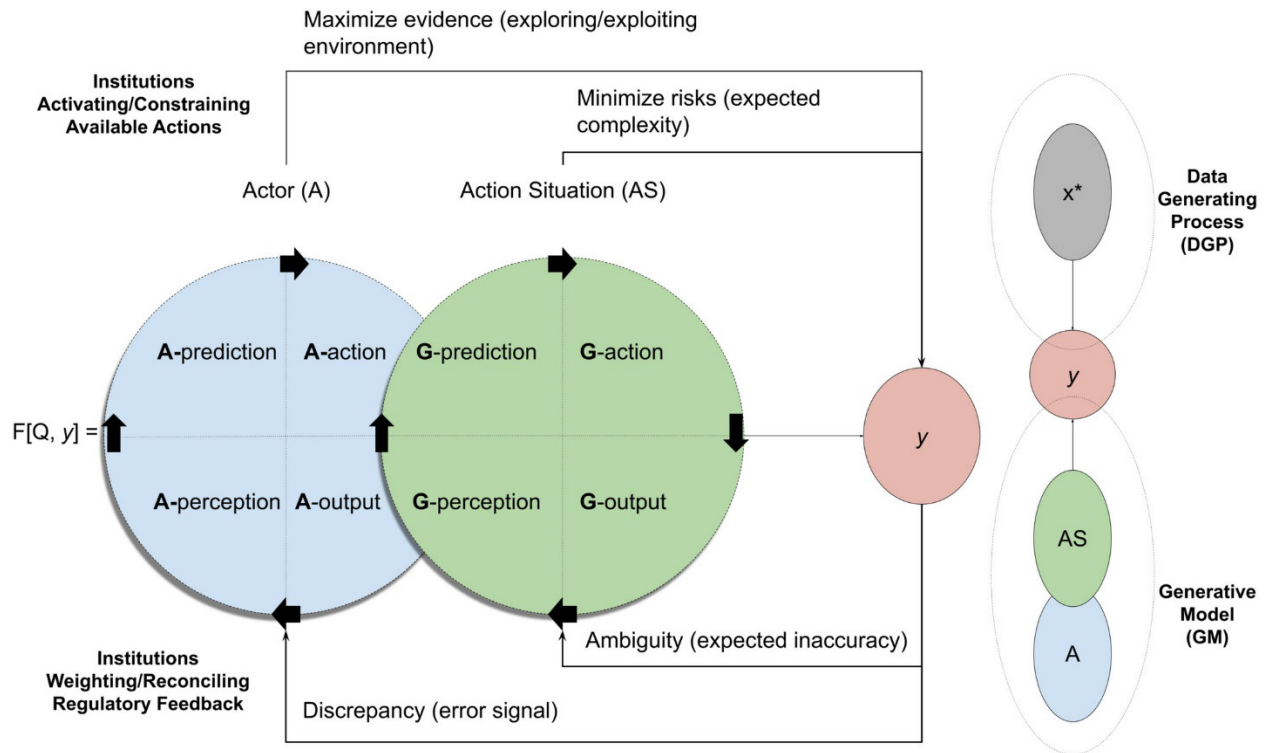


Figure 1: Collective Action Inference is a process in which actors within an action situation seek to minimize surprise, Q , about an environmental outcome, y , and rely on institutions that activate or constrain available evidence-gathering actions and determine how discrepancies in feedback are reconciled with prior predictions. The data-generating process (or underlying causal mechanisms) producing y cannot be directly observed.

Policy designers in an action situation (green loop) must undertake a more complex endeavor: they must predict the environment but also each other's likely choices in order to minimize expected surprise. In this case, constitutional-level rules define or legitimize the “collective entities involved in collective or operational choice processes,” including setting the overarching parameters for policy design (McGinnis [2011](#), 173). Constitutional-level rules set the table for group collective-choice processes where actors may possess different experiences, competencies, and resulting beliefs about the causal nature of y (Bayes and Druckman [2021](#)). Group heterogeneity (individuals with different experiences) may create conflicting welfare goals but also more diverse information about the nature of a problem (Deslatte et al. [2023](#)). Here, nested institutions function at the collective level to establish the procedures for policy design, such as evaluating different courses of action and selecting a course (a policy action or tool, or combination of them) most likely to successfully navigate between alternative futures (Friston [2010](#)). Thus, collective action inference involves forging consensus on what system outcomes are desired and whether specific policy actions can achieve those outcomes (Howlett and Leong [2022](#); Koebele and Crow [2023](#)). Within this process, policy designing depends on the “gathering and application of knowledge” about problems the system is facing or expects to face (Howlett [2019](#)). For instance, policy designers might need to accurately identify or predict economic or population growth and decline, social vulnerabilities, competition among resource users or providers, and, increasingly, environmental conditions such as severe hydroclimatic variability, which threatens built infrastructure or long-term resource supplies (Stevenson et al. [2022](#); Stokan et al. [2021](#); Wiechman et al. [2023](#)).

This view of policy design invokes the active inference treatment of *risk* as analogous to expected complexity and *ambiguity* as analogous to expected inaccuracy, which is depicted in Figure 1 (Parr et al. [2022](#), 35). Risk generally relates to potential outcomes with known probabilities (Füssel [2009](#)). While risk has been studied in a variety of contexts and disciplines, ambiguity introduces disagreement or uncertainty about the future probability distribution of events or threats (Deslatte et al. [2025](#)). In other words, policy designers could reasonably agree on the risks that a well-understood policy intervention could fail but be unable to reach consensus on the magnitude or probability of ambiguous threats posed by the climate system.

Ambiguity is problematic because humans rely on heuristics and cognitive biases as mental shortcuts to make decisions (Gigerenzer and Brighton [2009](#)). Groups—like individuals—tend to over- or underweight the likelihood of events based on the availability of memories and the emotional responses they evoke (Pachur et al. [2012](#)). They also struggle to accurately assess the scope of a societal risk or benefit relative to its exposure—for instance, the inability to accurately conceptualize climate risks posed to more vulnerable groups (Nelson et al. [2023](#); Slovic [2007](#)).

Given these challenges, one might surmise that public policies frequently fail (Brown et al. [2019](#); Dunlop [2020](#); Howlett and Leong [2022](#); McConnell [2010](#); Stone [2017](#)). Indeed, policy scholars often attribute “policy failure” to knowledge gaps or “surprises” in the policy design process (Leong and Howlett [2022](#)). Policymakers may lack institutionalized “foresight” or issue management standards, appropriate policy analysis or risk management protocols, or opportunities to experiment with policy tools, measurement, and evaluation (Howlett [2012](#), [2019](#)). While policy failures are often perceived as negative, they can be key for how groups learn ways to better navigate complex challenges—especially when information about the failure is fed back to policy designers through institutionalized channels (Levin et al. [2022](#); Ostrom [2009b](#)).

In summary, policy design processes are strongly impacted by higher-order institutional designs that structure how collectives use feedback to minimize surprise (depicted as the information pathways in Figure 1). As the cognitive theorist Andy Clark notes, institutions establish “new social and material worlds around ourselves, including new worlds to train ourselves to think about our worlds” (Colombo et al. [2019](#)). A challenge is that extant research on topical issues often fails to disentangle the varied levels and purposes of institutional designs from policy design processes (Deslatte [2020](#); Hawkins and Krause [2023](#); Howlett and Leong [2022](#); McGinnis [2019](#); Ostrom [2010](#)). Below, we lay out theoretical expectations for how institutional arrangements govern the roles and knowledge-building of groups in policy design.

3 Boundary, Information, and Choice Rules

As a model, adaptive rationality implies that actors iteratively engage in and refine information-processing strategies in response to ambiguity. Collectively, these strategies are regulated by structural features of an action situation. Information-processing strategies strike some balance between actively *exploiting* or *exploring* their information environment (Deslatte et al. [2023](#)). Collective action inference, as a theoretical process, implies these tradeoffs are influenced by who is allowed or prohibited from participating, the types of information required, allowed, or forbidden, and choices prescribed. Groups may selectively seek out belief-confirming information about future risks—*exploiting* the information environment—as a means of social identity protection, consensus-seeking, or simply preserving belief consistency (Bayes and Druckman [2021](#); Lord et al. [1979](#)). Filtering out disconfirming information is easier when the weight given to available memories or experiences is stronger. Conversely, groups may emphasize additional information search when the discrepancy between beliefs and evidence is greater, allowing them to discover new potential social, economic, or environmental features of problems. In this case, groups have weaker priors about the problem and make more effort to *explore* their environment to gather new information (Parr et al. [2022](#)). Ultimately, all inference processes, including those involved in policy design, strike a balance between the epistemic value of evidence (exploring) and the pragmatic value (e.g., going with what you know; exploiting). Below, we expand upon how rules can influence these tradeoffs.

3.1 Boundary Rules

Boundary rules determine who can enter or exit formal positions and participate in the policy design process (McGinnis [2011](#)). Because climate change creates unequal exposures to risks and

contested goals, we expect that the boundary rules conditioning the diversity of participation in collective-choice situations can influence awareness of different types or spatial scales of problems (Deslatte et al. [2023](#)). Boundary rules may authorize alternative types of governing authorities (Ostrom [2009a](#)). At the collective-choice level, they can establish the processes and types of groups allowed to participate in policy design and the degree of accountability the providers have to resource users. They can influence the extent to which vulnerable populations are engaged in policy design, the level of expertise in decision situations, and the incentives of those authorized to enter and exit their positions.

In the context of UW-CISs, prior work has identified important distinctions in the boundary rules relative to fully public or politically accountable infrastructure providers and fully privatized or insulated providers (Deslatte et al. [2022](#); Barnes et al. [2025](#)). Public providers, such as municipal utilities (a general or special-purpose government), may be more politically responsive because elected officials (e.g., city council members, county commissioners, government-appointed members, and elected special district board members) either directly design policies through the boards they sit on or they appoint unelected actors to do so (Deslatte et al. [2022](#)). In these systems, boundary rules specify how voters may fill either the council or water board positions and how citizens may be involved through advisory boards (Deslatte et al. [2025](#); Homsy and Warner [2020](#)).

Studies have found that publicly owned water systems (i.e., municipal utilities) tend to be more responsive to majority sentiments (Teodoro [2010](#)). These “political” systems may be generally more susceptible to political pressure and more responsive to public attitudes or pressure than privatized systems. For example, an increase in public concern toward climate issues may be more likely to prompt publicly appointed or elected water boards to design policies that address public concern, including adopting price-related policies or information-gathering efforts to ascertain climate impacts (Deslatte et al. [2023](#); Garcia et al. [2019](#)).

Water board members in investor-owned systems may not be directly or indirectly selected by local constituents and tend to restrict public participation in decision-making (Barnes et al. [2025](#)). On the one hand, this can lead to principal-agent dilemmas relative to longer-term goals such as climate adaptation, largely because the utility is more responsive to market trends and the profitability pressures of shareholders. For this reason, nearly all state governments regulate investor-owned water systems through Public Utility Commissions (PUCs) (Homsy and Warner [2020](#); Teodoro et al. [2022](#)). PUCs predominantly exist to ensure investor-owned systems do not use their monopolistic position over a community to overcharge for water provision (Onda and Tewari [2021](#)). On the other hand, recent evidence suggests that the political “decoupling” of environmental policies and politics could allow private utilities to more aggressively pursue conservation goals because they are shielded from the political repercussions of unpopular policies such as stringent conservation measures (Hansen et al. [2022](#); Teodoro et al. [2020](#)). When the utility's governing board is non-elected and buffered from the electoral incentives of mayors or city councils, we might expect to see greater attention to achieving operational efficiencies (Teodoro et al. [2022](#)). Thus, the relevant boundary conditions within a CIS can radically alter the generative model that public infrastructure providers rely on to predict future challenges and opportunities.

3.2 Information Rules

Information rules specify the information available to each position (Garcia et al. [2019](#); Ostrom [2009a](#)). At the constitutional level, information rules can detail the procedures, channels, modes, and types of feedback that are developed or exchanged at the collective and operational levels (Dunlop et al. [2022](#)). Information rules are crucial to effective policy design because they can influence the types and timing of information available to actors as they attempt to detect divergences between a preferred state of a system and the observed or forecast states (Baumgartner and Jones [2015](#); Constant et al. [2022](#)).

Anderies et al. ([2019](#)) argue that in CISs these institutional designs can be labeled “knowledge infrastructure systems” (KIs), which provide critical types of information to policy designers. KI can incorporate feedback from national, state, or local agencies tasked with data analysis; the media; universities; community organizations; and even resource users themselves who possess institutional knowledge or experience with the system (Anderies et al. [2019](#)). Recent theoretical and empirical work has identified four types of KI relevant for resource management: (*K1*) knowledge of the past, such as experience or longitudinal data on resource flows; (*K2*) scientific knowledge about variable interactions, such as population and economic growth, seasonal changes to inputs, and behavioral changes from incentives or regulations; (*K3*) probabilistic knowledge of future risks based on properties of uncertainty, which are difficult to model due to high spatial variability of hydroclimatic variables; and (*K4*) the capability to monitor and report on resource use or appropriation (Anderies et al. [2019](#)).

Information rules influence the development, curation, and mobilization of these four information types. This can include the timing of policy design processes, the planning horizons designers must use, and whether to explicitly account for climate impacts (via *K3*) in assessments of system reliability. However, all information comes at a cost (Anderies and Levin [2023](#)). Increased information can hinder policy design when it is mismatched with the analytic capacity of policymakers (Bendor [2015](#); Deslatte [2020](#); Simon [1991](#)). Information overload or misinformation can increase ambiguity and have the effect of strengthening prior beliefs or rendering decision processes more risk-averse (Parr et al. [2022](#)). Information costs can also dissuade collectives from developing some types of KI if their generative model deems it less valuable for minimizing surprise. From an active inference perspective, more ambiguous information feedback (i.e., unexplained error signals) should prompt CISs to pursue more exploratory evidence gathering to resolve serious discrepancies. However, institutions with unclear or underspecified information rules may prompt more exploitative strategies and free-ride on the exploratory efforts of others. Because urban water systems often focus on providing consistent water delivery or the production of near-constant outputs from highly variable inputs, these systems often focus on *K1*, *K4*, and, to a lesser extent, *K2* information types (Deslatte et al. [2024](#)). Given the previously discussed pressures to adapt infrastructure to both extreme events and slow changes to the hydroclimatic mean, policy designers experiencing these pressures should actively explore their information environments to discover new information and accurately update their predictions (Deslatte et al. [2023](#)). More diverse information flows, in turn, are expected to support adaptive policy design.

3.3 Choice Rules

Choice rules determine the authority that water governing boards have to set water rates, make investments, and otherwise identify and address long-term priorities (Deslatte et al. [2022](#)). Choice rules assign specific authorities to entities in collective and operational situations, such as mandating the timing of planning processes or determining evaluative criteria, legal standards, or procedures linked to available actions (DeCaro et al. [2017](#)). For example, variation in the authority for rate-making, conservation measures, and planning processes prescribed by choice rules can influence important decisions about how public infrastructure is maintained, expanded, or depleted. Choice rules may also specify the types of policy instruments available, prohibited, or required in policy designs (Imperial and Yandle [2005](#); Ostro et al. [1994](#)).

As the realities of climate impacts to water systems have come into clearer focus, a growing number of scholars have emphasized the need for governments to develop policy redundancies, contingencies, or response options to allow for pivots or adjustments during extreme events or long-term stressors (Walker et al. [2023](#); York et al. [2021](#)). Such designed *response diversity* may include a range of policy tools, programs, contingencies, or steps to be followed during water shortages or disasters. This could include delegated authority to impose, for example, supply-side reallocations or investments and demand-side water use restrictions or pricing changes (Deslatte et al. [2025](#)). Choice rules that facilitate a diversity of operational-level response options to unexpected situations are therefore assumed to aid in maintaining a system state by keeping options open in the face of uncertainty (Walker et al. [2023](#)). From an active inference perspective, policy designs that facilitate response diversity do so because they mitigate the expected uncertainty of future system outcomes and the expected complexity of future actions that will be necessary. Based on our previous arguments, differences in accountability and information within a CIS can be expected to influence the scope or scale of the response diversity policy designers select (Deslatte et al. [2023](#)).

In summary, we argue that policy designers select options in line with an active inference-based imperative to minimize surprise, while institutional features at multiple levels influence their ability to do so via exploration-exploitation tradeoffs. Policy designers select policies that balance the benefits from information gains (epistemic or exploratory value) with the benefits of making pragmatic decisions (exploitative value). This requires reconciling often ambiguous sensory input with contested group goals via the structural features of their decision-making situations. Institutions can render policy design more adaptive when they facilitate more diverse participation, information flows, and choice sets (Walker et al. [2023](#)). Doing so creates more predictively accurate “worlds ... to train ourselves to think about our worlds” (Colombo et al. [2019](#)). By this logic, policy designs that establish an overly exploitative balance risk being maladaptive. In the following section, we describe the research design for examining these characteristics in urban water systems.

4 Research Design

The analysis focuses on two water utilities in California, US—those serving the cities of San Jose and Santa Rosa—to examine the impact of a generic long-range planning process—the state-mandated process of developing and updating Urban Water Management Plans (UWMPs).

We organize this effort around (1) the system under examination (a heavily engineered urban water system); (2) the discrete planning periods over a decadal time scale (2010, 2015, and 2020); and (3) the relevant structural features for understanding the dynamics of the policy design process.

As previously noted, the CIS framework, depicted in Figure 2, organizes specific measures (e.g., institutional design, hydrology, issue salience, and policy design outputs in the form of plans) into categories of the resource system, users, public infrastructure (hard and soft), and its providers, which interact during policy design processes (links 1–4) (Anderies et al. 2007; Deslatte et al. 2022). Specifically, we identify key boundary, information, and choice rules at multiple levels guiding the agents (utility managers), features of the external environment driving perceptions (hydrological conditions, public salience of water problems), and the resulting response diversity of the policy designs that emerged as agents attempted to understand and alter future external system states.

Regulatory Feedback Loops within an Urban Water Coupled Infrastructure System

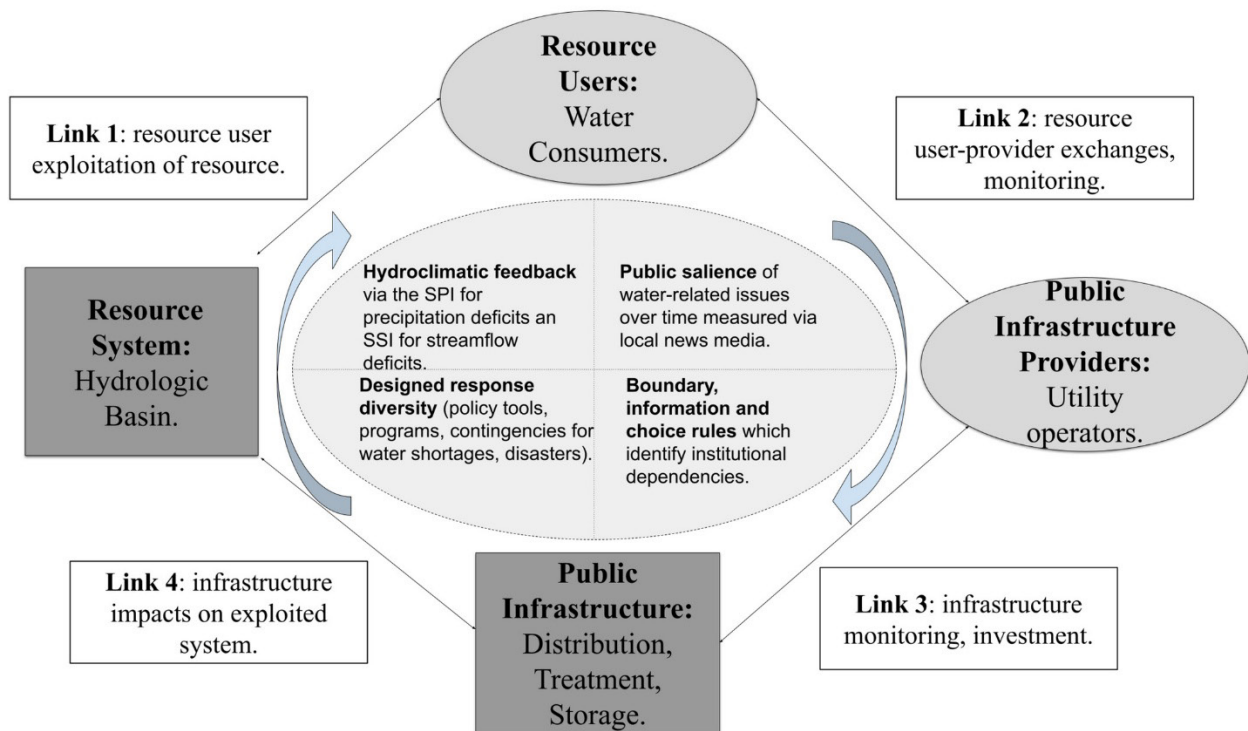


Figure 2: The CIS framework depicts a regulatory feedback loop between the resource system, the users, the public infrastructure providers, and the policies they design for resource management and monitoring.

Detailed in Table 1, data are drawn from planning documents and state and local statutes or ordinances, hydrological streamflow and infrastructure storage data, content of news media about water topics, interviews, and other archival records from public meetings. We then conduct multiple types of preliminary analysis—institutional analysis of rules, hydrological analysis of resource availability, and structural topic modeling of media content—which are used to conduct

process tracing of policy design efforts detailed in the planning documents and interview data from our two cases.

TABLE 1. Data types, sources, and methodologies.

	San Jose	Santa Rosa
Institutional data applied to Links 1, 3	CA Constitution ($N=9$); CA Public Utilities/Water Code ($N=122$); San Jose City Charter ($N=17$); San Jose City Code ($N=132$)	CA Public Utilities/Water Code ($N=122$); Santa Rosa City Charter ($N=16$); Santa Rosa City Code ($N=40$)
<i>Method:</i> Coding of syntactic components of institutional statements related to boundary, choice and information rules; network diagrams of institutional statements linking attributes, aims, Objects and Activation conditions/Execution constraints.		
Hydrologica data applied to Links 1, 4	Monthly Gridded Precipitation (PRISM); Daily Streamflow (USGS)	Monthly Gridded Precipitation (PRISM); Daily Streamflow (USGS)
<i>Method:</i> SPI/SSI is calculated by aggregating historical monthly time series of precipitation or stream flow using a 2-year/24-month accumulation period (abbreviated as SPI-24 or SSI-24) using the R package ‘SPEI’		
Media data applied to Links, 2, 3	U.S. Newsstream for <i>The Mercury News</i> (San Jose; 2010–2018, $N=820$)	U.S. Newsstream for <i>The Press Democrat</i> (Santa Rosa; 2008–2022, $N=1111$)
<i>Method:</i> Media from each city's newspaper of record was searched for relevant articles in U.S. Newsstream. Structural Topic Modeling (STM) was used to identify the primary topics and to assign news articles to a given topic for further analysis in the process-tracing procedure.		
Document, Interview data applied to Links 3, 4	2010, 2015, 2020 Urban Water Management Plans; Interviewees [SJ01, 02]	2010, 2015, 2020 Urban Water Management Plans; Interviewees [SR01, 02]
<i>Method:</i> Process-tracing of collective, causal sequence of perception or detection of errors about future water supply and demand conditions; prediction, or reconciliation with prior beliefs; evidentiary actions of utility planners and policymakers to gather new evidence; and responsive policy design		

4.1 Public Infrastructure Providers

We selected our cases based on previous work to identify institutionally and hydrologically diverse urban systems (Deslatte et al. [2022](#)), which produced a taxonomy of CIS types (Crawford and Ostrom [1995](#); Siddiki et al. [2019](#)). Santa Rosa and San Jose are positioned on opposite ends of the San Francisco Bay Area, and their respective water utilities reside on opposite ends of this institutional taxonomy. The Bay Area experiences a semi-arid Mediterranean climate characterized by cool, wet winters and warm, dry summers. Both cities' water utilities are required to develop and update UWMPs every five years under California's Urban Water Management Act (adopted in 1983). We then use the

IGT, along with the rule typology developed by Elinor Ostrom and colleagues (Carter et al. [2016](#); Dunlop et al. [2022](#); Ostrom [2009a](#)), to identify distinctions within the boundary, information, and choice rules present in state laws and local ordinances (Deslatte et al. [2022](#)). Importantly, constitutional, collective-choice, and operational rules do not strictly conform to levels of government; therefore, California's constitution, state laws, and city charters may all contain these three levels of rules. Using boolean search terms themed to water utilities, a team of four researchers identified, extracted, and syntactically coded institutional statements from relevant source documents in 2021–2022 as part of a larger effort to code institutional statements across eight cases using the IGT and then classify rules by type (inter-coder reliability > 0.8) (For more detail, see Deslatte et al. [2022](#), [2023](#), [2025](#)). The IGT decomposes institutional statements into syntactic components that distinguish the actors, actions, objects of action, and potential inducements for action (Frantz and Siddiki [2022](#)). We use an extended version of the IGT (Frantz and Siddiki [2022](#)), with the following components:

- *Attributes [A]*: an individual or organizational actor (e.g., utility director, city council, commission) assigned to specific actions (Aims).
- *Direct and Indirect Objects [DO/IO]*: the animate or inanimate Direct Objects (those who are the direct subject or receiver of action) and Indirect Objects (those affected by the action but not the direct receiver) that receive the action (Aim).
- *Deontics [D]*: a prescriptive or permissive operator that denotes the extent to which an action is compelled, restrained, or discretionary.
- *alms [I]*: the goal or action of a statement assigned to the attribute.
- *Context—Activation Conditions [AC] and Execution Constraints [EC]*: the condition(s) under which an institutional statement applies and instantiates new scenarios in which actions occur.
- *Or Else [OR]*: an optional sanctioning component that applies to the aim of the institutional statement.

4.2 'Soft' Public Infrastructure

To visualize the interactive elements of institutional arrangements, the IGT components are mapped as network diagrams, following recent guidance for identifying *dependencies* within institutional designs (Mesdaghi et al. [2022](#)). Dependencies are determined when the object of one statement is contingent on the activation condition or execution constraint of another statement. In essence, this means the action specified in one statement is dependent on a condition or constraint contained in another (Deslatte et al. [2023](#)). Attributes, context conditions, and direct/indirect objects are depicted as nodes, while deontics and aims are shown as edges or links between nodes. Individual institutional statements are linked, demonstrating dependencies (dotted lines), when the objects of one statement are connected to the conditions of another.

4.3 Hydrological Analysis of the Resource System

We operationalize relevant biophysical and community characteristics through hydrological analysis of streamflow data and topic modeling of media data. For the hydrological analysis, we focus on identifying periods of drought that influenced the policy design process. Drought is a particularly damaging climate extreme, 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 is characterized by an extended period of unusual precipitation or

streamflow deficit in relation to the long-term average conditions, usually quantified through two indexes: the Standardized Precipitation Index (SPI) (McKee et al., [n.d.](#)) for precipitation deficits and the Standardized Streamflow Index (SSI) (Vicente-Serrano et al. [2012](#)) for streamflow deficits. We computed SPI and SSI using the R package SPEI (Beguería et al. [2017](#)). When available, we substantiate assessments of dry or wet periods with data on reservoir levels, reservoir storage, and groundwater elevations.

4.4 Topic Modeling of Issue Salience Among Resource Users

To capture the dynamics of community resource users, local news media from each city's newspaper of record was analyzed to measure the public salience of water issues over time. We used each city's newspaper of record because these outlets are “intended for general circulation, published regularly at short intervals, and containing accounts of current events and news of general interest” (Martin and Hansen [1996](#), 585). The newspapers of record are The Mercury News (San Jose, CA) and The Press Democrat (Santa Rosa, CA). We searched for relevant articles in U.S. Newsstream, a commonly used news database containing the newspapers of record (Buntain et al. [2023](#)). Our query located articles with a main subject of water (capturing themes such as water shortages, droughts, water conservation, water utility actions, etc.) within the study period (2008 and 2022) in each publication. Full-text articles were batch-downloaded and processed in R to extract each article's year and text. We employed Structural Topic Modeling (STM) to identify the primary topics in each city's news article corpus and to assign news articles to a given topic for further analysis in the process-tracing procedure. The preprocessed corpora were then analyzed using the R package, STM, to identify the key topics in each city.

4.5 Process-Tracing of Policy Design and Evolution

Using these data, we then “trace” the policy design process by descriptively coding the UWMPs over three planning periods ($N=6$), along with interviews with water managers ($N=4$) using a codebook developed by the research team and described in Figure [3](#). Process-tracing emphasizes internal validity and the steps or activities that theoretically produced an observed, deterministic outcome (Beach and Pedersen [2019](#)). Our outcomes are the planning contingencies and tools—iteratively updated every five years—comprising the primary climate-adaptation response options. The codebook was designed to facilitate thematic analysis of “Causal Process Observations,” which can be defined as “an insight or piece of data that provides information about context, process, or mechanism, and that contributes distinctive leverage in causal inference” (Brady and Collier [2004](#), 252). CPOs are diagnostic evidence that allow the researcher to assess the validity of a hypothesis. Specifically, the codebook was used to identify “knowledge infrastructure” types and the inferential steps depicted in Figure [3](#). Planning documents were iteratively coded by three researchers, with multiple rounds of iterative revision until substantial agreement between coders was achieved (inter-coder reliability > 0.8 for a subsample of text). The first cycle of coding contains the steps of active inference (perception, prediction, action, and policy design output), while the second includes the knowledge infrastructure types ($K1-K4$) (see Deslatte et al. [2024](#) for more detail). Finally, we identified the iterative policy design options to compare across time periods and cases.

Causal Process for Collective Action Inference in UW-CIS

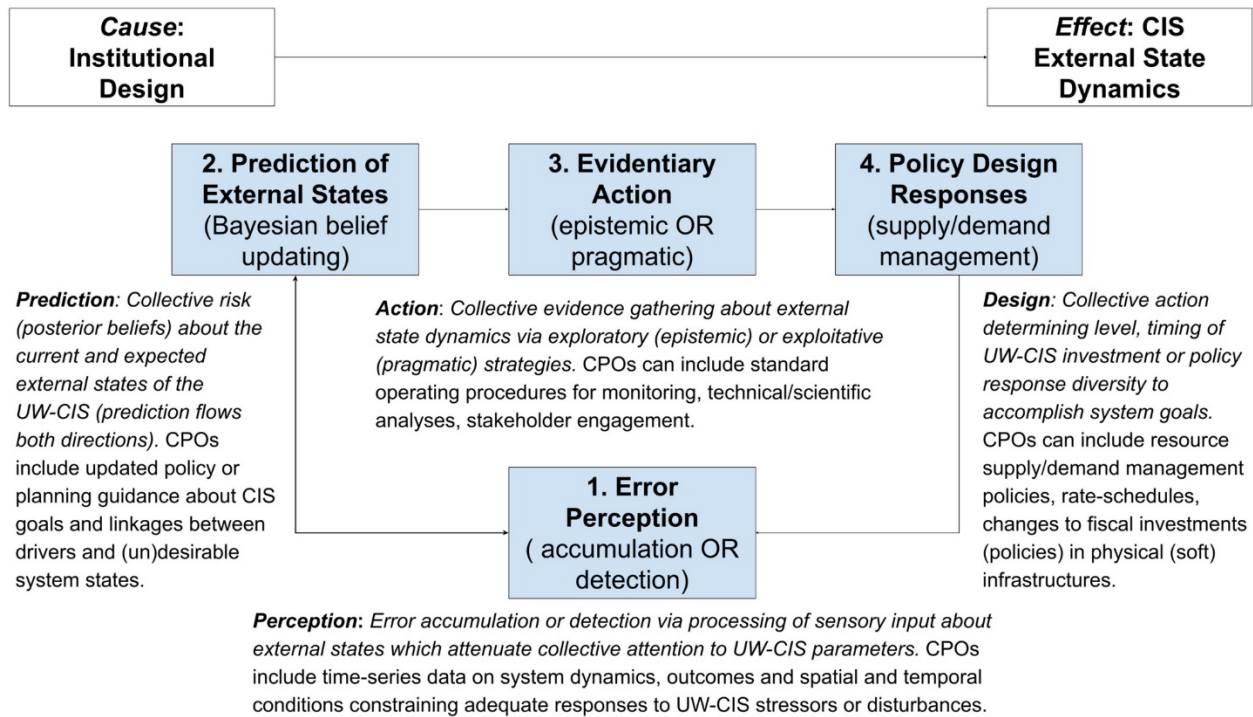


Figure 3: Steps for process-tracing of collective action inference in UW-CISs to *perceive* changes in external system states, update *predictions* of beliefs about future conditions, *actively* gather evidence, and *design* new policy responses.

5 Results

We find that successive rule changes to the procedures for water planning by the State of California—predominantly information and choice rules for interfacing with the resource system and users—prompted more “exploratory” information processing by both water utilities. These epistemic efforts were greater in the public utility—where boundary rules enabled broader public participation—compared to the investor-owned case; this is evidenced by greater development and use of climate data in planning. However, both utilities designed successively more diverse policy response options as a result of state requirements, drought experience, and updated predictions of drought-related water shortages in the future. Below, we examine key differences in boundary and choice rules between the CISs as well as distinctions in the hydroclimatic and media information available to policymakers. We then detail distinctions that emerged in policy designs under similar, evolving state planning mandates (information rules).

5.1 Collective Boundary and Choice Rules

We find important differences in the boundary and choice rules between our cases relative to policy design processes. The CIS framework depicted in Figure 2 organizes these interactions within link 2, depicting resource user-provider exchanges and monitoring.

The City of Santa Rosa provides water to approximately 54,000 residential and commercial users through its Santa Rosa Water department, overseen by a City Council-appointed Board of Public Utilities. This relationship is depicted in Figure 4, in which the Santa Rosa City Council (blue attribute) is required to appoint members of the Board (object). The Board is given “general policy authority” over management and planning for the utility, along with any additional “duties or authorities” the Council delegates. However, the Council must (deontic) maintain control over water rate-setting. Although we designate the appointment powers and discretion to delegate additional duties to the Board as “institutional dependencies”—meaning action requires an antecedent effort of others in the collective (Mesdaghi et al. 2022)—the siloing of rate-setting authority also ostensibly creates a nexus of interdependence between the bodies, given the importance of setting adequate water rates for most long-range planning and adaptation. In California, publicly owned water systems are predominantly self-regulated in terms of water pricing (Homsy and Warner 2020; Teodoro et al. 2020). Thus, water board members in these systems have broad authority to set investment and other climate-change policies with limited state oversight. Moreover, this institutional feature in Santa Rosa increases the odds that diverse viewpoints and contested welfare goals will be given more of an airing in policy decisions. “It really allows us the flexibility to make things happen,” said one utility official [SR02].

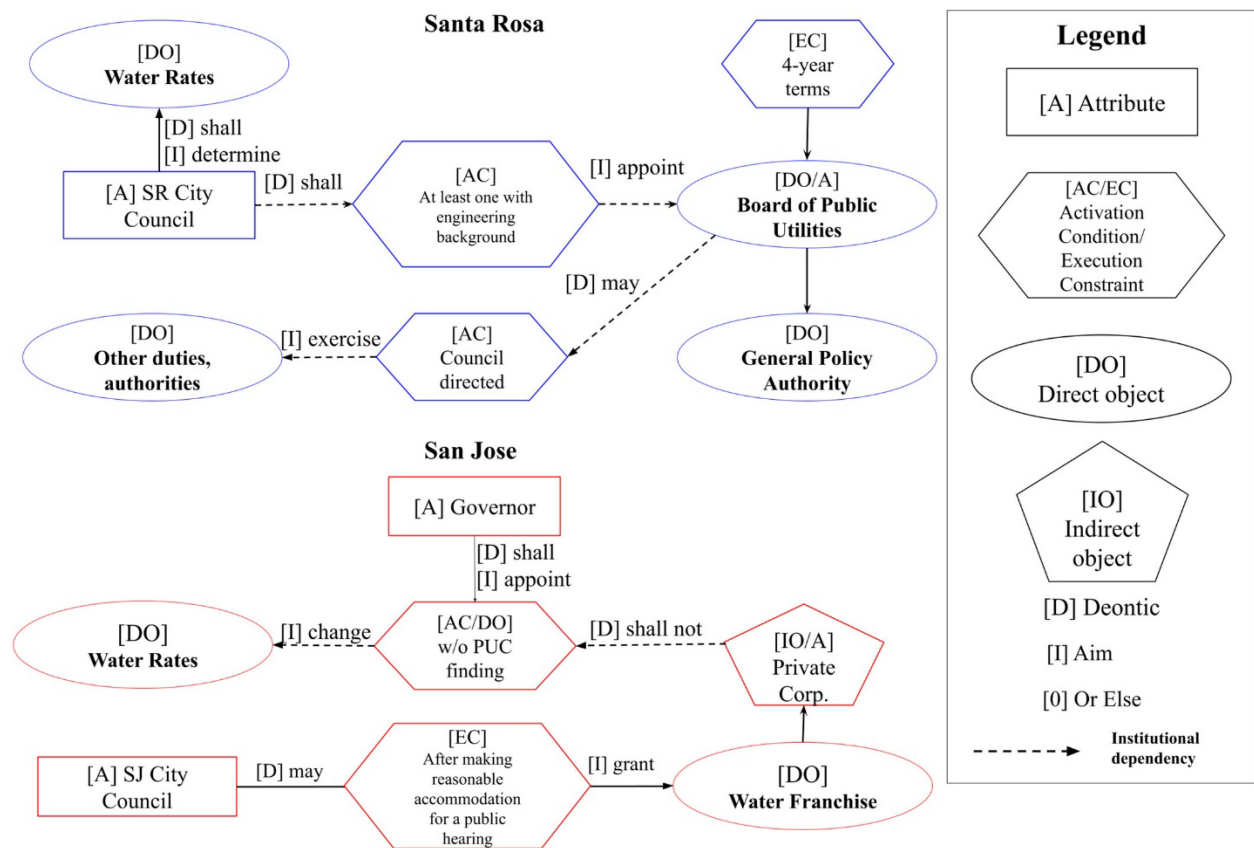


Figure 4: Santa Rosa and San Jose boundary conditions relative to policy authority and water rate-setting.

Conversely, San Jose relies on an investor-owned utility, the San Jose Water Company (hereafter, “San Jose”), to provide water to over 1 000 000 customers in Santa Clara County. The utility is one of the largest investor-owned urban water systems in the United States, and its water rates and operations are regulated by the California Public Utilities Commission (CPUC). As depicted in Figure 4, the primary role the San Jose City Council (red attribute) plays in overseeing the utility is its power to enter into a franchise agreement with a private provider. The franchisee is then barred from changing water rates or making any other contractual or service changes that may result in rate changes, without a “showing” before the CPUC and a “finding” that the change is justified. Given the fact that this process is overseen by appointees of the governor and conducted via a quasi-judicial process, the most likely access that resource users have to shaping substantial policy decisions rests in their capacity to formally petition or protest at the CPUC. Thus, board members of investor-owned systems are decoupled from local electoral punishment, answering to investors and, in the context of water pricing, investment, or conservation policy decisions, CPUC commissioners. Utility officials described this institutional design as a “complex, multi-layered ... multi-year process with everybody having a say, at one point or another,” [Interviewee SJ01]. Public input on policies tended to occur “primarily” through the CPUC.

These boundary rules (who can enter collective-choice positions) and choice rules (what actions they may, must, or must not take) are important for understanding how policy designers respond to or anticipate varying information feedbacks, whether they are precipitation and streamflow, elections, or infrastructure decline. While these variables may all have some marginal influence on outcomes, they evolve at different timescales, meaning policy designers may try to account for different subsets of them when they infer how, for instance, changes in infrastructure investment (via link 3 of the CIS) influence the exploited resource system (link 4), or whether additional demand-management policies will be necessary to influence user behavior (link 1).

One important consideration in case comparisons is the similarity in the environmental contexts. We examine this through hydrological and media data analysis. The San Francisco Bay Area suffered from a multi-year drought, from approximately 2012 until 2016. However, the drought had distinct impacts on the utilities, in part because of the differences in water sources. Approximately 95% of Santa Rosa's water is from surface sources managed by the Sonoma County Water Agency, drawn from the Russian River system. During an earlier 2007–2009 drought depicted in Figure 5, Santa Rosa experienced a significant decline in reservoir storage and has seen water diversions from the river system, contributing to drought deficits. The storage decline was further impacted by historic meteorological drought conditions Santa Rosa experienced from 2014 to 2017. “One of the big challenges is that we are so wholly dependent on this Russian River system,” said one Santa Rosa official [Interviewee SR01].

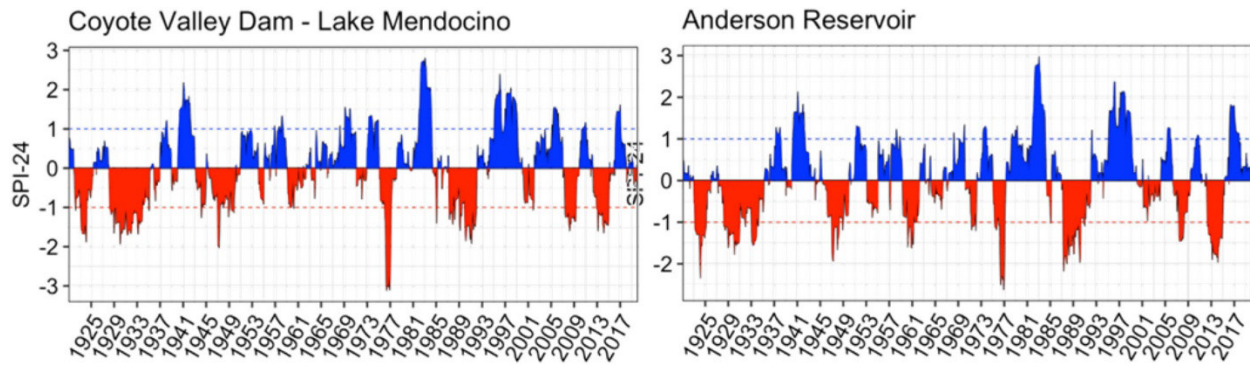


Figure 5: A metric of surface-water availability at Coyote Valley Dam (Lake Mendocino), which provides water to Santa Rosa, and Anderson Reservoir, serving San Jose. SPI-24 represents precipitation deficits over a 24-month or 2-year accumulation period. The dotted lines indicate SPI-24 equal to -1 and $+1$, where dry or wet conditions are considered to begin, respectively.

Meanwhile, San Jose's water is drawn from three primary sources: roughly half is from treated surface water delivered from the Santa Clara Valley Water District (SCVWD); nearly 40% comes from San Jose's groundwater resources sourced from the Santa Clara basin; and the remainder comes from surface water from watersheds in the nearby Santa Cruz Mountains. In 2015, San Jose implemented a 20% mandatory reduction in urban water usage demand due to drought conditions. As the drought persisted, the imported surface water available dramatically decreased, as two important water sources available to SCVWD were slashed; San Jose utilized groundwater to counteract the surface-water deficit, and as a result, groundwater elevations exhibited a noticeable decline from 2013 to 2015. Relatedly, stream and precipitation gauges, which had noted surplus flows/accumulation from 2010 to 2012, recorded deficits from 2013 to 2015.

The media analysis depicted in Figure 6 indicates that resource user attention to water issues was responsive to state and local policy actions as well as the impacts of climate on water quality, availability, and related events, such as the 2017 Tubbs Fire, which destroyed about 5% of the city's housing stock, killed 22 people, and led to some water contamination. In Santa Rosa, the topic of *water politics* was the most prominent during the period when state-level water regulations were being developed (2008–2015), while *water supply* and *quality* subsequently peaked in 2017 at the end of an extreme drought. In San Jose, *water politics* was similarly highest during the early study period as state-level water regulations were developed, while attention to *municipal water* and *outdoor water use* peaked in 2014–15—coinciding with San Jose's mandatory water use restrictions. The topic of *water infrastructure* later becomes the most prominent, possibly related to rate increases for infrastructure projects.

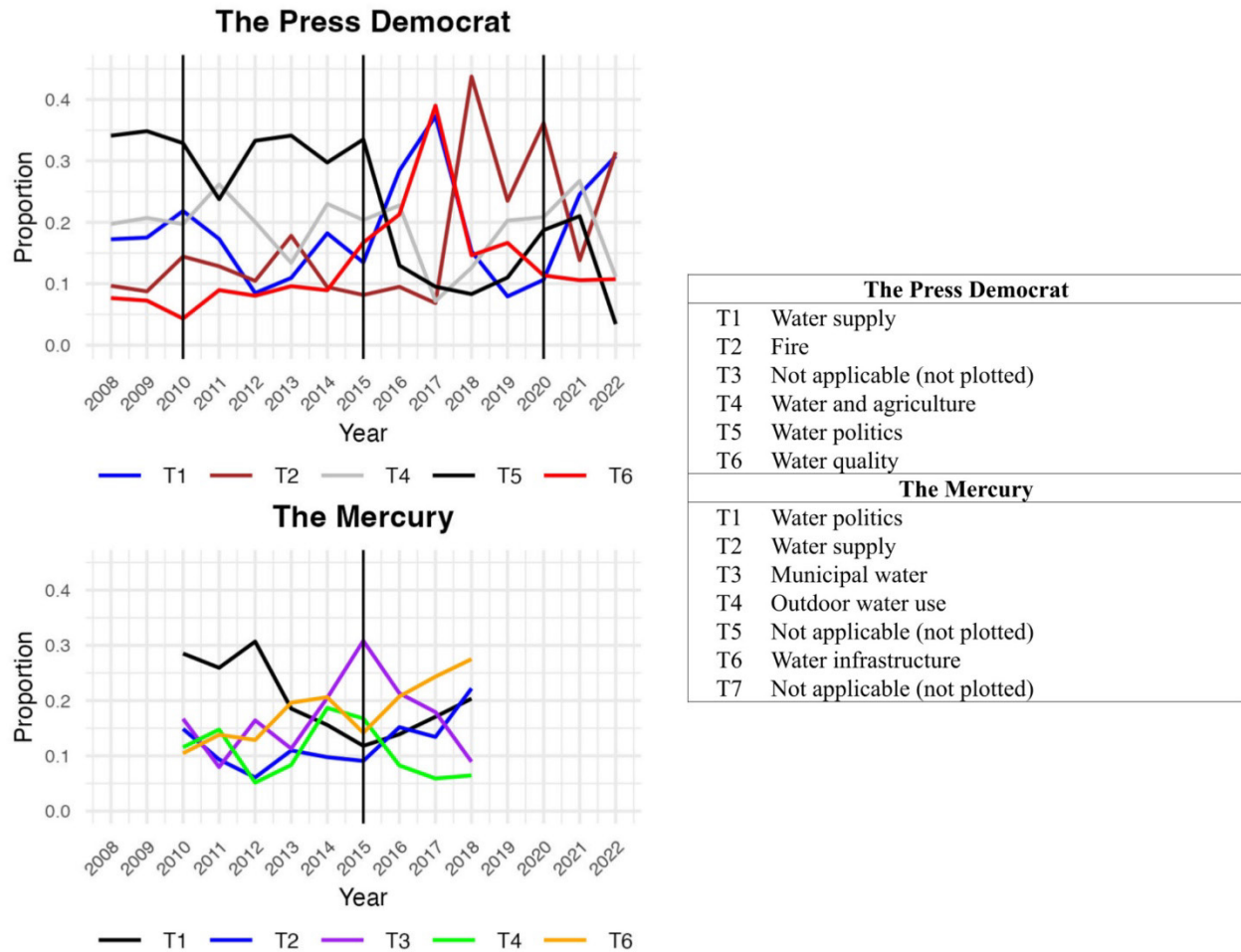


Figure 6: Depiction of the analysis of normalized media topic proportions per year for Santa Rosa, CA (The Press Democrat) and San Jose, CA (The Mercury News).

Thus, an important question is how these distinctive boundary and choice rules mediated any epistemic-pragmatic tradeoffs in policy designing under similar information rules imposed by the state.

5.2 Information and Choice Rules

We find evidence of important distinctions in the information curated and policy response options developed. Specifically, our public utility (Santa Rosa) engaged in more exploratory inference compared to the private utility (San Jose) and developed more comprehensive drought contingencies.

As noted, utilities are required to develop and update UWMPs every five years under California's 1983 Urban Water Management Act. Since 2009, the legislature has repeatedly placed additional supply- and demand-planning requirements (predominantly information rules) on utilities, detailed in Table 2 and depicted in Figure 7. These state actions imposed more institutional

directives on the policy design processes of local water providers. We briefly describe these changes and the subsequent distinctions in information feedback we observe across the cases.

TABLE 2. California state legislative mandates for urban water management planning during study period (2009–2021).

Planning period	2010 UWMP	2015 UWMP	2020 UWMP
Legislation	SB X7-7 (2009)	AB 2067/SB 1420/SB 1036 (2014)	SB 606/AB 1668 (2018)
Policy goal	20% reduction in statewide urban per capita water use by 2020	Greater detail of water demand reduction measures and water accounting	Encourage more efficient water consumption; eliminate water waste; strengthen drought resistance and drought planning
Planning changes (knowledge infrastructure types)	<ul style="list-style-type: none"> • Determine base daily per capita water use (K4) • Determine urban water use targets (K2) • Compare urban water use targets to 5-year baseline (K1) • Determine an interim urban water use target (K4) 	<ul style="list-style-type: none"> • Details of demand-management measures (DMMs) over previous five years and those needed to achieve 2020 goals (K1, K4) • Water system loss reporting (K4) • Estimates of water savings from codes, standards, etc. (K4) • Voluntary energy intensity analysis for water extraction and diversion (K4) • Voluntary analysis and definition of water features artificially supplied with water (K4) 	<ul style="list-style-type: none"> • Five-year drought for Water Reliability Assessments (K1, K4) • Volumetric water loss performance standards (K4) • Mandatory energy intensity analysis for water extraction and diversion (K4) • Preparation of drought risk assessment (DRA) and required elements in Water Shortage Contingency Plans (K1, K2, K4) • Seismic risk assessment (K2) • Reporting of water losses over past five years (K1, K4) • Ensure consistency between UWMP and Groundwater

drawing population data from the Association of Bay Area Governments' (ABAG) 2009 population projections (K2). San Jose also relied on a supply analysis conducted by SCVWD, and identified the potential for supply shortages after 2025 in a multiple-dry-year scenario.

San Jose's 2010 policy design for drought response limited its options to dealing strictly with water shortages, such as increasing reliance on groundwater extraction to make up for surface water supply shortfalls. The utility relied on SCVWD's assessments and projections that groundwater elevations had been increasing for 40 years and were not expected to become overdrafted. The analysis indicated that a multiple-dry-year scenario could result in shortages after 2025, and San Jose indicated it was collaborating with SCVWD to ensure that a multiple-dry-year scenario post-2035 would not result in a greater than 20% supply shortage. Notably, increased groundwater extraction by San Jose and other water agencies led to a measured lowering of the aquifer water table during the mid 2010s, although groundwater elevations were restored through recharge in subsequent years. San Jose also relied on a Water Shortage Contingency Plan (WSCP) written in 1992. The updated contingency plan included five water shortage "stages" that mirrored the stages developed by SCVWD ranging from 1 (normal conditions) to 5 (emergency conditions), each with associated interventions for demand reductions.

By contrast, Santa Rosa conducted a more detailed analysis, using all four prescribed methods for setting reduction targets. Its supply and demand analysis was based on more extensive population, employment, and land-use data collected through prior planning efforts, including the city's 2035 General Plan (K2, K4). Unlike San Jose, Santa Rosa provided a climate-change commentary, noting the city's efforts to track and reduce greenhouse gas emissions (GHGs) as well as other sustainability-based actions.

Santa Rosa's policy design for shortages was more inclusive of multiple hazards, envisioning actions necessary in case the water supply from the Russian River became contaminated; how the city would respond to an area-wide electrical power failure; designing system redundancy into its storage and distribution systems in case of severe earthquakes; as well as its own five-stage demand reduction approach, with actions the utility could take at all stages of a water shortage emergency.

One important distinction is that San Jose must submit its UWMP to the CPUC as part of any water-rate change (depicted in red in Figure 7) and would have to file with the CPUC before imposing conservation measures. If a water shortage prompted mandatory conservation, San Jose would use a CPUC-approved strategy known as Schedule 14.1, which describes mandatory waste prohibitions, enforcement mechanisms, provisions for rationing water, and a list of unauthorized uses. However, local governments and the CPUC would have responsibility and authority for water conservation ordinances within San Jose's service area.

5.2.2 2011–2015

In 2014, California adopted several provisions intended to prompt greater accounting and use of information feedback. Water suppliers were required to provide narratives describing their water demand-management measures (DMMs); detail ongoing and planned water DMMs; quantify

distribution system losses; and adjust projections to account for water savings from adopted codes, standards, ordinances, or transportation and land-use plans; analyze and define water features that are artificially supplied with water, including ponds, lakes, waterfalls, and fountains, separately from swimming pools and spas; and finally, include energy consumption-related information, such as estimating energy used to extract or divert water supplies. Also in 2014, the legislature passed the Sustainable Groundwater Management Act, requiring preparation of a Groundwater Sustainability Plan (GSP).

Both utilities relied on distinctive KIs for updating forecasts. San Jose again relied on population projections (*K2*). The utility outlined 12 Best Management Practices (BMPs), equivalent to DMMs, to comply with the new requirement, although their implementation was dependent on SCVWD. Because SCVWD provided 90% of San Jose's supply, the utility relied on SCVWD for analyses of demand reduction measures and supply reliability. Additionally, the utility deferred on climate change to its wholesaler, which was considering supply and distribution system resiliency options. Relative to policy responses, San Jose modified its shortage contingency plan to distinguish it from its regional wholesaler. The changes amounted to giving the utility authority to impose mandatory use restrictions more quickly and included new demand reduction actions such as prohibitions on non-essential uses and a drought surcharge program for customers. San Jose also had new discretion to enforce the actions and levy penalties.

By contrast, Santa Rosa engaged in a wider variety of analyses and collaborations. The city modeled 25 conservation measures and their effect on demand (*K3*, *K4*) and completed analyses of system losses and “passive” water savings (i.e., due to codes, standards, and other related frameworks). In 2011, Santa Rosa joined a regional alliance with other nearby cities and water suppliers. The city also adopted a Groundwater Master Plan (GMP) in 2013 and participated in the development of a regional Santa Rosa Plain Watershed Groundwater Management Plan (SRPGMP) in 2014 to protect groundwater resources among stakeholders. Notably, in the 2015 UWMP, Santa Rosa expanded consideration of potential climate-change impacts. The Santa Rosa City Council adopted a Community-wide Climate Action Plan (2012) and a Municipal Climate Action Plan (2013), which outlined GHG, energy, and water demand savings measures undertaken by the city, Santa Rosa Water, and the greater community, which included both mitigation and adaptation measures. “In this area, there's been a keen interest in climate change and climate variability, and really understanding how that impacts all aspects [of] water supply,” said one Santa Rosa official [Interviewee SR01].

The 2015 UWMP provided a qualitative description of how climate change could affect supply and demand. Santa Rosa concluded its water supply was not thought to be vulnerable to climate-change impacts based on a review of the topics and factors, including source, protection for invasive species and saltwater intrusion, and ample storage capacity to bridge dry years. Relative to policy responses, Santa Rosa developed a new shortage contingency plan that included seven rationing stages designed to provide more timely information on environmental conditions, for instance, shifting from monthly delivery reports to weekly reports as conditions worsened (*K4*).

5.2.3 2016–2020

In 2018, the California Legislature again revised its planning requirements with the goal of more rapidly identifying shortage conditions, encouraging more efficient water consumption, and strengthening drought resistance (the green objects in Figure 7). Specifically, the state modified dry-year water reliability planning by expanding the scenario for a multi-year drought from three years to five years and requiring suppliers to prepare a drought risk assessment (DRA)—a scenario in which the next five years would be equivalent to the driest five-year period on record. Suppliers were required to address seismic risk to facilities and include energy-use estimates for water supply management. Suppliers had to include water loss audit reports and plans to meet water loss performance standards. Importantly, stand-alone water shortage contingency plans (WSCPs) became mandatory and had to include an Annual Water Supply and Demand Assessment to determine if conservation measures should be invoked.

Both utilities responded using different information types and reliance on external organizations. San Jose developed a sound-based leak detection system that incorporates artificial intelligence, where unique soundprints of distribution system leaks can be readily identified in a non-invasive manner. Regarding climate change, San Jose qualitatively considered climate-change stressors that could affect water supply and conveyance but largely deferred to SCVWD and their climate planning efforts (K3). San Jose also deferred to SCVWD's information for its DRA, which considered all water supply sources, including imported water, local surface-water storage, recycled water, and local groundwater. San Jose revised its contingency plan to revert back to a five-stage shortage framework, declaring an emergency after a 40% shortage. The utility again coordinated its planning with SCVWD and other local water retailers to ensure the sustainability of the Santa Clara Valley subbasin. San Jose noted it had emergency intertie connections with neighboring utilities, but no contracts were in place specifying quantities of water that could be obtained.

By contrast, Santa Rosa internally analyzed climate impacts, determining the utility could experience drought conditions resulting in a reduction of surface water due to climatic conditions (K3). Notably, updating the 2015 UWMP, this effort determined climate change could impact surface-water supplies. As a result, Santa Rosa outlined mitigation and adaptation-related measures across a range of climate-related issues, including water demand. Santa Rosa also revised its contingency plan to go beyond the state minimum requirements, including a new worst-case stage of water rationing in case of a 50% or greater water shortage. Mandatory use restrictions would also be triggered sooner in a drought. Cumulatively, these changes amount to more aggressive responses as shortage conditions worsen.

6 Discussion and Conclusions

In physics, neuroscience, mathematics, machine learning, and other fields, active inference is presenting scholars with a unifying principle: all intelligent organisms act to minimize surprise. What then matters is where designers draw the lines between what is considered within and external to the system (e.g., the self, the collective, the community), and thus what is being inferred about external states. We argue this approach can motivate the study of institutional

designs that support boundary-regulating information feedback mechanisms and policy designs that attempt to navigate between these possible states.

Our examination of two water utilities suggests that they designed policies using distinct, institutionally mediated models of the environment. Santa Rosa, perceiving higher risks associated with their reliance on a single water source, developed a more comprehensive knowledge infrastructure system to design a broader climate-focused shortage contingency plan. The process was guided by boundary and choice rules intended to foster greater deliberation and public engagement. In interviews, Santa Rosa managers credited having a separate Board of Public Utilities for creating an added policy-focused “feedback loop” that managers and citizens could use to consider longer-term or more complex issues, specifically climate impacts. While the primary, applicable information rules were constituted at the state level and applied to all public water providers, they fostered an increasingly exploratory or “epistemic” information-processing strategy in Santa Rosa relative to San Jose, which primarily relied on the climate planning efforts of other agencies. San Jose managers, while touting the benefits of being insulated from electoral politics, also noted that climate-related innovations would be subjected to a more rigorous return-on-investment logic by shareholders and regulators.

Our developing theoretical lens of collective action inference suggests that constitutional and collective-choice institutional designs can work in tandem to motivate policymakers to recognize and minimize the divergence between prior beliefs about the world and new data. California's increasing state institutionalization of climate planning relative to water supplies influenced this divergence by requiring water suppliers to process more diverse information, engage more diverse populations, and consider an expanding range of worsening scenarios. While we observe clear differences in the inference strategies of our cases at the collective-choice level, both cases progressively improved the predictive accuracy of their modeling, and both surpassed the state's 2020 water use reduction goal. As one San Jose interviewee noted, water suppliers have little choice but to consistently strive for more accurate and timely “models” of their environment: “Water scarcity is not going away. Climate change is going to drive these things. And sort of clinging to the old policy models, financial models, or water rights models for that matter, are not going to work in the long run” [SJ02].

Our study provides important insights for how institutions may be altered to better enable adaptive responses in the face of environmental uncertainty. While California's planning requirements contain sanctions for water systems that do not comply, they essentially constitute new information feedback procedures. They enable the flexible development and use of technical and scientific knowledge for policy designing. Practically, similar types of knowledge infrastructure for environmental dynamics could be feasible in states and country contexts where climate change is politicized or regulatory approaches are less politically palatable. Similarly, overly regulatory processes that constrain exploration of policy solutions—such as the often litigious state regulation of investor-owned utilities that discourages risk-taking—may be less climate adaptive.

Our study also has several limitations. Theoretically, while formal mathematical support for the central principle of active inference (free energy) is proliferating, far more theoretical work is needed to extend it into collective action. Empirically, our process-tracing allows for some cross-

case comparisons given our effort to control for many exogenous features but still suffers from low external validity. Additional conceptual refinement, measurement, case-based studies, and larger-N research are all necessary to move from a diagnostic understanding of institutions to a prescriptive one. Nevertheless, we hope our approach to developing behavioral and structural linkages can help motivate the search.

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