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Institutions, Voids, and Dependencies: Tracing the Designs and Robustness of Urban Water Systems

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Introduction

1 Climate change and urban growth both pose grave challenges to current and future water supplies. Urban water systems are composed of both natural and social components and are responsive to biophysical, political, and social stressors. For example, the 'Day Zero' drought in Cape Town, South Africa, and the aridification of the Colorado River Basin in the western United States both demonstrate how biophysical and social or political variables may interact to threaten water quantity or quality, and by extension, human health and prosperity. While extreme examples, these types of events are likely to become more commonplace in the coming decades as climate change exacerbates variability in weather patterns, and as population growth and degrading water infrastructure place greater stress on urban water systems. The ability to anticipate and adapt to such threats will be crucial for enhancing the sustainability of these integrated socio-environmental systems (SESs).

2 Institutions are the sets of rules and norms that structure human behavior, providing the "social-cultural scaffolding" which enables human collectivities to adapt when anticipated states of the world change (Clark, 2013; North, 1990; Scott, 2013). Among their many impacts, institutions may facilitate or inhibit the sustainability of resources by influencing information flow through a system. Analyses of the institutional role in climate-adaptive behavior have been meager to date, however, due in part to

limitations in both theory and methods. Fortunately, recent advances in studies of information processing, particularly concerning knowledge of the human brain's predictive-processing systems, provide promising pathways for better understanding how formal and informal institutions steer human-induced adaptation and maladaptation of urban water systems.

3 For both cognitive and engineered control systems, climate-adaptation can be premised on detecting errors between a desired or predicted state of the world and the observed one. Error detection is necessary for adjusting policies, inputs or management activities to make system outputs more *robust* to specific disturbances. This process is made more difficult, however, when existing rules, norms or regulative guidance (i.e. institutions) are ambiguous or do not exist at all (Hajer, 2003; Mesdaghi et al., 2022). For instance, while the Intergovernmental Panel on Climate Change (IPCC) has definitively articulated the certainty surrounding anthropogenic climate change and current and anticipated impacts on ecosystems and resources (IPCC, 2022), formal mitigation or adaptation guidance for human population centers has not kept pace with this scientific consensus (Woodruff et al., 2018). Climate change is especially prone to creating ambiguity due to both collective-action and cognitive barriers, including the relative newness of climate-related problems (Biesbroek et al., 2009; Mesdaghi et al., 2022; Vilcan & Potter 2020), lingering uncertainties about how climate change will impact the risks and vulnerabilities of specific locales (Shaw and Theobald 2011), and psychological biases that cause humans to minimize longer-term risks and engage in directionally motivated reasoning (Bayes & Druckman, 2021; Kunda, 1990).

4 This article aims to conceptually link cognitive science and its action-oriented predictive-processing approach to institutional designs and their capacity for enabling collective action. We do so by developing a Bayesian application of the Robustness of Coupled Infrastructure Systems (CIS) Framework to analyze aspects of error signal detection in urban water systems (Anderies & Janssen, 2013; Deslatte et al., 2021). This, in turn, allows us to identify what we deem institutional "dependencies" and "voids," and to assess how they may facilitate or inhibit system robustness. The analysis proceeds in three steps. First, we use the Institutional Grammar Tool (IGT) to analyze the formal institutions that govern water-utility investment in Phoenix, Arizona, USA. Ratemaking and investment are two major ways that urban water utilities respond to stressors to preserve desired system outputs. The IGT allows us to decompose formal institutional statements into their semantic and syntactic components. We then connect the identified institutional statements via network diagrams that map pathways for information flow in action situations, which allow us to identify key institutional characteristics that may influence the decision-making processes (Mesdaghi et al., 2022). Finally, we use key informant interviews, participant observation, public records, and administrative data to process trace (Beach & Pederson 2019) actual decision-making around a series of ratemaking cases from 2015-2021 to assess how the formal institutions identified in the previous steps affected both the decision process and the resulting investment policy change. This effort represents an initial step toward systematically assessing how institutional arrangements may impact climate responses vis-a-vis information exchange during periods of heightened attention to risks.

System errors, fast and slow

5 Increasingly, the fields of data science and neuroscience are producing insights into human information processing that hold potential value for institutional design and analysis. Institutions have been defined as "human-constructed constraints and opportunities" wherein choices are made, and their "consequences" are realized (McGinnis, 2011a; Ostrom, 2009). The information actors use to reason through choices and understand consequences are therefore "affected by the rules or absence of rules that structure the situation" (Ostrom, 2009, p. 3). Thus, designing institutions that foster humans' ability to process information and adapt to change – particularly when their expected or desired state does not match what they experience – is critical in the context of climate stressors.

6 Advancements in our understanding of the brain's hierarchical predictive-processing abilities – and the inspiration this has provided to the development of neural networks and machine-learning – are increasingly coalescing on the predictive power of human cognitive models, and how adjustments are made to tune expectations to realizations (Clark, 2013; Kaplan et al., 2016; Hastie et al., 2009). Humans, and the human-designed institutions which guide their actions, are dependent on generative "hypothesis machines" to interpret information (Hawkins, 2021). The neocortex, responsible for higher brain functions such as perception and decision-making, is thought to function via cascading top-down predictions about the nature of the world that interact with bottom-up sensory input (Hawkins, 2021). In this hierarchical process, error identification occurs when predictions and inputs do not square, leading to "biased competition" (Grossberg, 2013). In this competition, one hypothesis pertaining to the system state wins, and alternative hypotheses – even when driven by new information – are sidelined. In other words, when a human's prior belief about some aspect of the world is challenged by new information, they experience cognitive dissonance and may update their belief or double-down on their prior expectation (Kaplan et al., 2016; Kahneman & Egan 2011; Kunda, 1990; Zummo et al., 2021).

7 This hierarchical predictive-processing framework has relevance for understanding collective human agency (Clark, 2013), specifically by providing insight into how individuals in organizations may adapt, or fail to adapt, to changes in their environment, based on the information they receive. Governments, firms and civic associations exist to produce specific outcomes; when performance does not meet identified goals (i.e. creating an "error" signal), these organizations are expected to adjust their policies, production capabilities, or practices to increase alignment (Besanko et al., 2009; Deslatte 2020a). When specific organizations act to preserve or enhance desired system outputs, such as drinking water quality or quantity, they are acting to maintain robustness. Formal institutions moderate this process by providing ways for organizations to detect errors and make adjustments which attempt to preserve the robustness of system outputs. Much like the human brain, however, institutional designs may also facilitate competing hypotheses that cause organizations to double-down on their actions rather than adjust, in part because they influence how much attention an organization pays to error in a specific context. Ideally, institutional designs evolve over time to enhance predictability of social or economic interactions (Biesbroek et al., 2009; Puffer et al., 2010; North, 1990), providing programmatic scripting that enables actors to adjust to unsatisfying outcomes.

8 In the absence of formal institutions, informal institutions (e.g., norms) may emerge to provide discursively developed and culturally transmitted guidance for error correction. In this sense, institutions – regulation along with social conventions, marketing, symbols, media and patterned practices – function and change to minimize prediction errors (Clark, 2013; Gentsch et al., 2015; Hohwy, 2018; Lyons et al., 2019). But, in the absence of guidance or consensus on how to respond to errors, whether through formal or informal channels, designing robustness to known stressors can increase vulnerability to less frequent ones. In such scenarios, errors may accumulate and, eventually, undermine the ability of the system to function as desired.

9 In heavily engineered SESs, errors can accumulate quickly or slowly over time. For example, a municipal water utility may make adjustments to water rates structures, and investments in storage, treatment, or transmission infrastructure under institutions that set specific goals (affordability, economic growth) and direct attention to relevant information on social or environmental systems to accomplish these goals, especially when error is detected (Garcia & Islam, 2018; Deslatte et al., 2021; Treuer et al., 2017). Importantly, however, repeated efforts to correct errors to meet short-term goals can undermine longer-term system sustainability (Bodini et al., 2012). Such long-range goals tend to be more inherently ambiguous and dependent on difficult-to-predict factors (Anderies et al., 2013; Carpenter et al., 2001). Water management efforts may thus encounter greater challenges measuring errors that impact long-term system sustainability (Ladyman & Wiesner, 2020), or may under-weight, omit, or downplay error signals that represent disconfirming but more ambiguous information (Bayes & Druckman, 2021). In other words, new information may be interpreted and "explained away" using other information that is clearer or more salient or immediate (Kudo & Mino, 2020; O'Neill et al., 2015). Thus, institutions must be designed to process information in ways that support the sometimes-contradictory processes of detecting and responding to error around both short- and long-term needs.

Voids and dependencies: an interaction hypothesis

10 To explore the implications of the predictive-processing framework on organizational behavior, analysts have begun to study the characteristics of institutional designs that slow or speed response to changing stimuli. Two such characteristics are *voids* and *dependencies*. Institutional voids reflect a lack of formal requirements or sanctions which are intended to routinize patterns of human behavior (Biesbroek et al., 2009; Vilcan & Potter, 2020). Voids are often equated with ambiguity and a lack of clear property rights in emerging economic markets, but they may be generalized to political-economy and management decision contexts. In this sense, voids may reflect a lack of guidance to emerging or novel threats (climate change), because the institutional system was designed to be robust to more high-frequency or understood concerns (political rent-seeking, historical weather patterns). Importantly, the absence of formal incentives or directives means that culturally transmitted or professional norms may govern human agency. Thus, voids hold the potential to increase ambiguity and allow for inaction or climate denialism. Conversely, they may provide flexibility to innovate or be entrepreneurial by not constraining the diversity of responses in the face of novel disturbances (DeCaro et al., 2017).

11 Institutional dependencies occur when prescribed actions do rely on some external activation condition and thereby influence the frequency of responses (i.e., “capital investment plans shall be reviewed annually by the board and city manager”). Dependencies increase a form of transaction cost (search) for making policy choices as collective actions become dependent on antecedent constraints or actions of others (Hong & Sohn, 2014). Institutionally designed dependencies may serve the purpose of allocating authority to higher levels of an organization or dividing it between stakeholder groups. Because some degree of coordination may be required, dependencies increase the "external" search costs of acquiring adequate information to persuade the parties as well as the opportunity costs of time devoted to the search. This is distinguished from the "internal" search costs associated with the cognitive effort of processing information, including some combination of mental abilities, prior knowledge, and education of the actors. In social dilemmas like climate change, we assume internal search costs are high due to the uncertainty surrounding climate impacts. External search costs are more variable depending on the problem type and context. Generally, decision-making dependencies should increase the likelihood that actors will truncate or minimize information search costs. However, the perceived severity of a situation may influence whether individuals detect errors, allocate attention, and incur these costs to search for solutions. In isolation, dependencies drive response frequency but could lead to error accumulation over time as search costs motivate actors to ‘satisfice’ or make due with less information (Deslatte, 2020b; Mooney, 2004; Hong & Sohn, 2014).

Institutional Void Hypothesis (H1a): Voids have a positive influence on climate-related response diversity.

Institutional Dependency Hypothesis (H1b): Dependencies have a positive influence of climate-related response frequency.

Interaction Hypothesis (H1c): The marginal effect of voids on response diversity is highest when dependency-driven responses are more frequent; as responses become less frequent, response diversity also decreases.

12 Research examining the institutional structure of water utilities in the U.S. has identified wide variations in how authority is formally allocated between interdependent actors (Deslatte et al., 2021; Garcia et al., 2019). A critical concern is how system performance is impacted by the *absence of formal guidance* (i.e. voids) *in the presence of formal dependencies* which govern the exercise of this authority (Mesdaghi et al., 2022). We posit that institutional voids inherently lead to ambiguity in the context of climate. However, they also allow for greater response diversity when paired with dependencies that drive greater response frequency. In this sense, voids and dependencies may work in tandem to influence decisions in response to error signals, as actors seek to make system outputs more robust to specific disturbances (i.e., drought). Their interaction influences *a priori* constraints on rational action and motivates mutually dependent actors to iteratively search for information. In the context of climate change, these expectations may be stated more formally as:

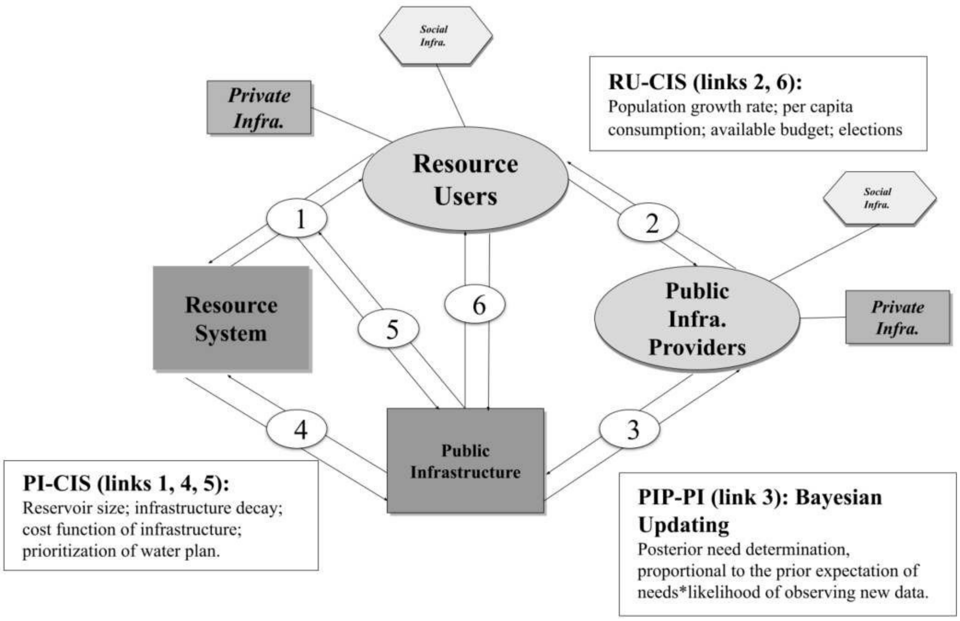
13 To investigate these hypotheses, we develop an analytical strategy based on a Bayesian model of error adjustment within the CIS Framework, which we describe next.

Analytic strategy

The CIS Framework and Bayesian Updating

14 The CIS framework, a sibling to the widely used Institutional Analysis and Development (IAD) framework, was developed to study the dynamics, or fast and slow feedbacks, within and between components of heavily engineered resource systems (Anderies et al., 2006; Anderies et al., 2013; Deslatte et al., 2021; Anderies et al., 2004). The CIS identifies four key components of such systems: the public infrastructure providers (PIPs); the resource users (Rus); the "hard" (physical) and "soft" (rules) public infrastructure (PI); and the resource system (RS). As such, it provides an organizational structure for studying feedback between system components that may support or destabilize system robustness, defined as the ability of institutional configurations to preserve natural and social system outputs (e.g., water quality and quantity) despite variability in inputs. Urban water systems designed to be robust to variability in streamflow or precipitation rely on forecasting future states and making adjustments when confronted with error. We develop a Bayesian conceptual model of investment determinations, as one area where utilities may adapt in response to error, to motivate our inquiry. Figure 1 depicts the CIS components, their interactions, and key system state variables/parameters.

Figure 1. The Robustness of Coupled Infrastructure Systems (CIS) Framework as advanced by Anderies, Barreteau & Brady (2019) to urban water infrastructure systems via a Bayesian updating parameters.



Other key system parameters are located along theorized information or material flows between the system's primary components (PIP, PI, RU, and RS).

Source: The authors

15 Our adaptation of the framework thus focuses on information flows between components related to CIS investment-related error detection and response (links 3

and 4). We first conceptualize the system's interactions as a PIP-PI "controller" which receives regular information signals on performance metrics from sensors within the PI. Variables fed to the PIP (link 3) are used to determine demand-side management policies, as well as investments needed in reservoir storage capacity and delivery efficiency, based on projected demand. The goal of the PIP-PI controller is to combine top-down expectations with bottom-up sensory signals to meet anticipated water demand. Drawing inspiration from the cognitive and data science literatures discussed above (Hawkins, 2021; Kwakkel et al., 2016; Strubell et al., 2020), error is generated through differences between measurement, prior expectations of system conditions, and uncertainty surrounding the impacts of climate change. Here, Bayesian intuition is useful. Bayesian inference works by specifying prior distributions for unknown parameters and updating them (into posterior distributions) via a likelihood function (Gill & Witko, 2013; Gill, 2014). Based on Bayes' theorem, we can specify the input signals as fixed observations of a range of unknown probability density functions reflecting investment needs:

$$\pi(u|X) = L(X|u)p(u)/p(X), \qquad (1)$$

16 where is a standard likelihood function introducing new information, X, is the resultant posterior distribution for anticipated investments. Here, prior investment needs are fixed and are a function of past attention and thus can be treated as observed alongside new system state signals, producing a joint distribution:

$$p(X|u) = p(X_1|u)p(X_2|u)\ldots p(X_{n-1}|u)p(X_n|u). \qquad (2)$$

17 Thus, the posterior distribution is a probabilistic statement about the predicted need for investment. It quantifies the uncertainty surrounding climate and is linked to *a priori* constraints on rational response imposed by the institutional design. Importantly, the PIP-PI controller functions not as a passive processor of new information alone; instead, it facilitates assessment of investment needs via a form of active, probabilistic inference about the system state guided by prior knowledge about interactions with the environment. Institutional designs will influence these interactions through the joint distribution of prior determinations and new information about future needs. Institutions impact the flow of sensory input (information), which is met by probabilistic beliefs about present or future conditions. Any resultant prediction error feeds back through the 'soft' PI (institutions) to guide attention allocation. An implication of this approach is that prior experiences with the system guide perceptual inference and expectations about investment actions - and may even overpower recognition and response to new sustainability threats (Kaplan et al., 2016; Van Bavel & Pereira, 2018). These institutions can "structure our worlds and actions so that most of our sensory predictions come true" (Clark, 2013, p. 60). From this perspective, attention and exchanges with the external world are goal-oriented, affect-laden methods for reducing prediction error. Institutions, as "socio-cultural scaffolding," may streamline efforts to align prediction errors with expectations, but they can also produce designs more resistant to change (Clark, 2013).

18 The empirical question which follows is what characteristics of institutional design allow for better understanding and prediction of system states, improving the odds of system robustness over some planning horizon? We next discuss an empirical strategy for identifying our candidate institutional characteristics: voids and dependencies.

Empirical Approach

19 We selected the case of Phoenix, Arizona's water utility, to empirically assess our hypotheses based on previous work that identified distinctions within institutional statements pertaining to investment determinations which drive the rate-making process (Deslatte et al., 2021). Phoenix is located within the hottest desert region in North America, with a growing metropolitan population that surpassed five million people in 2020. The city's Water Services Department (WSD) is the largest water utility in the region, serving 1.7 million customers. The utility draws water from four primary sources: the Salt and Verde River watersheds through canals managed by the Salt River Project (SRP); the Colorado River, through the Central Arizona Project (CAP); groundwater wells; and reclaimed water devoted mostly to industrial uses. These supplies have been developed through a complex process of interstate and federal water rights negotiations and contracts, which divide Colorado River water between seven basin states and allocate portions of SRP supplies to specific "on-project lands." The "off-project" service areas in northern Phoenix primarily receive water from a combination of CAP and groundwater sources. As of 2022, the Colorado River Basin had experienced its driest 22-year period in over a century[1]. Through both rate increases and conservation measures, the utility has engaged in multiple policy efforts to adapt to the drought and maintain system robustness. As noted, our empirical strategy consists of three steps described in more detail below.

Step 1: Institutional Grammar Coding

20 Originally designed to facilitate game theoretic modeling, the IGT decomposes institutional statements into syntactic components that distinguish the actors, actions, objects of action and potential inducements for action (Siddiki et al., 2019; Crawford & Ostrom, 1995). It has since been expanded as researchers adopt new mixed-methods (Deslatte et al., 2021), network theory (Mesdaghi et al., 2022), and computational modeling applications (Frantz & Siddiki, 2022). This study uses an extended version of the IGT (Frantz & Siddiki, 2022), with the following components:

- **Attributes [A]:** an individual or organizational actor (e.g., utility director, city council, commission) expected to carry out/not carry out the action (Aim) of a statement.
- **Direct and Indirect Objects [DO/IO]:** the animate or inanimate object that receives the action (Aim). The expanded IGT distinguishes between 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).
- **Deontics [D]:** a prescriptive or permissive operator that denotes the extent to which an action is compelled, restrained, or discretionary. A deontic specifies whether an attribute "may", "must", or "must not" take action.
- **Aims [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. The updated IGT delineates between Activation Conditions, which specify a preceding condition that must be present for statement to be operative, and an Execution Constraint, which sets temporal or spatial limitations on an action (i.e., "annually"). In the absence of any context components, a statement is presumed to be operative under all conditions and with no constraints.

- **Or Else [OR]:** an optional sanctioning component which applies to the aim of the institutional statement. Often, statements embedded in legal or regulatory documents may be associated with implicit sanctions.

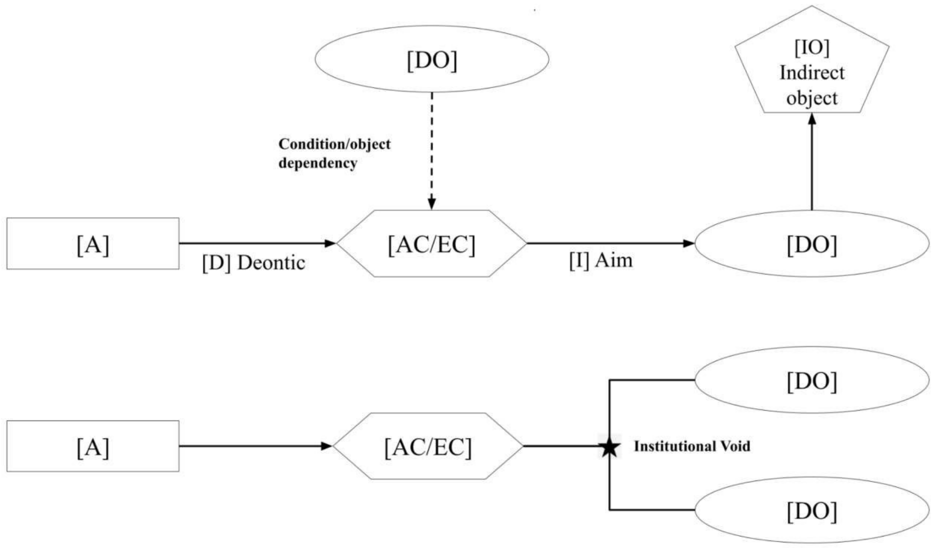
21 Statements pertaining to Phoenix's water utility were identified in city charters and ordinances, state statutes, and administrative codes, which were searched using "water" and "water utility" search terms. Relevant statements were sampled for coding based on inclusion and exclusion criteria developed by the research team. Inclusion criteria included whether the statements pertained to the following: the administrative or governance structure of the CIS, water planning processes, supply/demand management authority, user rights and restrictions, or infrastructure investment and maintenance. Exclusion criteria included statements deemed to be routine operational activities, such as zoning regulations for water-related infrastructure, utility requirements for street work, meter inspection procedures, and rules for water main construction/repair.

22 The exercise produced a corpus of statements (N=297), which were coded by two coders (inter-coder reliability > .8) and from which a subset of statements pertaining specifically to water utility ratemaking and investment determination were identified.

Step 2: Institutional Network Diagram

23 We then follow the guidance of Mesdaghi and colleagues (2022) to identify institutional dependencies and voids by constructing network diagrams from the coded institutional statements. The network diagrams depict an action situation (McGinnis, 2011b), composed of venues where specific actors are empowered or constrained from taking actions. The IGT components are reflected as either nodes or edges, with Attributes, Context conditions, and Direct/Indirect Objects depicted as nodes, while Deontics and Aims are shown as edges or links between nodes (Mesdaghi et al., 2022). Individual institutional statements are linked, demonstrating *dependencies* (dotted lines), when the objects of one statement are connected to the conditions of another. Institutional *voids* are depicted by a "star" when two statements are identical except for their objects or their aims. In this sense, the statements may present ambiguity about decision-making criteria or create the potential for conflicting decisions (Biesbroek et al., 2009; Hajer, 2003; Vilcan & Potter, 2020). This exercise visually illustrates the pathways through which information flows in specific action situations within the PIP-PI controller. Figure 2 depicts hypothetical institutional dependencies and voids (for a more complete description of the institutional network analysis approach, see Mesdaghi et al., 2022). In these situations, we expect to find that the interaction of voids and dependencies can influence measurement error detection and belief-updating regarding system robustness.

24 **Figure 2**. Institutional dependences result when two of more statements share connections between objects and conditions.



Voids may be points of concern when they reflect the potential for conflicts or ambiguity in sequences of actions.
Source: The authors

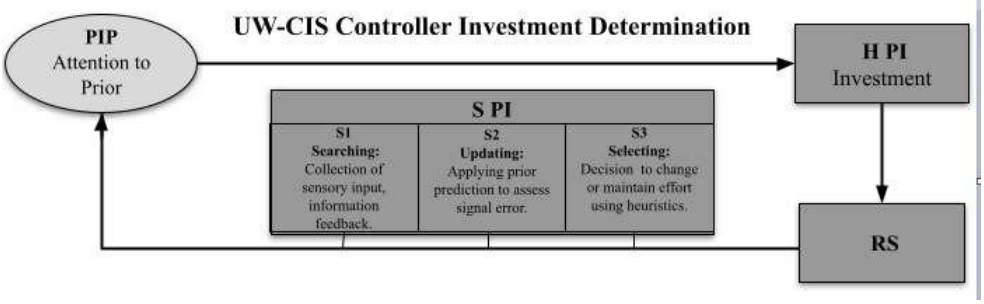
Step. 3: IGT-Informed Process-Tracing

25 Guided by these diagrams, the subsequent analysis then follows a Bayesian-inspired evidence-evaluation approach for process-tracing (Beach & Pedersen, 2019). As depicted in more detail in Table 1 and Figure 3, this process-tracing approach calls for identifying the discrete activities within a single case which must occur via a "causal process" to produce the observed, deterministic outcome (i.e., posterior estimate of investment need). Mapping this causal sequence involves conceptualizing "steps," or actions that are theorized to lead to the updated assessment of investment needs, and then examining empirical evidence for each of these steps. In our case, our understanding of the steps has been empirically informed through prior work as well as the IGT and IN graphs. They include: *searching*, which involves the collection and reporting of data, resulting in signals of system performance; *updating*, which is interpreting incongruous measurement information through prior beliefs or expectations (Bayes et al., 2020; Siciliano et al., 2017); and *selecting*, which is the act of using heuristic decision rules to reduce the internal cognitive costs of decision-making.

26 Process-tracing facilitates identifying the actors (attributes) linked to each activity (aim), what the "empirical fingerprints"' would look like if these activities occurred, the evidence type available, the theoretical certainty such evidence provides (high certainty means it must exist), and its uniqueness (low uniqueness means it might support an alternative explanation). Thus, the analyst must evaluate the strength of evidence that each deduced action occurred and is related to the outcome, as well as attempt to inductively identify any theoretical gaps in the causal process. We gathered empirical material for process tracing from public hearings and interviews (account evidence), rate-filing proceedings (sequence evidence), planning documents and analyses of water demand trends (pattern evidence), and media accounts (trace evidence) stemming from recent utility rate-making processes. Interviews with water managers were conducted between October 2021 and March 2022. Interviewees were

asked about the water management challenges the city has faced, strategies pursued in response to challenges, how the utility makes and communicates management decisions, and the sustainability of the city's water management approach. All interviews were transcribed and qualitatively coded for key themes related to the research questions, interview questions, and extant literature.

Figure 3. UW-CIS Controller Investment Determination.



The informal PIP-PI controller process where posterior investment need determination occurs via steps of searching new sensory inputs, updating predictions and selecting strategies.

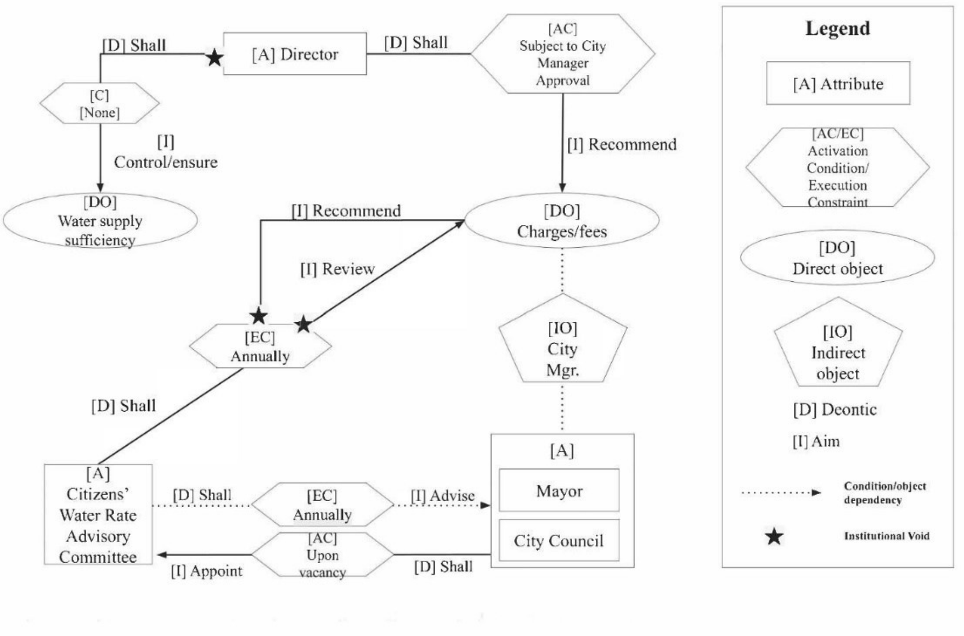
Source: The authors

Results

Institutional Dependencies and Voids

27 Using the IG syntax in figure 4 to map the institutions governing investment decisions in Phoenix, we observe both institutional voids (stars) and dependencies (dotted lines) which involve the interactions between the utility director, the city manager's office, the Phoenix City Council (which maintains final rate-making authority as the PIP), and a Citizens' Water/Wastewater Rate Advisory Committee appointed by the council. The institutional void in the top left corner illustrates that the Director [A] holds responsibility to control/ensure [I] water supply sufficiency [DO]. This authority is characterized as a void because there is no formal institutional guidance – such as exists for U.S. federal mandates for multi-hazard mitigation planning – which may prescribe or prohibit specific considerations or evaluative criteria for supply "sufficiency." In other words, there are no state or federal regulatory directives, and the formal rules embedded in city code are silent as to how the director or her agents determine "supply sufficiency" in the face of increased climatic variability and risk. The absence of such formal rules or norms may be a hindrance to developing adaptation strategies (Mesdaghi et al., 2022), or it could present "spaces of opportunity" whereby creative-thinking or experimentation can occur without formal hindrances (Biesbroek et al., 2009). As we elaborate on below, we find the latter to be the case; managers repeatedly relayed in interviews that their positions in the process – as well as a long experience with drought and desert life – afforded them flexibility to innovate in the face of novel, dynamic threats.

Figure 4. Institutional Diagram of City of Phoenix UW-CIS Investment Determination.



Source: The authors

28 A second institutional void (diagonal from bottom left corner) involves the role of the Citizens' Water Rate Advisory Committee [A] which shall [D] annually [EC] both review [I] and recommend [I] adjustments to the rate-structure/charges/fees [DO]. Such actions then flow through the City Manager's office [IO], then to the City Council [A] for final dispensation. The members of the committee are nominated [I] by the Mayor [A] and confirmed [I] by the City Council [A]. The Committee [A] also has a direct interaction with the Council through the directive that it shall [D] annually [EC] advise [I] the council on rate-related water issues, and ostensibly acts as a mechanism for citizens (Resource Users) to exercise voice in council water decisions. This combination of position, choice and information rules functionally maps out a choice aggregation process. As with the WSD Director's required task to ensure water supply sufficiency, there is no formally articulated evaluative criteria, planning tool or performance outcome for the Committee to use in order to guide its review process or recommendations. In actuality, this void allowed actors to coalesce around an "affordability" evaluative criterion for water-rate hikes, while, unsurprisingly, political considerations also factor into such decisions. As one interviewee noted, elected council members generally "don't want to raise rates. They don't want it on their voting record."

29 An institutional dependency within this arrangement (top right corner) results from the requirement that the Director [A] also shall [D] recommend [I] charges/fee adjustments [DO] subject to City Manager approval [AC]; thus, the activation condition for the Director's review is connected to the same object (rate recommendations) the Committee must also review and act upon. The Committee, which is compelled to annual action, is thus dependent upon the actions of the Director, while the Director's recommendation requires the condition of City Manager approval to activate. In routine matters, such dependencies may not significantly increase decision costs, as actions are coordinated on a regular (annual) cycle using somewhat static information.

However, the institutions present were not designed to address dynamic climate stressors. There are no formal incentives or coercive mechanisms for developing or prioritizing long-term climate risk assessments or vulnerability studies or adaptive practices, nor for investment determinations to be proactively based on such evaluations. Interviewees indicated that such formal, regulatory guidance was not feasible given the complexity surrounding climate change.

30 In the absence of formal institutions that prescribe planning or management tools specific to climate adaptation, it is possible that actors involved in evaluating ambiguous signal errors will come to divergent conclusions and produce conflicting recommendations. Alternatively, we have hypothesized that, relative to climate change, the dependencies create an incentive for consensus to emerge between the Committee, the Director and the City Manager as they work to forward a recommendation to the Council. This institutional design which engaged the city manager's office in the policy process was credited for allowing broader considerations into water management activities. Our process tracing sheds light on this view.

Process-Tracing for CIS Investment Determination

31 We find within-case evidence to support our primary hypothesis (1c), which implies that voids and dependencies should allow actors to increase response diversity and frequency, as they iteratively adjust to signal error over time. From 2015-2018, the City Council approved a series of water-rate increases to address both the drought and aging infrastructure[2]. In 2021, the City approved another 6.5% water rate-increase staggered over two years, which was expected to raise $1.7 billion to make more infrastructure upgrades and prepare for CAP shortages. The infrastructure upgrades planned or underway included constructing a "drought pipeline" to move water from central Phoenix to off-project areas; installing new production and aquifer storage and recovery wells; increasing access to banked water; and additional efforts to minimize water loss through pipe leaks and breaks. Each of these rate adjustments occurred as a result of an observed process of information search, updating of expectations about the system state, and heuristic shortcuts or framing used by various actors for collectively selecting a response. We use primary and secondary data to trace these decision-making processes. Table 1 displays our theorized steps (searching, updating, selecting), the corresponding data and theoretical expectations.

Table 1. Process-Trace of Phoenix CIS Posterior Investment Determination

IG-Extended Statement (Action Situation)	Citizens Water Rate Advisory Committee Shall Annually Review/Recommend Charges/Fees through the City Manager to the City Council		
	Searching	**Updating**	**Selecting**
Entities (Attributes, Objects)	Water suppliers, experts, WSD	Managers, Committee(s), City Council	Committee(s), Managers, City Council

Activities (Deontics, aims, Conditions)	Hydrologic measurement; user data compilation, analysis.	Meetings, discussion; airing of assumptions.	Method for choosing investment strategy from alternatives.
Empirical fingerprint	Water supply/ demand forecasts, financial plans, scenarios.	Accuracy-based reasoning or deliberation; re-evaluation of goals and previous actions or outcomes.	Heuristic-based emphasis frames/messaging; (de)weighting specific characteristics of choice situations.
Evidence Type	Account, Pattern	Account, Pattern, Sequence	Account, Pattern, Trace
Theoretical Certainty	High	High	High
Uniqueness	Low	Low	High

32 Source : The authors

Searching

33 Interviewees described a relatively continuous process of information search, in which utility managers tasked with maintaining supply sufficiency would seek to monitor signals of current and future performance. Pattern evidence from planning documents details the water supply/demand data, historical patterns or variability, and future scenarios or forecasts which managers monitor. The WSD is required to maintain short-run supply and demand data that feed into the city's five-year financial and capital improvement planning, which has historically formed the basis for rate increases. WSD widened its range of data sources after its 2015 rate hikes due to climate-related ambiguity, informing rate-changes observed in 2018 and 2021. For example, more recent long-range scenario planning integrated research and forecasts from, among other sources, the U.S. Bureau of Reclamation, the University of Arizona, and the SRP, in order to prepare four supply-and-demand scenarios through 2070 that account for climate change. As one interviewee noted:

> "One of the challenges I will say over the past five or six years has been … trying to get reliable sources of information on water supplies projections. But I think that's been something that everyone has had a problem with. When you're relying upon surface water supply, specifically, the impacts of climate change have been significant. And they haven't always been easy to project. … I'm not even sure I would say that today we have a very reliable way of projecting impacts to supplies. Obviously, we don't, because if we did, we would have already fixed the problem that we are under." [PH02 Interview].

34 In recent years, the WSD has also turned to hiring external consultants and drawing on data from wholesalers. While supplies from the SRP are expected to be resilient to climate impacts throughout the city's 2070 planning horizon, the WSD's 2021 Water Resources Plan (WRP) notes that Colorado River supplies are far more difficult to forecast and will likely continue to be negatively impacted by climate change. The WRP supply scenarios incorporate roughly 110 years of measured and modeled flow data

records and historical modeled flow based on tree ring records for some 900 years. Demand scenarios based on population changes were developed by the State of Arizona and Maricopa (County) Association of Governments. While relying largely on external modeling, "[WSD] developed our own projections of what was happening on the Colorado River, as well," [PH05 Interview].

35 As a result, the CAP-reliant off-project service areas are expected to witness "significant supply deficits" under future scenarios of long-term dry conditions and reduced snowpack runoff caused by climate change (Elizabeth Koebele2023-06-19T09:34:00EKAILANE Sofiane2023-06-08T14:55:00ASWRP, 2021, p. 92).
Given the increased risk of diminished CAP supplies and increased reliance of surrounding, developing suburbs on groundwater supplies, the Phoenix WSD noted the need to implement ongoing deficit mitigation strategies in coming years, including infrastructure system improvements and regional collaboration, increased demand management, and water supply augmentation (WRP, 2021, p. 96).

36 Despite the challenges, interviewees noted that the utility's history with dealing with drought and the increasing situational awareness of climate impacts has had a positive influence on its capacity to respond:

> "We know with respect to climate change, this is not something that, short-term, is going to go away. This is something that we're going to live with, you know, for decades to come. And it's allowed us to be flexible, and to adapt to the changes that have happened to us." [PH03 Interview].

37 While voids may facilitate greater decision diversity (H1a), signal error can also prompt actors to introduce disinformation or to rationalize away disconfirming information. We next turn to how dependencies influenced updates of prior beliefs about system performance.

Updating

38 Evidence suggests that our identified decision-making dependency aided in updating expectations through broadening deliberations of policy impacts. Updating involves squaring prior expectations about the adequacy of the system and rate structure with new disconfirming information. Because institutional dependencies are thought to increase external search costs along with decision frequency (H1b), such designs in highly ambiguous problem contexts can produce "biased competition" between alternatives and allow individuals to explain away error signals without making adjustments.

39 In our case, the WSD director's rate recommendations were developed alongside the work of the Citizens Water Rate Advisory Committee and elevated through the City Manager's Office, which interviewees indicated placed greater attention to finding broadly agreeable solutions:

> "We need to know that the really large, you know, the policy impacts of the decisions that are being made, are understood at the city manager level, because they're more existential to the whole city, and not just the utility operations." [PH03 Interview].

40 Thus, the empirical fingerprint of this step is some accuracy-based reasoning or deliberation in choice contexts which would indicate updating of priors. This occurred throughout a series of hearings from 2018-2021, in which WSD managers sought to

build support for additional water rate-increases for new drought-related infrastructure. Their primary argument was two-fold: the ongoing drought in the Colorado River basin was likely to worsen; and Phoenix's century-old network of 1,700 miles of water pipelines was in need of repair. One response from policymakers – indicative of disconfirming information – was to question why previous rate-hikes and investment increases approved in 2015 were now insufficient:

> "We've had presentations before where it was indicated Phoenix was in pretty good shape," Councilmember Jim Waring said in one 2018 hearing. "So now it sounds like maybe not quite as good of shape as before for sure. And that is the result of a dramatically worsening situation that is, frankly, beyond our control … that we couldn't have anticipated."

41 To reduce decision-making ambiguity, WSD staff relied on hydrology scenarios from scientists and predictions from federal agencies such as the U.S. Bureau of Reclamation, which had forecast a 14% chance that historic "Tier 3" water shortage restrictions could be put in place within five years. Managers emphasized that the worsening conditions were a deviation from historical patterns and were unlikely to be ameliorated any time soon:

> "The scientists are calling for us to stop saying 'normal' or 'average' and to start talking about a river basin that is aridifying," WSD's then-Director Kathryn Sorensen told a city council committee in September 2018. "No one is quite sure what that means at this point, but it's probably not good."

42 The 2018 WSD rate proposal increased the city's five-year capital improvement plan from the $700 million approved just three years earlier to $1.5 billion, $400 million of which would be dedicated to "resiliency" efforts to build new water transmission lines. In testimony to Congress and to Phoenix councilmembers, Sorensen repeatedly noted that the city had been planning for three decades to withstand a Tier 3 shortage declaration, but that "[w]hat I'm worried about is what happens next, and if it continues to get worse," she said. "I'm worried about the Colorado River system crashing. That's what we need to be focused on." Meanwhile, some council members sought assurances through the 2018 rate-hearing process that their current situation was not the result of policies that encouraged population and economic growth:

> "So, the problem isn't 'we're building more houses,'" said one council member. "We can't 'efficient' our way out of this."

43 By fall 2020, the city had developed a new five-year financial plan which would require additional 3.5% rate increases from 2021-2025. These increases would be devoted to replacing aging water infrastructure. Remedying these infrastructure issues was described as a necessary effort to reduce future risks and unpredictability. Moreover, policymakers appeared to emerge from this process with updated expectations about the worsening drought conditions and future uncertainty:

> "I believe we're headed into a worse drought," said Vice Mayor Thelda Williams in a March 2021 committee hearing. "Water is going to be less available, more expensive. So, we don't want to make any errors in how we deliver that water."

44 Thus, the weight of account, sequence and pattern evidence suggests that this interaction of diversity of information flows (via voids) and broadened policy engagement (via dependency) positively influenced accuracy-based updating of beliefs about changing conditions. The final step requires evidence of the decision-rules for selecting a course of action.

Selecting

45 Selection is the culmination of heuristic- based inference strategies in which actors rely on environmental cues to "cognitively shortcut" the decision process and reduce internal search costs (Katsikopoulos et al., 2021). Heuristics are ubiquitous in individual and organizational decision-making, but often require experimental methods to assess with any specificity (Bingham & Eisenhardt 2011; Gigerenzer et al., 2022). In our case, the act of selection was deterministic: collective choices to raise water rates were made repeatedly. We find evidence that managers, water users and policymakers relied on three distinct emphasis frames – the scientific basis of climate change, affordability of rates, and PI system performance respectively – to develop communicative justifications or rationales for these choices (Chong & Druckman, 2007). While many motivations underlie framing, the net effect is to truncate search costs and persuade others by emphasizing some salient variables (cues) about a policy or issue and ignoring others – the presence of multiple frames may suggest each group employed a "take the best" inference strategy by using distinctive rationales to arrive at similar conclusions (Gigerenzer & Brighton 2009). Interview evidence supports this contention:

> “I would say the primary stressor for me from a policy standpoint has been … how you frame it. Is it a long-standing drought? Is it a mega drought? Is it climate change? I tend to think it's the latter. Um, and so trying to deal with what I would now call the ‘full-scale adaptation to climate change’ has been a significant stressor.” [PH02 Interview].

46 Conversely, the WSD and Citizens Water Rate Advisory Committee (CWRAC) reached consensus on recommendations over a year-long series of deliberations that settled upon a framing around affordability. Guided by WSD staff, the committee formed an “affordability” subcommittee and enlisted the help of a prominent water utility researcher from Texas A&M University to develop a definition and metrics for affordability “reasonable for our community,” including converting the basic water and sewer costs in Phoenix to the equivalent hours of earning minimum wage, and an affordability ratio set at the 20th income percentile. Both metrics depicted Phoenix rates as more affordable compared to peer communities. This form of “strategic imitation” is a heuristic that allowed the committee to ultimately conclude the rate proposals still kept the city’s water costs affordable.

47 This affordability framing was central to the WSD’s public outreach efforts around the rate increase proposal in fall 2018. In this sense, the committee functioned as a forum where framing focused on equity considerations was developed. Subsequent WSD public messaging highlighted the relatively low frequency of recent rate increases and how the proposed rates favorably compared to other large U.S. cities. Importantly, the affordability framing introduced new performance information which was considered in the subsequent 2020-21 deliberations.

48 These deliberations also focused on more high-profile pipe breaks and infrastructure problems to emphasize the point that much of the city's century-system would require increased investments to maintain performance. Historically, this has not always been an easy case to make. As one interviewee noted:

> “With one of the biggest distribution systems literally in the country, there's just a constant need to rehabilitate and replace aging infrastructure, but very little political will to increase rates to pay for it. So that was just always a huge challenge.” [PH05 Interview].

49 The 2021 rate proposal featured a more aggressive public awareness campaign and highlighted cases of high-profile pipe ruptures and collapses. The deliberations focused on the age of the existing system and investments in cheaper technologies in the 1980s which had not proven as durable as expected. "What we've seen very recently," one manager explained to the council, "is the failure to invest in infrastructure."

50 The primary institutional dependency identified – the interaction of WSD and the CWRAC – did not appear to substantially slow institutional response and may have facilitated the "piloting" of frames likely to support the frequency of responses. While WSD staff acknowledged and framed the stressors around climate change, the institutional voids pertaining to how both WSD and CWRAC determine supply sufficiency allowed alternative rationalizations and frames to take root. The foreshadowed possibility of a declared Colorado water shortage and the salience of the drought likely aided in their framing effort, though it ultimately focused more on water affordability. Moreover, the voids facilitated internal deliberations about climate-change vulnerability which were subsequently incorporated into the public-facing WRP and Climate Action Plan, both adopted in 2021. As one interviewee noted:

> "We're in charge of trying to make sure that … the lifestyle of the people who live in our community is … equitable, is livable. I think it's really put cities in a position to have to deal with climate change in a way that, unfortunately, has been more adaptation than not." [PH02 Interview].

Discussion and Conclusion

51 In August 2021, the U.S. Bureau of Reclamation declared its first-ever official water shortage on the Colorado River, triggering a reduction in water releases from the Glen Canyon and Hoover Dams in 2022 impacting Arizona water supplies. Also in 2022, the IPCC's Working Group II Sixth Assessment Report noted that scientists had high confidence that climate change had impaired North American freshwater resources and reduced supply security (IPCC, 2022, pg 14-4). This was especially true in the western U.S., where resource exploitation and deteriorating water management infrastructure had "heightened the risks" of supply disruption. While some evidence suggests climate adaptation is occurring at the level of individuals and households, the report's authors concluded that "misinformation and politicization of climate change science" had created polarization in the public and policy domains in the US and hindered urban-scale climate action (IPCC, 2022, p. 14-3).

52 Institutional voids can facilitate such biased responses when they allow for simple heuristics, rhetoric, or misinformation to address uncertainty (Bayes & Druckman, 2021; Garcia et al., 2022). Institutional dependencies can also hinder adaptation when the rules, norms or strategies in place, designed for historical issues or conditions, are ill-suited for emerging threats (Mesdaghi et al., 2022). This study illustrates that the lack of formal institutional guidance can also facilitate the opposite – the incorporation of diverse views and information into repeated interactions – although this outcome is far from guaranteed. During the 2015-2021 rate-making processes, we find evidence that all three process-tracing steps facilitated response diversity. However, the lack of explicit rules for incorporating climate-related information also allowed policymakers, the public, and managers to avoid linking climate science and related guidance to decision-making. This is what Hajer (2003) described as the "double dynamics" of

policymaking within institutional voids. Actors must not only negotiate solutions to pressing problems but also new norms which may be "perceived as socially acceptable and politically feasible" at the time (Biesbroek et al., 2009).

53 Institutions can provide the incentives and sanctions to drive successful climate responses (Ostrom, 2009). They can also slow or stymie climate action when they facilitate error accumulation. In the absence of institutions providing explicit guidance for climate adaptation, individuals will fill the void with something. We developed a Bayesian-inspired application of the CIS framework to identify both dependencies and voids across institutions which, in the case of Phoenix urban water management, were not designed to grapple with long-range climate risks. Process-tracing illustrated how, within a PIP-PI controller, specific actors holding institutionally defined positions worked across both dependencies and voids to assess and augment information on a climate-related threat, update prior predictions, and frame a rationale for a posterior CIS investment determination.

54 In the Phoenix 2021 Water Resources Plan and Climate Action Plan, we see some evidence of water managers attempting to fill these voids with new water forecasts (measurement), updating, and framing that more explicitly links drought conditions to climate change. Garcia et al. (2022) have suggested such planning should be considered a part of the "soft" PI within the CIS Framework, in that they provide rational analysis and science-backed predictions, as well as the potential for more appropriate, Bayesian-like quantifying of uncertainty. However, recent research on the quality of such urban-scale resilience and adaptation planning has found substantial variance and shortcomings (Woodruff et al., 2018). Moreover, such planning in the U.S. is not legally binding.

55 Our study has several limitations. Process-tracing based on a single case has obvious external validity weaknesses and requires, at a minimum, extending this methodology to additional cases to continue the development of a behavioral theory of collective action. We also draw within-case conclusions based on a study period in which a historic drought has heightened attention to climate change. Would a similar diversity and frequency of response be present in a counterfactual scenario where the institutional design was the same but attention to climate was lower? Institutional analysts have been justifiably skeptical of "panacea" solutions to complex problems (Ostrom et al., 2007). However, the data revolution and our advancing understanding of human cognitive infrastructure suggest institutional guidance is necessary to navigate modern information environments (Anastasopoulos & Whitford, 2018; Lavertu, 2016; Gill, 2021). Stronger climate-relevant evaluative criteria for making determinations about the adequacy of supply in or robustness of a water system warrants greater attention. In the absence of such criteria, the mounting behavioral evidence suggests voids will most often be filled by directional, short-term goals which discount global long-range challenges.

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NOTES

1. https://www.doi.gov/ocl/colorado-river-drought-conditions
2. https://kjzz.org/content/746603/phoenix-approves-12-percent-water-rate-hike

ABSTRACTS

Urban water systems across the United States are facing a variety of challenges to existing supply and demand dynamics. Responding to these challenges in complex socio-environmental systems (SES) requires integrating various types of information – ranging from hydrologic data to political considerations and beyond – into policy and management decisions. However, the design of institutions, i.e., the formal rules in which urban water utilities are embedded, impact the flow of information, especially across diverse actor groups critical to developing and implementing policy or programmatic responses to signal error. This study develops a Bayesian application of the Robustness of Coupled Infrastructure Systems (CIS) Framework to analyze how the institutional design of a major U.S. urban water system impacts information flow and, ultimately, the goal of resource-delivery robustness. We utilize process-tracing along with an institutional analysis approach called the Institutional Grammar Tool (IGT) to parse formal institutions into their semantic and syntactic components and assess how they may influence a system's capacity to respond to changing stressors. Our findings have important implications for the (re)design of institutions that better facilitate information flow among key policy actors and support policy changes that promote sustainable long-term urban water supply.

INDEX

Keywords: coupled infrastructure systems, urban water management, resilience, robustness, sustainability

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