Institutional Dynamics Impact the Response of Urban Socio-Hydrologic Systems to Supply Challenges

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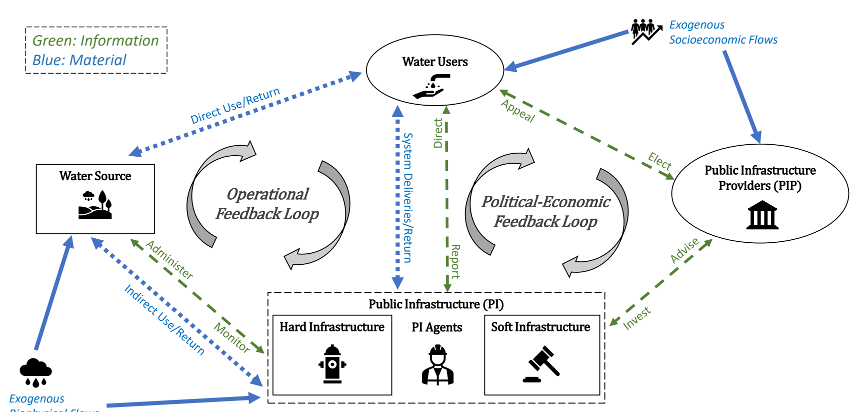
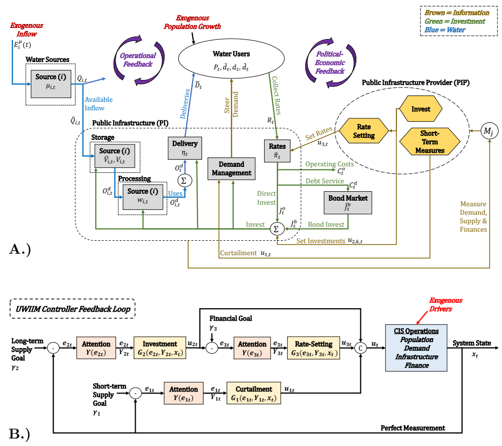
Abstract

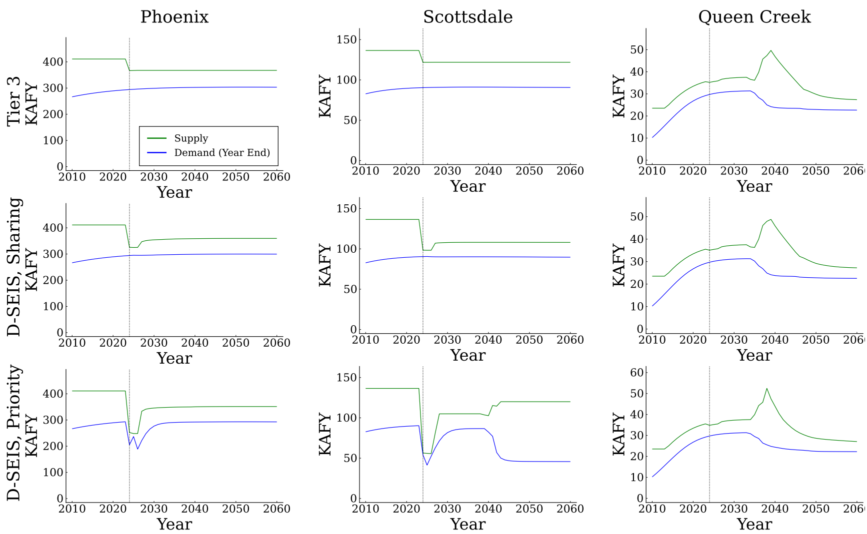
Designing urban water systems to respond to the accelerating and unpredictable changes of the Anthropocene will require changes not only to built infrastructure and operating rules, but also to the governance arrangements responsible for investing in them. Yet, inclusion of this political-economic feedback in dynamic models of infrastructure systems and socio-hydrology has significantly lagged behind operational feedback concerns. We address this gap through a dynamical systems application of the Coupled Infrastructure Systems (CIS) Framework, which provides the conceptual building blocks for analyzing social-ecological systems through various classes of infrastructure and the flows of material and information among them. In the model, political-economic feedback involves three decisions - infrastructure investment, rate-setting, and short-term demand curtailment - and each decision is constrained by institutional friction, the aggregation of decision and transaction costs associated with taking action. We apply the model to three cities in the Phoenix Metropolitan Area to compare how institutional friction interacts with a city's water resource portfolio and financial position to determine its sensitivity to reductions in Colorado River water availability. We find that the slowing effect of institutional friction on investment and rate-setting decisions can increase the sensitivity of a city's supply, but it can also promote objectives that compete with over-response (e.g., rate burden). The effect is dependent on the initial operating capacity of the CIS and flexibility within the institutions, highlighting the need to consider political-economic and operational feedback together when evaluating infrastructure systems.

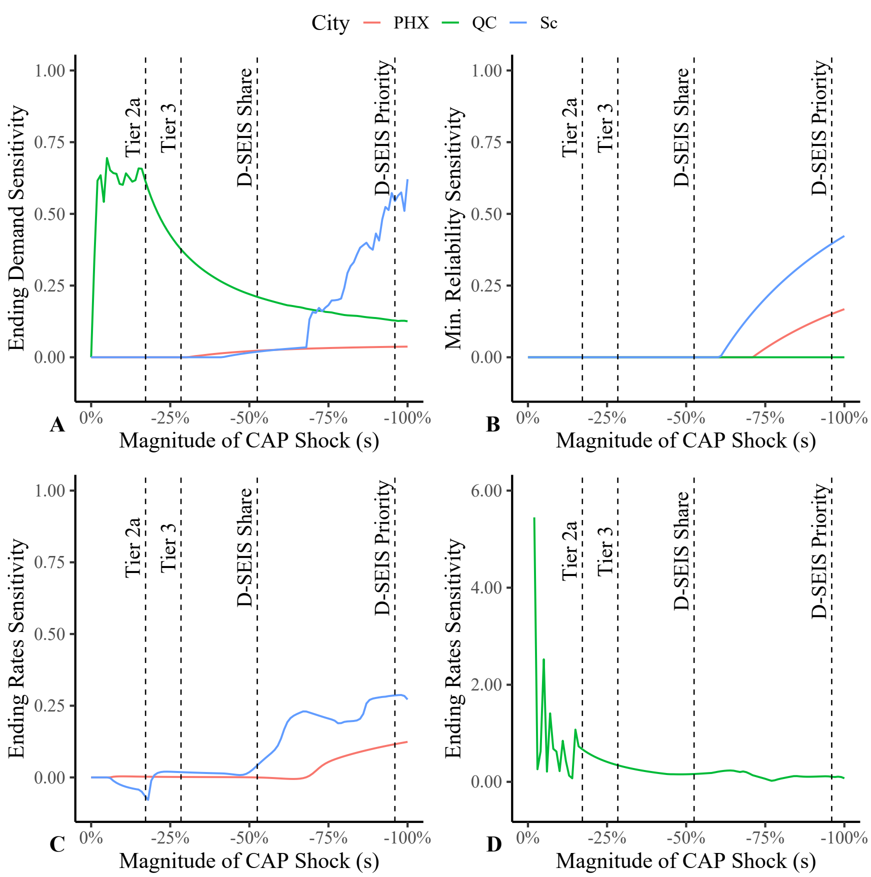


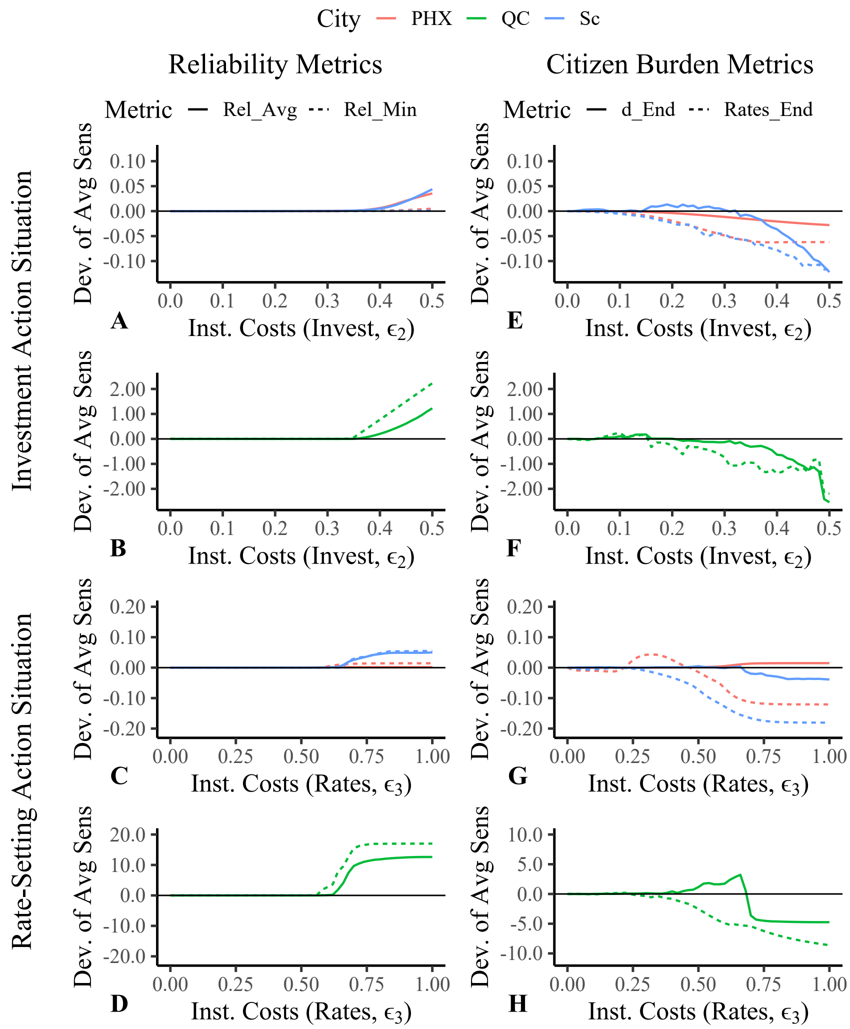


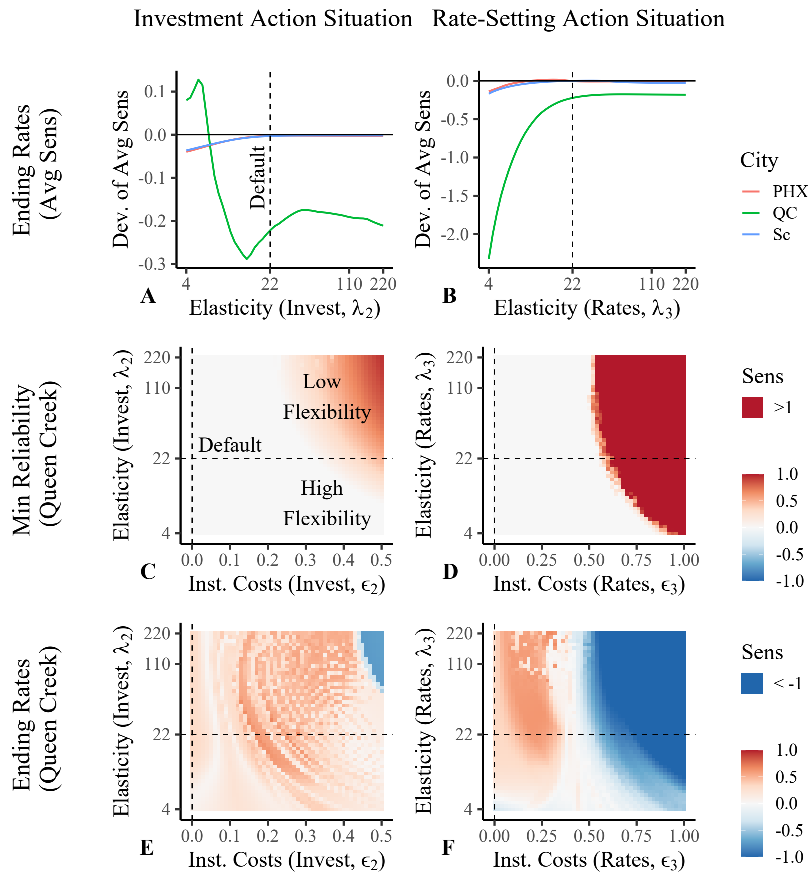
Brown = Information
Green = Investment
Blue = Water
Exogenous Inflow
Water Sources
Source (i)
Available Inflow
Operational Feedback
Exogenous Population Growth
Water Users
Political-Economic Feedback
Public Infrastructure Provider (PIP)
Public Infrastructure (PI)
Storage
Processing
Delivery
Deliveries
Steer Demand
Collect Rates
Demand Management
Rates
Set Rates
Rate Setting
Invest
Short-Term Measures
Operating Costs
Debt Service
Bond Market
Direct Invest
Uses
Bond Invest
Set Investments
Curtailment
Measure Demand, Supply & Finances
A.)
UWIIM Controller Feedback Loop
Long-term Supply Goal
Attention
Investment
Financial Goal
Rate-Setting
Exogenous Drivers
CIS Operations
Population
Demand
Infrastructure
Finance
System State
Short-term Supply Goal
Curtailment
Perfect Measurement
B.)

1

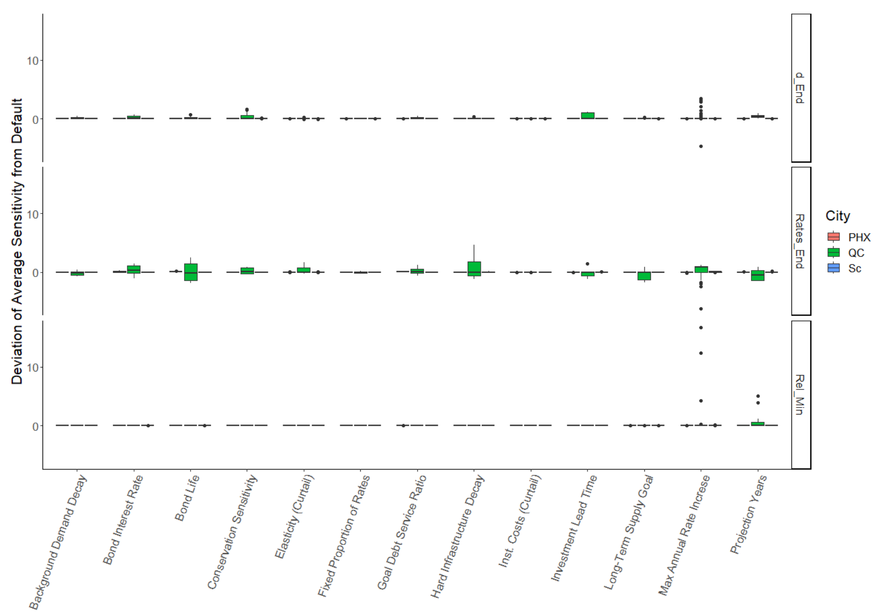

Phoenix
Scottsdale
Queen Creek
Tier 3
D-SEIS, Sharing
D-SEIS, Priority
KAFY
Year
Supply
Demand (Year End)


City
PHX
QC
Sc
Tier 2a
Tier 3
D-SEIS Share
D-SEIS Priority
Ending Demand Sensitivity
Min. Reliability Sensitivity
Ending Rates Sensitivity
Magnitude of CAP Shock (s)
A
B
C
D

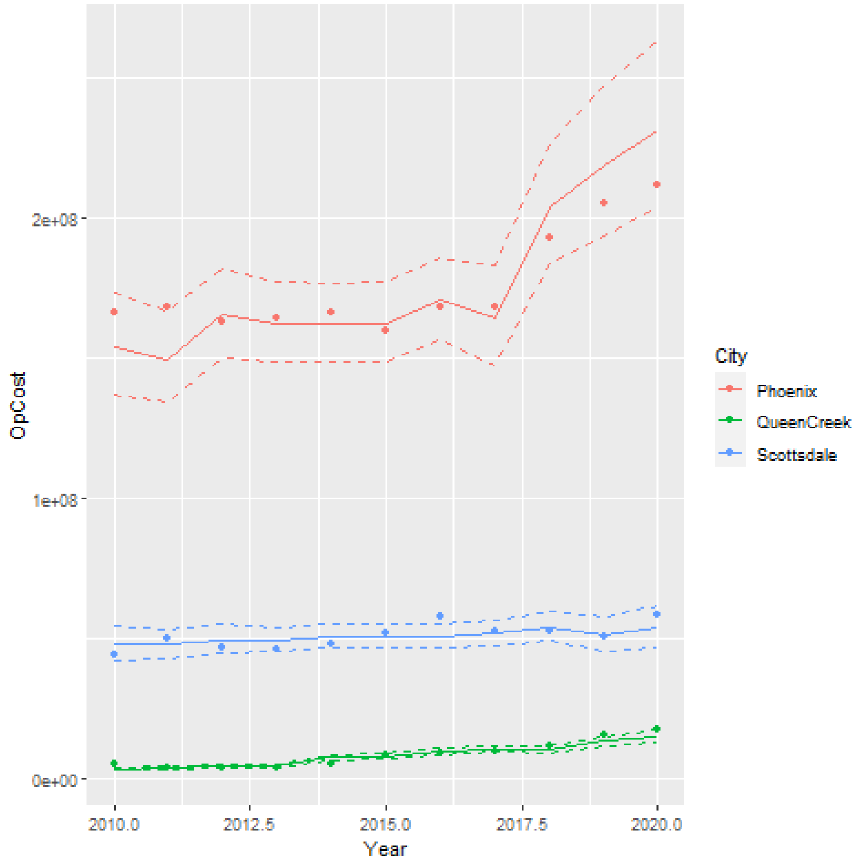

City PHX QC Sc
Reliability Metrics
Citizen Burden Metrics
Metric Rel_Avg Rel_Min
Metric d_End Rates_End
Investment Action Situation
Rate-Setting Action Situation
Dev. of Avg Sens
Inst. Costs (Invest, ϵ2)
Inst. Costs (Rates, ϵ3)
A
B
C
D
E
F
G
H

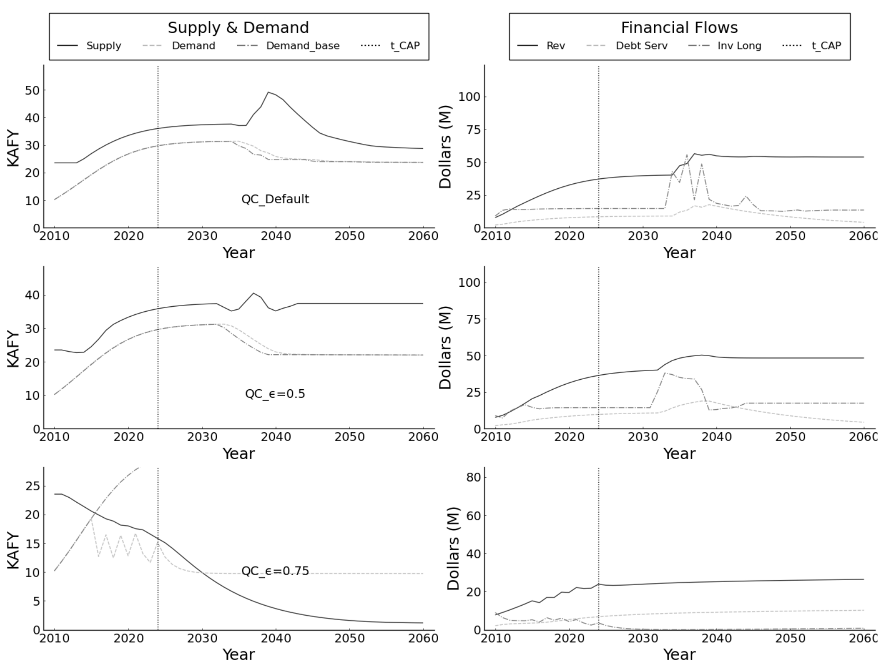


Investment Action Situation
Rate-Setting Action Situation
Ending Rates (Avg Sens)
Min Reliability (Queen Creek)
Ending Rates (Queen Creek)
Dev. of Avg Sens
Default
Elasticity (Invest, λ_2)
Elasticity (Rates, λ_3)
Inst. Costs (Invest, ϵ_2)
Inst. Costs (Rates, ϵ_3)
Low Flexibility
High Flexibility
City
PHX
QC
Sc
Sens
>1
< -1
A
B
C
D
E
F



Deviation of Average Sensitivity from Default
d_End
Rates_End
Rel_Min
City
PHX
QC
Sc
Background Demand Decay
Bond Interest Rate
Bond Life
Conservation Sensitivity
Elasticity (Curtail)
Fixed Proportion of Rates
Goal Debt Service Ratio
Hard Infrastructure Decay
Inst. Costs (Curtail)
Investment Lead Time
Long-Term Supply Goal
Max Annual Rate Increse
Projection Years


OpCost
2e+08
1e+08
0e+00
2010.0
2012.5
2015.0
2017.5
2020.0
Year
City
Phoenix
QueenCreek
Scottsdale


Supply & Demand
Supply
Demand
Demand_base
t_CAP
Financial Flows
Rev
Debt Serv
Inv Long
t_CAP
KAFY
Dollars (M)
Year
QC_Default
QC_ϵ=0.5
QC_ϵ=0.75

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Key Points:

- Having sufficient supply redundancy can outweigh the negative effect of slow institutions on a city's ability to address supply shocks.
- The supplies of cities with institutions that require more stress to act are more sensitive to shocks, but their rates are less sensitive.
- Adding flexibility to institutions can ease the burden of large investments on ratepayers and improve the reliability of slow institutions.

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Abstract

Designing urban water systems to respond to the accelerating and unpredictable changes of the Anthropocene will require changes not only to built infrastructure and operating rules, but also to the governance arrangements responsible for investing in them. Yet, inclusion of this *political-economic feedback* in dynamic models of infrastructure systems and socio-hydrology has significantly lagged behind *operational* feedback concerns. We address this gap through a dynamical systems application of the Coupled Infrastructure Systems (CIS) Framework, which provides the conceptual building blocks for analyzing social-ecological systems through various classes of infrastructure and the flows of material and information among them. In the model, political-economic feedback involves three decisions - infrastructure investment, rate-setting, and short-term demand curtailment - and each decision is constrained by institutional friction, the aggregation of decision and transaction costs associated with taking action. We apply the model to three cities in the Phoenix Metropolitan Area to compare how institutional friction interacts with a city's water resource portfolio and financial position to determine its sensitivity to reductions in Colorado River water availability. We find that the slowing effect of institutional friction on investment and rate-setting decisions can increase the sensitivity of a city's supply, but it can also promote objectives that compete with over-response (e.g., rate burden). The effect is dependent on the initial operating capacity of the CIS and flexibility within the institutions, highlighting the need to consider political-economic and operational feedback together when evaluating infrastructure systems.

Plain Language Summary

Urban water systems must grapple with accelerating social and environmental change that requires them to not only consider future infrastructure needs, but also, the configuration of decisions responsible for infrastructure investment. Unfortunately, inclusion of *political-economic feedback* has lagged behind *operational* feedback in models that examine water systems response to changing environments. We present a modeling approach to trace the flow of water, information, and investment in a general urban water system that must make three annual decisions: infrastructure investment, rate-setting, and short-term demand curtailment. Each decision is influenced by costs to taking action and the flexibility involved in setting action magnitudes. We apply the model to three cities in the Phoenix Metropolitan Area to compare how these institutional constraints interact with existing infrastructure and finances to affect their sensitivity to reductions in Colorado River water. We find that when institutional barriers to action increase, cities are more sensitive to supply shocks, but such barriers can benefit other objectives like rate burden. The effect is dependent on the presence of redundant supplies, demand growth, and decision-making flexibility, highlighting the need to consider both political-economic and operational concerns when evaluating water systems.

1 Introduction

Urban water systems seek to provide a stable supply of water at low costs to their users. Like most infrastructure systems, to achieve these goals, they must address variation of multiple environmental (e.g., streamflow change) and socioeconomic (e.g., population growth) drivers (Chester et al., 2020; Treuer et al., 2017). Many cities have coped with these variations through a combination of built infrastructure and soft infrastructure, i.e., institutions (Padowski et al., 2016; Hoffmann et al., 2020), but growing urban populations and climate change threaten their ability to continue meeting demand (Gleick, 2018; Larsen et al., 2016; McDonald et al., 2014).

Yet, transitioning urban water systems is difficult. Many systems were designed during a century of relative stability (Chester et al., 2019) and empirical studies confirm that the actors governing urban water systems are hesitant to change given significant social and climatic stressors (Hornberger et al., 2015; R. Brown et al., 2011; Hughes & Mullin, 2018). For decades, experts have offered alternative investment pathways, including moving from "supply-focused," hard infrastructure towards "soft paths" (e.g., Hering et al., 2013; Christian-Smith et al., 2012; Gleick, 2002; Hornberger et al., 2015), but without well-developed understanding of the political-economic system responsible for bringing about desired changes, water management transition can resemble a Sisyphean task (van de Meene & Brown, 2009; Pahl-Wostl et al., 2010; Brelsford et al., 2020; Winz et al., 2009).

Working towards this broader perspective, socio-hydrology has elevated the "two-way feedback" between social and hydrological systems (Di Baldassarre et al., 2013; Sivapalan et al., 2012), but due to its epistemological grounding in natural science, it has struggled to fully capture the layers of feedback *within* human systems (Xu et al., 2018; Lu et al., 2018; Blair & Buytaert, 2016). In this paper, we contribute an additional distinction in human water-systems by introducing both operational and political-economic feedback. Using the Coupled Infrastructure Systems (CIS) Framework (Anderies et al., 2016), we conceptualize urban water systems as arrangements of multiple infrastructures (hard and soft) that process flows of water and information. All CISs, must deal with variation in key inflows through the interaction between infrastructures and human agents, creating multiple forms of feedback control to govern the system (Rodriguez et al., 2011; Anderies, 2015a). We group these feedback processes into *operational feedback*, which concerns the behavior of humans and infrastructures within a specific infrastructure system (e.g., operating a reservoir, implementing use restrictions, etc.), and *political-economic feedback*, which concerns the investment in or alteration of the infrastructure system.

Analyzing the two forms of feedback provides deeper insight into the *robustness* of urban water systems. By robustness, we refer to the preservation of a system's desired performance to a specific input disturbance (the opposite of sensitivity) (Anderies et al., 2013). Robust control is a common design approach in water systems engineering (e.g., Herman et al., 2015; Kasprzyk et al., 2013; Herman et al., 2020; Trindade et al., 2020), but a gap remains regarding the inclusion of political-economic feedback processes. While Herman et al. (2020) recognize a considerable degree of "endogenous uncertainty" associated with human-environmental system response that can significantly alter the findings of dynamic models, they situate this uncertainty in the way the human-environmental system responds to a selected policy or disturbance (operational feedback), not the policy selection process itself (political-economic feedback).

Current approaches treat outputs from political-economic processes as (i) parameters to be sampled (e.g., Krueger et al., 2019; Gober et al., 2010; Rehan et al., 2015; Koutiva & Makropoulos, 2016), (ii) solutions to be optimized (e.g., Kasprzyk et al., 2013; Cohen & Herman, 2021; Trindade et al., 2020), or when they are endogenous, (iii) outputs of strict decision rules that implicitly assume rational actor theory (e.g., Kanta & Zechman, 2014; Muneepeerakul & Anderies, 2020; Bakarji et al., 2017; Baeza et al., 2019) or (iv) outputs of a single dynamical equation that ignores the layered networks of institutions responsible for filtering and translating information into action (e.g., Di Baldassarre et al., 2013; Elshafei et al., 2014; Mazzoleni et al., 2021; Garcia et al., 2016). Meanwhile, ample empirical evidence suggests that these outputs endogenously evolve with the socio-hydrologic system (e.g., Sullivan et al., 2017; Garcia et al., 2019; Treuer et al., 2017; R. R. Brown et al., 2009) and are not necessarily reflective of rational, long-term, goal-directed behavior (e.g., Hansen & Mullin, 2022; Mullin & Hansen, 2022; Hornberger et al., 2015; Winz et al., 2009).

In this manuscript, we investigate the scaffolding of political-economic feedback, institutions. Institutions mediate the identification of perceived problems and their translation into actions by constraining the space of possible actions (Ostrom, 2011). Just as networks of hard infrastructure steer the flow of water, so too do networks of soft infrastructure steer the flow of information and actions at both the operational (e.g., use restrictions) and political-economic level (e.g., city goals) (Pahl-Wostl et al., 2010; Anderies et al., 2016; Brelsford et al., 2020). Socio-hydrologists and others concerned with human-water systems recognize the importance of institutions and have developed ways to incorporate their consideration into water system operation (e.g., Brelsford et al., 2020; Lund, 2015; Konar et al., 2019; Yu et al., 2017; Herman et al., 2020; Trindade et al., 2020), but the way institutions shape information processing in political economic processes remains under-studied.

One tool from the field of policy studies used to address the role of institutions on information processing is the concept of *institutional friction*. Institutional friction refers to the emergent information, decision, and transaction costs within a policy system that incentivize inaction among relevant decision-making actors even when error, the gap between goals and reality, exists (Workman et al., 2009; Jones & Baumgartner, 2005a). While institutional friction has been used in abstract dynamical system models of information processing (Jones & Baumgartner, 2005a), it has not previously been applied in a model of infrastructure investment.

This manuscript presents a novel approach to incorporate institutional friction into analysis of urban water coupled infrastructure systems implemented in the Urban Water Infrastructure Investment Model (UWIIM). Coupled to a simple urban water dynamical system that captures operational feedback in balancing supply and demand, we define three information processing nodes in the political-economic system as closed-loop controllers (Anderies et al., 2007) whose attention is distorted by institutional friction. These nodes are long-term infrastructure investment, short-term demand curtailment, and rate-making.

To demonstrate the UWIIM in context, we compare the urban water systems of three cities in the Phoenix Metropolitan Area (PMA): Phoenix, Scottsdale, and Queen Creek. The area faces a common hydrologic challenge: declining availability of Colorado River water due to basin-wide aridification and chronic over-allocation (Udall & Overpeck, 2017; Overpeck & Udall, 2020), and rapid population growth (Gober et al., 2016; Healy, 2021). We examine the following question: *how does institutional friction in investment and rate-making decisions interact with a city's water resource portfolio and financial position to affect the sensitivity of its water supply, demand, and ratepayer burden to sudden, long-term reductions in water availability.*

2 Model

The Coupled Infrastructure Systems (CIS) Framework (Anderies et al., 2016) conceptually grounds the model. Nodes in a CIS are actors, resource users or public infrastructure providers (PIPs), and infrastructures of multiple types, including natural infrastructure (e.g., a watershed), and public infrastructures (hard/built and soft/institutional). With Yoon et al's (2022) typology, PIPs are governing actors, users are utilizing actors, and public infrastructure (PI) agents are provisioning actors. The PI agents implement directives from PIPs and operate the infrastructure system (Anderies et al., 2019). The CIS allows us to map flows of material (e.g., water) and information between actors and infrastructures to visualize feedback loops of interest that govern system dynamics (Anderies, 2015b).

Action situations are spaces of interaction between actors, institutions, and their environment that produce relevant outcomes (Ostrom, 2011), and they are the primary units of human information processing in a CIS (Anderies et al., 2016). Taken together, the CIS is an information and material processing network that endogenously controls responses to variation in exogenous flows. This is what the CIS Framework defines as *governance* (Anderies, 2015b) and it consists of two loops of interest: operational feedback and political-economic feedback.

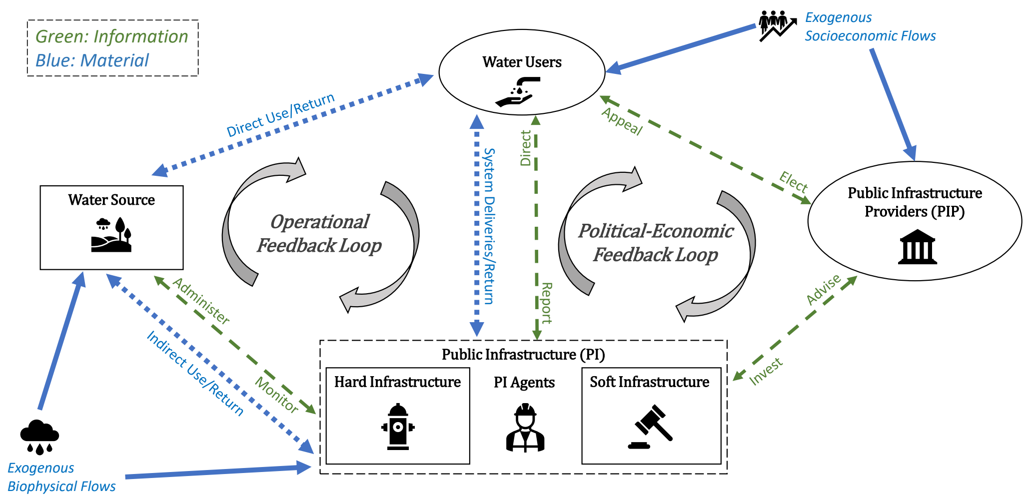

Figure 1. Summary of actors (ovals), infrastructure (rectangles), and flows (blue dotted and green dashed are internal material and information flows, respectively) in a general urban water coupled infrastructure system (UW-CIS). Exogenous material flows are depicted by solid blue lines. Two overall feedback loops govern the system: Operational Loop and Political-Economic Loop.

The UW-CIS (Figure 1) begins with a portfolio of water sources, often natural infrastructure, that catch, transmit, and store precipitation and runoff. In urban systems, characterized by high population density and occupational specialization (West, 2017), users are supplied through large public infrastructure systems. These public infrastructure systems store, treat, and distribute water and are operated by PI agents. Of course, this operation is quite complex and requires the PI agents and users to process information from the infrastructure system given PIP directives. This *operational feedback loop* is often the focus of conventional urban water models.

The political-economic loop can take on many forms given the structure of system ownership (Deslatte et al., 2021). Because the infrastructure system is shared, a PIP (city council, special district, company, etc.) is responsible for investing in the system. With their authority, the PIP makes investment decisions taking into account information from the PI agents and users. Together, the operational and political-economic feedback loops allow the UW-CIS to process material and information to ensure desired performance goals are met despite biophysical and socioeconomic variation.

2.1 Model Overview

The Urban Water Infrastructure Investment Model (UWIIM) is a discrete time, dynamical system that models the flow of water, investment, and information in a stylized UW-CIS with annual time steps (Figure 2a). Refer to the Supporting Information for detailed definition.

The system consists of a homogenous user population of size P_t with per capita demand d_t and a network of infrastructures that use water from available sources (indexed by i) to meet demand. The number of sources included in an application of the UWIIM is flexible to allow for case-specific representations (e.g., our PMA cases have access to three possible sources, so $i \in [1,3]$). Each year, the UW-CIS receives water inflows, $Q_{i,t}$, from source i that can be stored, used, or released back into the environment.

Each source is characterized by two time-varying parameters: mean annual streamflow ($\mu_{i,t}$) and its coefficient of variation ($c^v_{i,t}$). In our simple demonstration case, we are only interested in mean changes, so we set $c^v_{i,t}$ to near zero. For each source, the system has storage infrastructure of volumetric capacity, $\bar{V}_{i,t}$. $V_{i,t}$ refers to the volume of water stored from i at the beginning of t ($V_{i,t} \leq \bar{V}_{i,t}$). Outflows from source i, $O_{i,t}$, come in two forms (indicated by superscript): city withdrawals to satisfy demand, $O^d_{i,t}$, and releases (e.g., flood control), $O^f_{i,t}$. Two types of hard infrastructure determine how much of $O^d_{i,t}$ can be delivered to users: processing and delivery infrastructure. Processing capacity is source-specific, $w_{i,t}$, and is defined as the proportion of the city's maximum available water (i.e., total volumetric capacity plus expected annual inflow, $\bar{V}_{i,t}+\mu_{i,t}$) that it can process in year t, taking into account pumping and treatment infrastructure. Delivery efficiency, η_t, is a proportional coefficient that refers to, on average, the amount of demand the city can meet per unit of processed water from all of its sources, taking into account lost water and re-use. In essence, we treat re-use as an increase to delivery efficiency because the city is able to deliver more water to users per unit of water extracted from a surface or groundwater source (if net re-used, $\eta_t > 1$). Two forms of soft infrastructure operate the system, demand management and rate policy, and two exogenous drivers, defined by the model user, can disrupt the UW-CIS: population growth and water inflow. The UWIIM stores the system's state variables in vector x_t.

The UWIIM models the political-economic feedback loop through a network of controller feedback loops that make changes to the infrastructure system to meet supply and financial goals (2b). We model three representative action situations as controllers: short-term curtailment, long-term investment, and rate-setting. Each converts perceived error, $e_{j,t}$, between the desired system state, γ_j, and x_t (assuming perfect measurement) into actions, u_jt, through an algorithm, $G_j(e_{j,t}, x_t)$. We account for the distorting influence of institutional friction (Jones & Baumgartner, 2005a) through the use of an attention filter before $G_j(e_{j,t}, x_t)$ (Figure 2b).

2.2 Operational Feedback Loop

The operational feedback loop seeks to meet demand with available supply, S_t. S_t is the annual volume of water that can be delivered to users and is the product of water available in a given year, A_t, and η_t. A_t is the sum of available water from each source i in t, $A_{i,t}$. Each $A_{i,t}$ is the minimum of the amount of water from source i the city is legally entitled to use in year t, $A^l_{i,t}$, and the water that can be technically processed by the city from source i in year t, $A^w_{i,t}$. $A^l_{i,t}$ translates the water from source i in storage, $V_{i,t}$, and flowing in, $Q_{i,t}$, into legal availability. We assume each city has legal access to proportions a^v_i and a^q_i of $V_{i,t}$ and $Q_{i,t}$, respectively. $A^w_{i,t}$ converts the processing capacity, $w_{i,t}$, back into volumetric units by multiplying it by its normalizing denominator, $(\bar{V}_{i,t} + \mu_{i,t})$ (Table 1).

For population growth, we opt for a basic logistic definition with carrying capacity κ and intrinsic growth rate r (Garcia et al., 2016; Liu et al., 2015; Elshafei et al., 2014). d_t is the per capita demand at the start of t before taking into account curtailment enacted in t, $u_{1,t}$. $\tilde{d}_t$ is the actual per capita demand after subtracting $u_{1,t}$. When calculating the per capita demand for the next year, d_{t+1}, we account for conservation rebound, the return of demand to baseline demand, $\bar{d}_t$, a separate state variable, with a common equation in socio-hydrology that takes a community sensitivity parameter α (Garcia et al., 2016; Gonzales & Ajami, 2017). By baseline ($\bar{d}_t \geq d_t$), we refer to the demand if no curtailments had ever occurred, reflecting hard infrastructure (e.g, efficiency improvements) and long-term policies (e.g., building codes) (Garcia et al., 2016). We use the general infrastructure dynamical equation for $\bar{d}_t$ (Equation 1) where δ represents the back-

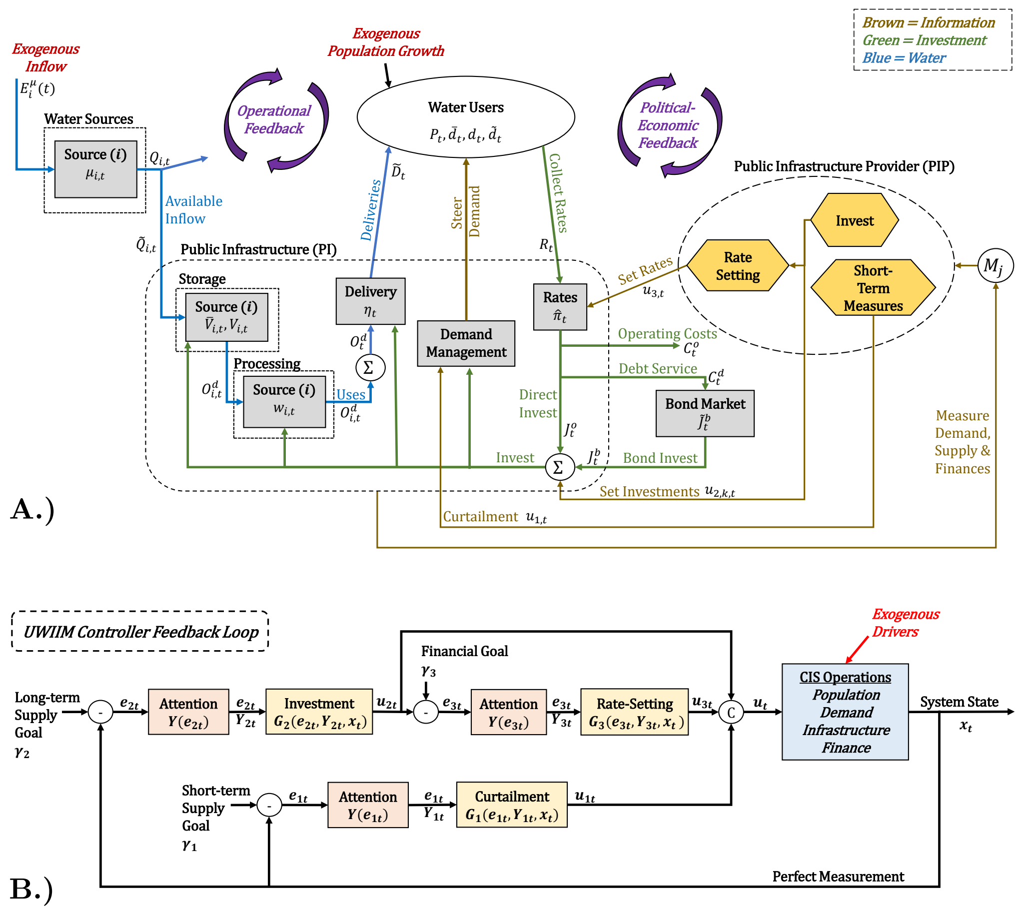

Figure 2. Overview of the Urban Water Infrastructure Investment Model (UWIIM). CIS representation (a) maps flows of information, water, and investment. Grey boxes depict infrastructure and yellow hexagons represent action situations. See Table 1 for variable definitions. The network (b) plots the order of information processing in the political-economic feedback loop with the attention (pink) and response (yellow) steps of the controllers governing the CIS (blue).

ground conservation rate (Garcia et al., 2016). Each per capita demand variable can be translated to total system demand by multiplying it by P_t (Table 1).

2.2.1 Infrastructure

The vector $I_{k,t}$ contains the capacities for each infrastructure, k. Its size depends on the case being modeled (e.g., in our PMA cases, $k \in [1,7]$). Some infrastructures like w are source specific, in which case, there is a unique capacity for each source. $I_{k,t}$ decays each year according to a decay parameter, δ_k, and increases with investment, $u_{2,k,t}$ (Muneepeerakul & Anderies, 2020, 2017). We add $E_k(t)$ to capture exogenous drivers that can be defined by the model user in scenario definition (e.g., our Colorado River scenarios). The general difference equation is as follows,

$$I_{k,t+1} = (1-\delta_k)I_{k,t} + H_k(u_{2,k,t}, x_t; \tau_k^i) + E_k(t) \tag{1}$$

We represent investments as increases to capacity rather than dollar amounts. To keep units common, $u_{2,k,t}$, is in volumetric flow units (e.g., volume of water that can be processed in a given year). Each variable stored in $I_{k,t}$ is not given in the same units, so the function $H_k(u_{2,k,t}, x_t)$ (Supporting information) transforms the volumetric $u_{2,k,t}$ into the relevant units for $I_{k,t}$. Because infrastructure investments often carry lag time between investment and implementation, the τ_k^i parameter specifies the delay between investment and infrastructure change.

2.2.2 Water Balance

The stored water from each source i at time t, $V_{i,t}$, increases with the city's legally entitled inflow, $a_i^q Q_{i,t}$, and decreases with city withdrawals, $O_{i,t}^d$, and releases, $O_{i,t}^f$ (Table 1). $O_{i,t}^d$ reflects source priority (in order i) to calculate the water needed to meet demand with,

$$O_{i,t}^d = \min\left[\left(1 - \sum_{i'>i}\theta_{i'}\right)\left(\frac{\tilde{D}_t}{\eta_t} - \sum_{i'<i} O_{i't}^d\right), A_{i,t}\right] \tag{2}$$

where θ_i specifies the minimum proportion of demand that must be met with source i regardless of higher priority availability. We calculate $O_{i,t}^f$ such that $V_{i,t} \leq \bar{V}_{i,t}$.

2.2.3 Finances

The PIP can only raise revenue through rates paid by users. The UWIIM rate structure allows for per-user (connection) charges and per-use (volumetric) charges, based on $\tilde{d}_t$. When setting rates, we assume the PIP knows the population but not future curtailments, so it predicts demand will resemble the baseline, $\bar{d}_t$, in its target per-capita revenue, $\hat{\pi}_t$. To calculate the actual revenue generated, R_t, we simplify the split between volumetric and connection components with the assumption that the PIP seeks the same proportion of revenue from connection charges, β_p^π (Table 1).

R_t covers operating costs (C_t^o), debt service requirements (C_t^d), and a portion of infrastructure investment (J_t^o). Operating costs, C_t^o, account for volumetric and user economies of scale with fitted exponents, z_d and z_p respectively, and normalizing constant g_o. We use $\bar{D}_t$ in the equation because the infrastructure needed to meet baseline demand is not abandoned during curtailment (Table 1).

J_t^o refers to investments that come directly from R_t as opposed to bonds, J_t^b. We assume bond life, τ_b, and interest rate, i_b, remain constant over time and that the PIP pays off debt in equal increments, so to keep track of accrued debt, we use a state vari-

Table 1. Dynamic Variables in the UWIIM

Name	Symbol	Definition
Demand		
*Population	P_t	$P_{t+1} = P_t + r(1 - \frac{P_t}{\kappa_t})$
*Per Capita Demand (Year Start)	d_t	$\tilde{d}_t \left[1 + \alpha\left(1 - \frac{\tilde{d}_t}{\bar{d}_t}\right)\right]$
Per Capita Demand (Year End)	$\tilde{d}_t$	$\tilde{d}_t = d_t - u_{1,t}$
Total System Demand	$\bar{D}_t,\, D_t,\, \tilde{D}_t$	$\bar{D}_t = \bar{d}P_t,\, D_t = d_tP_t,\, \tilde{D}_t = \tilde{d}_tP_t$
Supply & Water Balance		
Supply	S_t	$S_t = \eta_t \sum_i A_{i,t}$
Available Water (Total)	$A_{i,t}$	$A_{i,t} = \min\left(A^l_{i,t}, A^w_{i,t}\right)$
Available Water (Legal)	$A^l_{i,t}$	$A^l_{i,t} = a^v_i V_{i,t} + a^q_i Q_{i,t}$
Available Water (Tech.)	$A^w_{i,t}$	$A^w_{i,t} = w_{i,t}(\bar{V}_{i,t} + \mu_{i,t})$
City Withdrawal	$O^d_{i,t}$	Equation 2
Flood Release	$O^f_{i,t}$	$O^f_{i,t} = \max\left[V_{i,t} + a^q_i Q_{i,t} - O^d_{i,t} - \bar{V}_{i,t}, 0\right]$
*Stored Water	$V_{i,t}$	$V_{i,t+1} = V_{i,t} + a^q_i Q_{i,t} - O^d_{i,t} - O^f_{i,t}$
*Source Inflow	$Q_{i,t}$	Scenario Definition
Infrastructure: $I_{k,t} = \left(\bar{d}_t, \eta_t, \bar{V}_{i,t}, w_{i,t}, \mu_{i,t}\right)$		
*Per Capita Demand (Baseline)	$\bar{d}_t$	Equation 1
*Delivery Efficiency	η_t	Equation 1
*Storage Capacity	$\bar{V}_{i,t}$	Equation 1
*Processing Capacity	$w_{i,t}$	Equation 1
*Mean Inflow	$\mu_{i,t}$	Equation 1 & Scenario
Finances		
*Per Capita Rate Policy	$\hat{\pi}_t$	$\hat{\pi}_{t+1} = \hat{\pi}_t + u_{3,t}$
Revenue	R_t	$R_t = P_t\hat{\pi}_t(\beta^\pi_p + (1 - \beta^\pi_p)\frac{\tilde{d}_t}{\bar{d}_t})$
Operating Costs	C^o_t	$C^o_t = g_o P_t^{z_p} \bar{D}_t^{z_d}$
Debt Service	C^d_t	$C^d_t = (1 + \tau_b i_b)\, \tilde{J}^b_t$
*Average Bond-Sourced Investment	$\tilde{J}^b_t$	$\tilde{J}^b_{t+1} = \frac{1}{\tau_b}\left[(\tau_b - 1)\tilde{J}^b_t + J^b_t\right]$
Bond-Sourced Investment	J^b_t	$J^b_t = J_t - J^o_t$
Direct-Sourced Investment	J^o_t	$J^o_t = \min\left(J_t, R_t - C^o_t - C^d_t\right)$
Investment (Dollars)	J_t	$J_t = \sum_k F_k(u_{2,k,t})$
Action Situation Controllers		
Signal (Curtailment)	M_1	$M_{1,t} = \frac{S_t}{D_t}$
Signal (Investment)	M_2	$M_{2,t} = \frac{\hat{S}_{t+\tau_p}}{\hat{D}_{t+\tau_p}}$
Signal (Rates)	M_3	$M_{3,t} = \frac{\hat{R}_{t+1} - \hat{C}^o_{t+1}}{\hat{C}^d_{t+1}}$
Error	$e_{j,t}$	$e_{j,t} = \gamma_j - M_{j,t}$
Attention	$Y_{j,t}$	$Y_{j,t} = \frac{1}{1+\exp(-\lambda_j(e_{j,t} - \epsilon_j))}$
Response (Curtailment)	$u_{1,t}$	$u_{1,t} = d_t\alpha\left(1 - \frac{d_{min}}{d_t}\right)Y_{1,t}$
Response (Investment)	$u_{2,k,t}$	$\hat{u}_{2,k,t} = \beta_{k,t}e_{2,t}Y_{2,t}\hat{D}_{t+\tau_p} + \hat{H}^m_{k,t}$, Check $J_t \leq \bar{J}_t$
Response (Rates)	$u_{3,t}$	$\hat{u}_{3,t} = \frac{e_{3,t}Y_{3,t}\hat{C}^d_{t+1}}{\hat{P}_{t+1}}$, Check $u_{3,t} \leq \psi_r\hat{\pi}_t$

*Indicates a model state variable stored in x_t through model runs. Superscripts on variables indicate type (e.g., in J^b_t, b indicates investment dollars sourced from *bonds*).

able $\tilde{J}_t^b$ to keep a τ_b-year moving average of the bond-sourced investment. The debt service paid in a particular year, C_t^d is then a function of $\tilde{J}_t^b$ (Table 1).

Decisions to make capital investments can be quite complex because project details and city context vary greatly. We choose the following simplified treatment in our model. For each infrastructure type k, the cost, $J_{k,t}$, of increasing its volumetric capacity an amount, $u_{2,k,t}$, follows a power law relationship contained in $F_k\left(u_{2,k,t}\right)$ and defined as,

$$J_{k,t} = F_k\left(u_{2,k,t}\right) = \begin{cases} g_k\left(\eta_t u_{2,k,t}\right)^{z_k} & \text{delivery efficiency} \\ g_k\left(u_{2,k,t}\right)^{z_k} & \text{all other infrastructure} \end{cases} \tag{3}$$

Because the marginal costs of delivery efficiency investments increase with added efficiency, $F_k(\cdot)$ for η uses the interaction $\eta_t u_{2,k,t}$ as the exponential base. If the PIP wishes to maintain $I_{k,t}$, the maintenance investment needed, $\hat{H}_{k,t}^m$, is calculated with $H_k^{-1}(\cdot)$, the inverse of the $H_k(\cdot)$ functions (Supporting Information).

2.3 Political-Economic Feedback Loop

In the the political-economic loop PIPs take actions to track goals. We model this through controller feedback loops (CFBLs), a helpful tool for modeling action situations in social-ecological systems (e.g., Anderies et al., 2007; Rodriguez et al., 2011; Anderies, 2015b). A CFBL consists of (i) a dynamical system that outputs state variables of interest (x_t) and (ii) a mechanism of closed-loop feedback control that measures the output, compares it to a goal, and responds with action back into the system (Anderies et al., 2007).

We model three representative action situations (Figure 2b): short-term curtailment measures, long-term investment, and rate-setting. The first two occur in parallel, and rates are set with investment information. Each, in reality, is a collection of many networked action situations (Deslatte et al., 2021; McGinnis, 2011), but we aggregate the "representative" action situation based on the emergent policy output of interest (e.g., an investment plan).

2.3.1 Goals, Signals & Error

$M_j(x_t)$ translates x_t into the relevant metric for each goal, γ_j (Table 1). Curtailment and investment examine the ratio of supply to demand. Curtailment only considers the current state, and investment makes projections τ_p years into the future, considering future population, groundwater volume, and already planned investments (Supporting Information). We assume the PIP has perfect information on population growth and approximates per capita demand at baseline, maintained infrastructure, and inflow at mean. For rate-setting, the PIP calculates the expected debt service capacity ratio of the next year given the current rate policy, expected operating costs, and planned investments. Error is the difference between γ_j and $M_j(x_t)$.

2.3.2 Controller Design & Representative Action Situations

All controllers follow two steps to produce an action, $u_{j,t}$, given $e_{j,t}$ and x_t (Figure 2b). The first step generates attention attributable to $e_{j,t}$, and the second step responds to the attention-mediated error with an action akin to a proportional controller (Rodriguez et al., 2011).

Each controller, being human-driven, is subject to disproportionate information processing challenges where actions pursued are not necessarily proportional to the actual scale of the error (Workman et al., 2009). To address this, socio-hydrologic models (e.g., Yu et al., 2017; Garcia & Islam, 2021; Garcia et al., 2016; Di Baldassarre et al., 2013; Mazzoleni et al., 2021) have often quantified the salience of water issues in a social system. Our attention variable is similar, but we (i) focus the attention relevant to a particular action situation as opposed to the social system at-large and (ii) incorporate institutional friction. Regarding institutional friction, our approach builds on the original Jones and Baumgartner (2005b) model but differs in two ways: (i) our function is continuous over error and (ii) response, $u_{j,t}$, is now a nonlinear transformation of error, $G_j(\cdot)$. We model attention, $Y_{j,t}$, as the proportion of error actually registered by the controller. If $Y_{j,t} = 1$, the error is fully perceived by the controller and a proportional response will be calculated. If $Y_{j,t} = 0$, there will be no response (Table 1).

Institutional information processing can be disproportionate because actions carry costs associated with gathering information, searching for a solution, coming to an agreement, and implementing the solution (Jones & Baumgartner, 2012; Jones et al., 2003; Workman et al., 2009). We aggregate this into an *institutional costs* parameter, ϵ_j. We use a *response elasticity* parameter, λ_j, to define the slope of the sigmoid as it converges to full attention (higher λ means steeper slope). In this sense, λ_j can represent the institutional ambiguity or *flexibility* present within the system that distorts actor perception of the system's proximity to its action threshold, ϵ_j.

$G_j(e_{j,t}Y_{j,t}, x_t)$ has two parts: (i) calculate a potential response, $\hat{u}_{j,t}$ and (ii) account for saturation constraints, $sat_j(\hat{u}_{j,t}, x_t)$. Short-term curtailment follows prior socio-hydrology models with a logistic decay function to account for diminishing conservation returns as the system approaches minimum per capita demand, d_{min} (Garcia et al., 2016; Mazzoleni et al., 2021; Gonzales & Ajami, 2017). Because $\hat{u}_{1t}$ accounts for d_{min}, there are no other saturation checks.

The investment response, $u_{2,k,t}$, is a vector of investments for each infrastructure k in volumetric units. $\hat{u}_{2,k,t}$ is a function of the perceived supply gap and maintenance needs, $\hat{H}^m_{k,t}$, which we assume will occur regardless of attention. The supply gap refers to needed expansion. We distribute the supply gap across k according to coefficients $\beta_{k,t}$, the infrastructure investment strategy of the city. Starting β_k values are parameters, but $\beta_{k,t}$ can vary in a given year if investments need to be re-distributed from infrastructures that have reached their maximum capacities (Supporting Information). Each year has a maximum investment capacity, $\bar{J}_t$, that takes into account the debt service implications for the following year (Supporting Information). The saturation function compares the total investment dollars needed to fund $\hat{u}_{2,k,t}$, $\hat{J}_t$, to $\bar{J}_t$ and outputs the minimum converted back into volumetric units as $u_{2,k,t}$.

Rate-making calculates the change in per capita rate policy needed to address the perceived revenue gap, $\hat{u}_{3,t}$. The saturation function checks that $\hat{u}_{3,t}$ is less than ψ_r, the maximum rate increase allowed by the socio-political system, to get $u_{3,t}$.

2.4 Performance Metrics & Sensitivity

We measure three performance metrics: (i) *reliability* (Ajami et al., 2008), or the proportion of $\bar{D}_t$ met by S_t, (ii) rates ($\hat{\pi}_t$), and (iii) demand ($\bar{d}_t$). Over a model run, we aggregate the reliability, rate, and demand time series in four ways: mean reliability, minimum reliability, rates at the end of the model run, and demand at the end of the model run. To measure robustness, we create sensitivity measures (Anderies et al., 2007; Rodriguez et al., 2011), which are ratios of percent change in a performance metric to percent change in an input, for each of the four performance metric aggregations.

3 Case: Phoenix Metropolitan Area

We use the UWIIM to compare the sensitivity of water systems within the Phoenix Metropolitan Area (PMA) to change in Colorado River availability. Cities in the arid PMA rely on a mix of heavily regulated surface water delivered via canals and local groundwater. The Salt and Verde Rivers drain a watershed contained within central and east Arizona and combine into the Salt River before entering the PMA where a network of canals managed by the Salt River Project (SRP) distribute flows to city water treatment plants. SRP water follows a land-based seniority system, where it can only be delivered to lands demarcated by the Kent Decree in 1910 (Feller, 2007; Phillips et al., 2009; Salt River Project, 2017). Water from the Colorado River is conveyed to the PMA through the Central Arizona Project (CAP) canal. The Arizona Department of Water Resources (ADWR) regulates groundwater use within Arizona. The cities now face a situation where most renewable water has already been allocated, if not over-allocated, while experiencing a prodigious population and economic growth (Healy et al., 2021).

The city definitions used in this study are adaptations of a complex water resources planning environment onto the general structure we use in our simple model. This study is not intended to predict the future state of the three real cities or provide decision support, but to understand how institutions can alter the sensitivity of various operational contexts to environmental changes. The baseline parameter and initial conditions provide three different artificial testbeds to demonstrate this relationship, not replicate an actual city water system in the PMA.

3.1 PMA Model Definition

The three cities differ in their infrastructure capacity, financial position, demand profile, and water entitlements (Table 2). Designations of Assured Water Supply (DAWS), completed for most PMA cities in 2010, provide commonly formatted water resource information. We, thus, set 2010 as the start year for all model runs and use DAWS estimations to set model parameters and initial conditions related to the water resource portfolio of Scottsdale (ADWR, 2013) and Phoenix (ADWR, 2010). Queen Creek does not have a DAWS, but they have a Certificate of Assured Water Supply (CAWS) for their 2011 system (ADWR, 2011b) and the H20, Inc. system (ADWR, 2011a) that they acquired in 2013. We triangulated these official filings with published supply and demand data from ADWR (ADWR, 2022a), the CAP sub-contract registry (CAP, 2022a), and city plans (City of Phoenix, 2011, 2021; Sunrise Engineering, Inc., 2017; Scottsdale Water, 2021). See Supporting Information for details.

We define legal and technical availability parameters for SRP ($i = 1$), CAP ($i = 2$), and groundwater ($i = 3$) with a few additional case-specific considerations. η_t accounts for re-use water (Supporting Information). We account for the land-specific nature of SRP rights by only allowing the city to use their base SRP allocation for a portion of their demand, ξ_1, but additional SRP rights accrued after the Kent Decree can be used throughout the city. We account for the priority of CAP water entitlements possessed by each city in our CAP shock scenarios (Supporting Information). We assume surface water storage is negligible, and Phoenix and Scottsdale can fully process their available surface water. We set Queen Creek's surface processing capacity to near zero to calibrate the cost functions.

We estimate initial groundwater storage (V_0^g) with ADWR allocations, provided as a total volume to be used over 100 years, and long-term storage credits. Currently, Queen Creek depends on recharge support from the Central Arizona Groundwater Replenishment District (CAGRD) to offset its groundwater use in excess of its allowance. However, modeling the future of CAGRD is beyond the scope of this exploratory study (Ferris & Porter, 2019), so to examine Queen Creek's non-CAGRD potential, we add to

Table 2. City Variation in the PMA UWIIM Adaptation

Variable	PHX Value	Sc Value	QC Value	Units	Source
Water Resources					
CAP (Low) Approx.	37280	3306	4162	AFY	CAP
CAP (High) Approx.	147426	77794	495	AFY	CAP
SRP (Base) Approx.	220647	19000	0	AFY	D/CAWS
SRP (Added) Approx.	57300	8600	0	AFY	D/CAWS
Proportion of Demand on SRP Eligible Land	0.5	0.17	0	N/A	WRP
Groundwater Allowance	3699500	1290528	1474600	AF	D/CAWS
Groundwater Credits (Banked)	240989	93846	289535	AF	D/CAWS, QC (2017)
Processing Capacity (Surface)	Full	Full	Negligible	N/A	WRP
Processing Capacity (Ground)	43000	34827	24520	AFY	WRP
Delivery Efficiency	0.9742	1.0562	0.9339	N/A	ADWR
Demand					
Population	1458275	217943	32197	persons	CAFR
Population Intrinsic Growth Rate	0.088	0.143	0.240	N/A	CAFR
Population Carrying Capacity	1686528	242300	101553	persons	CAFR
Per Capita Demand	163.17	338.75	282.85	GPCD	ADWR
Finances					
Per Capita Rates	238.36	398.11	241.06	$/person	CAFR
Average Debt Service	111.5	20	5.7	$M	CAFR
Proportion of Rates from Fixed Fees	0.6322	0.3586	0.5801	N/A	UNC EFC

WRP = Water Resource Plan; CAFR = Comprehensive Annual Financial Report; D/CAWS = Designation/Certificate of Assured Water Supply; CAP = Central Arizona Project; ADWR = Arizona Department of Water Resources; UNC EFC = (UNC Environmental Finance Center, 2022).

their V_0^g the recent purchase of 175 KAF of groundwater credits and credits equal to their estimated excess pumping prior to 2024 (Supporting Information).

We use city Comprehensive Annual Financial Reports (CAFRs) 2010-2021 triangulated with the EPA's Safe Drinking Water Information System (US EPA, 2022), ADWR reports (ADWR, 2021), and the Water Rates Dashboard for Arizona (UNC Environmental Finance Center, 2022) to fit population and financial parameters (Supporting Information). Investment cost function parameters assume (i) investment dollars are split according to average proportions of Phoenix Capital Improvement Plans (CIPs) 2010-2021 (City of Phoenix, 2022), (ii) $J_0^b \sim \tilde{J}_0^b$, and (iii) $J_0^o \sim (\gamma_3 - 1)C_0^d$. The latter assumption accounts for the fact that some cities do not start 2010 at γ_3, so the J_0^o requirement forces early rate increases in the model to bring the system to γ_3. Demand management is not reported in Phoenix CIPs, so we rely on the reported cost of the Southern Nevada Water Authority's rebate program to infer its cost function (Supporting Information). τ_k^i, has a baseline value of 3 years for hard infrastructure and 1 year for demand management.

β_k only relates to investments that expand infrastructure capacity, not maintenance. We assume Scottsdale and Phoenix do not need additional surface water treatment capacity ($\beta_{w_s} = 0$), and given that much of their reclaimed water is already committed to exchange agreements, we assume the first infrastructure priority would be groundwater processing followed by delivery efficiency and demand management (City of Phoenix, 2021; City of Scottsdale, 2022). Queen Creek has the opportunity to gain surface processing, but their recent plans suggest that they are leveraging almost exclusively groundwater (Sunrise Engineering, Inc., 2017).

Sensitivity analysis of the empirically grounded parameters indicate that the results remain consistent for reasonable uncertainties in parameter values (Supporting Information).

3.2 PMA Colorado River Availability Scenarios

Multiple scholars (Wheeler et al., 2022), the Bureau of Reclamation (DOI, 2022), and water users (Goddard & Atkins, 2022), argue that the existing water distribution rules are not enough to address the Colorado River's pressing state, which may require a 2-4 MAFY basin-wide cut in use (DOI, 2022). The Bureau has undergone a Supporting Environmental Impact Statement (SEIS) process to reform the 2007 guidelines (Bureau of Reclamation, 2022) and published a draft (D-SEIS) in April (Bureau of Reclamation, 2023b) that includes two alternatives to share needed cuts by the traditional priority system or adopt a use-proportional sharing approach.

Our CAP scenarios assume 2024 will be a year of considerable change in basin operations and require an immediate, long-term decrease in use. We note that drought-induced shortages are not necessarily long-term, so these scenarios are meant to be exploratory of hypothetical long-term cuts to river use, not policy diagnoses.

The CAP has a tiered system of sub-contracts that we simplify into low and high priority sub-contracts. High priority includes Municipal and Industrial (M&I), Indian, and P3 rights (CAP, 2022b). Low priority use includes Non-Indian Agriculture (NIA) and excess water use. The Supporting Information details the method we use to convert a possible shortage in Arizona's allocation (Δ_{AZ}) to the shortage for PMA users (Δ_{PMA}). $\bar{\mu}_2$ is the annual water (AFY) that PMA cities, together, are entitled to use in a non-shortage year, and it totals 448,663 AFY. We define $E_2^{\mu}(\cdot)$ (from Equation 1) to take a parameter s, which is the proportional change in PMA CAP availability ($\frac{\Delta_{PMA}}{\bar{\mu}_2}$), as,

$$E_2^{\mu}(\bar{\mu}_2, t) = \begin{cases} s\bar{\mu}_2 & t = t^* \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

The May 24-month study projects a most-probable Lake Mead level consistent with a Tier 1 shortage (Bureau of Reclamation, 2023a), but Arizona leaders have cautioned that 2024 cuts could resemble a Tier 3 shortage ($s = -0.284$), if additional cuts are added by the D-SEIS (CAP, 2023). In May, the basin states released a compromise proposal for the Bureau to consider in its D-SEIS, along with the two alternatives, that includes total cuts of 3 MAF by 2026 (Buchatzke et al., 2023), but the details regarding how the cut will be shared among users like the CAP remains unknown.

3.3 Running the Model

We run each configuration of the model for 50 years because the shock is a simple step disturbance. Because the model is deterministic, multiple runs of the same configuration were not needed. Investments and rate-setting are driven by a goal supply buffer of $\gamma_2 = 1.2$ and a minimum debt service coverage ratio of $\gamma_3 = 2$ (Rafelis, 2021), respectively. The most Phoenix has raised rates within a year is 13%, so we set $\psi_r = 0.15$.

The institutional friction parameters are difficult to define for a specific city, so we define the baseline values in the following way. For ϵ_j, we assume no costs at baseline ($\epsilon_j = 0$). The response elasticity, λ_j, refers to the degree of flexibility in the action situation, altering the amount of partial response generated in the neighborhood of ϵ_j. Higher λ_j implies little partial response, closely resembling a binary switch near ϵ_j. We, thus, relate λ_j to the range of error values, Δe_j, around ϵ_j that will generate a significant attention response ($Y > 0.1$). We use a baseline Δe_j of 0.1 for investment and rate-setting and 0.02 for short-term measures, assuming short-term measures are taken with less uncertainty because the stressors are presently felt, which implies λ_j values of 22 and 110, respectively (Supporting Information).

3.4 Exploration of Institutional Friction's Effect

We examine the effect of varying institutional friction parameters, ϵ_j and λ_j, on the cities' sensitivity to Colorado River restrictions. We tested each institutional friction parameter setting on the full range of s values in $[0, 1]$. We vary investment institutional costs, ϵ_2 from its no-costs baseline up to $\epsilon_2 = 0.5$, which implies that the PIP would not act until there is only supply for 60% of projected demand. Given the very conservative, reliability driven nature of water utilities, this is a very unlikely formal threshold, but the institutional costs of major investment can be an overwhelming informal barrier to glaringly needed supply or demand improvements (Muller, 2018). For rate-setting, we vary it up to $\epsilon_3 = 1$, where the utility only acts once debt requirements cover all net revenue. We choose the λ_j range based on the extreme cases of $\Delta e_j \in [0.01, 0.5]$, which implies $\lambda_j \in [4, 220]$ (Supporting Information). We vary λ_j on a log scale due to its position as a coefficient within an exponential expression.

4 Results

We present the results of running the UWIIM for each PMA city under the baseline assumptions (4.1) to understand their responses to various magnitudes of CAP shortage. Then, with this baseline established, we analyze the effect of varying institutional friction on the city response (4.2).

4.1 Baseline Operational Capacities of Each City

Absent consideration of institutional variation, the unique infrastructure, demand, and financial context of each city shapes their response to CAP shortages. To contextualize our shortage approximations, we highlight the s values equivalent to a Tier 2a and Tier 3 shortage and the two alternatives proposed in the April D-SEIS (Supporting Information).

Phoenix and Scottsdale are primarily dependent on surface water, but they differ in how they leverage non-CAP supplies to respond to a CAP shortage. Phoenix relies on their much larger SRP allocation while Scottsdale relies on its higher groundwater processing capacity. Both sources provide a reliable buffer to the cities for the Tier 3 and sharing-based D-SEIS scenarios (Figure 3). We identify the "break away" points where the CAP shock overcomes the city's operational capacity and compromises supply reliability at s values of -61% and -72% for Scottsdale and Phoenix, respectively (Figure 4b). However, Scottsdale's reliance on non-renewable groundwater to buffer against higher CAP shocks causes them to run out of surplus credits near 2045, requiring additional investments in re-use and ultimately, serious demand reductions that Phoenix can avoid (Figure 3, 4a). The additional investments pertaining to Scottsdale's groundwater reliance makes their rates more sensitive than Phoenix's rates (Figure 4c).

Queen Creek is a groundwater dependent city, but the substantial amount of groundwater credits it has secured, without CAGRD, can only hold the city until around 2040.

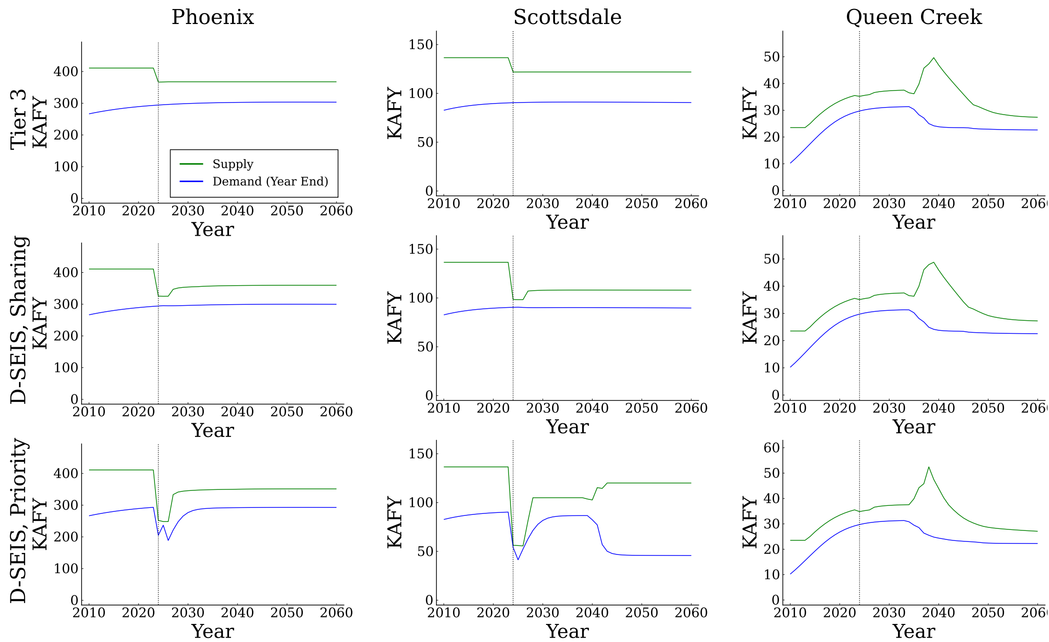

Figure 3. Supply and demand time series for each city given a long-term cut to CAP availability in 2024 equivalent to a Tier 3 shortage ($s = -0.284$), the priority-based ($s = -0.957$), and the sharing-based ($s = -0.525$) D-SEIS alternatives. D-SEIS approximations assume the 2.083 MAF basin-wide shortage scenario.

In the baseline model runs, Queen Creek registers that its credits will run out in the PIP's five-year projection window (τ_p) and responds with investments in re-use, demand management, and surface water processing (if CAP water is available) that prevent it from experiencing any reliability problems (Figure 3, 4b). Prior to 2024, Queen Creek experiences rapid demand increase driven by population growth but is able to maintain supply reliability through groundwater processing investments. At baseline parameter settings, s determines how much available CAP water they can leverage. With less CAP availability, they have to cut demand more and pass higher costs to their ratepayers. Queen Creek's small and mainly low priority CAP allocation makes these two measures very sensitive to s values smaller than -20% (near a Tier 2a shortage) (Figures 4a,d), after which, they lose most of their allocation regardless of s, and their sensitivity curves decay to zero. With the high sensitivity region, for each 1% drop in CAP availability, Queen Creek must cut demand by an additional $0.53 - 0.69\%$. Rate sensitivity, in this zone, is much more volatile (Figure 4) due to the nonlinear interaction between s, groundwater use, and shifting investment priorities ($\beta_{k,t}$), which each have their own cost curve.

4.2 Institutional Friction Effects

The two institutional friction components, costs and flexibility, alter the response of PMA cities in different ways. We focus on the role institutional friction plays in each city's *vulnerable range* of s, identified in the baseline analysis (Figure 4). For Phoenix and Scottsdale, this range is $s < -0.6$, and for Queen Creek it is $s > -0.2$.

4.2.1 Institutional Costs

Across all three cities, increasing institutional costs, ϵ_j, in both the investment and rate-making action situations increases the sensitivity of the city's supply to its vulner-

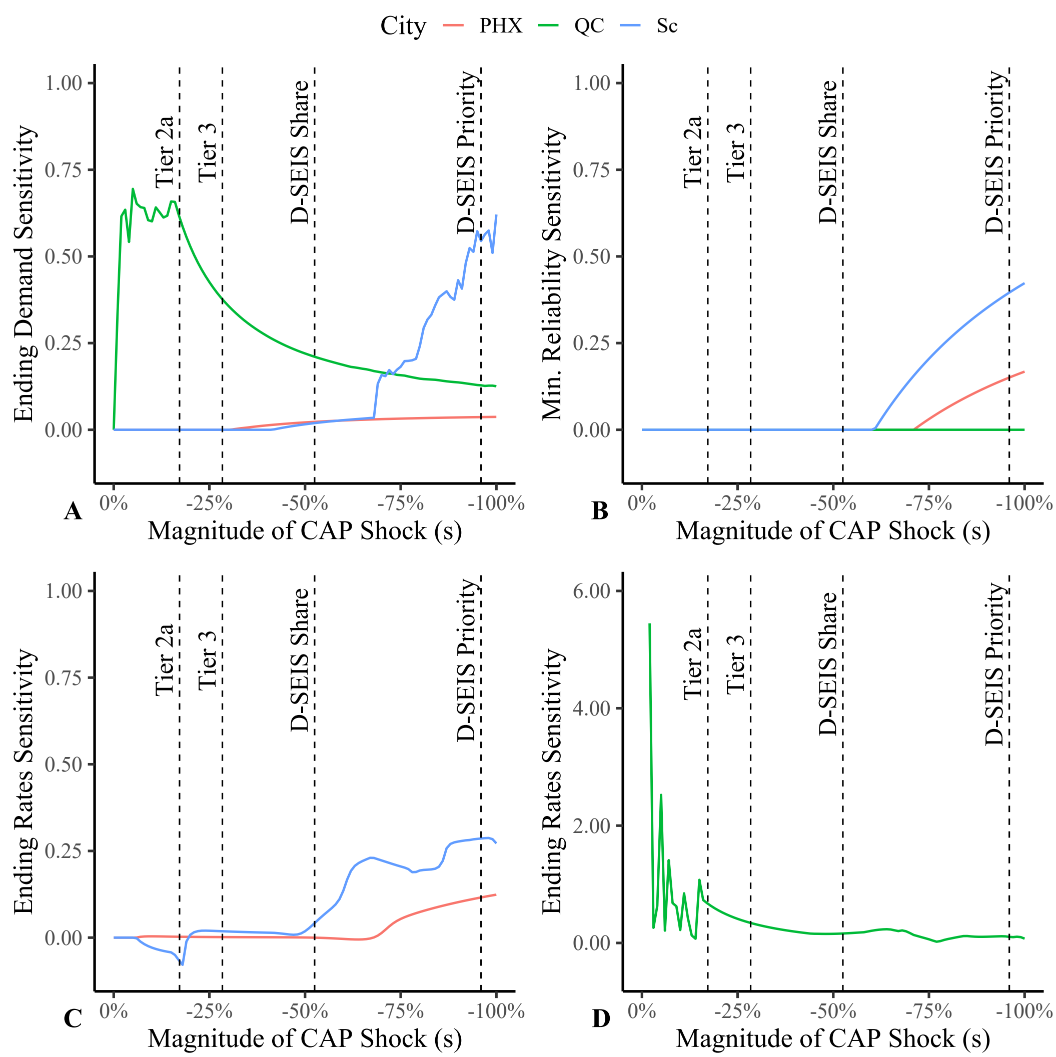

Figure 4. Effect of CAP shock magnitude (s) on the sensitivity of ending demand (a), minimum reliability (b), and ending rate pressure (c-d) experienced by each city with other parameters at the baseline setting. Mean reliability experienced minimal change and is therefore, not depicted here. We distinguish Queen Creek's rate sensitivity (d) due to its larger scale.

able range of s. With more institutional costs, the PIP allows more error to accumulate before acting.

Low institutional costs in both rate-setting (e.g., $\epsilon_3 < 0.6$) and investment (e.g., $\epsilon_2 < 0.35$) do not significantly impact reliability (Figures 5a-d). For Phoenix and Scottsdale, investment institutional costs increase the sensitivity of average reliability more than minimum reliability (Figure 5a) because the CAP shock is sudden and the investment lag time (τ_k^i) is independent of ϵ_2, making the "worst year" primarily dependent on s. ϵ_2, thus, affects how quickly the system bounces back to a desirable reliability, which is reflected in the average reliability metric.

Queen Creek's precarious position, explained above, necessitates major investment and rate increases, so slowing their response increases their reliability sensitivity by orders of magnitude more than Phoenix and Scottsdale (Figures 5b,d). In the rate-setting action situation (Figure 5d), high ϵ_3 places Queen Creek in a demand curtailment trap where they must continuously cut demand as they fail to keep up with 2010-2020 growth and are left with not enough revenue to fund needed investments (illustration in Supporting Information).

The reliability sensitivity curves for investment and rate-setting have opposing concavities (Figures 5a-d). For investment, the concave up shape of the average reliability sensitivity curve reflects the fact that increasing ϵ_2 increases the range of perceived shortages that will *not* generate action from the PIP, so each marginal increase in ϵ_2 has a larger effect on average reliability (Figures 5a-b). For rate-setting, the concave down shape in both reliability curves suggests that when the city is more hesitant to increase rates but still willing to invest, the city funds partial investments within the existing rate structure (Figures 5c-d). These sensitivity curves eventually converge to a "pass through" level where the shortage signal affects the city's reliability at the same rate (recall, sensitivity is a slope of output change to input change).

The slowing effect of institutional costs, in both rate-setting and investment, can benefit the citizen burden metrics: demand and rates (Figures 5e-h). Slowing investment prevents the implementation of demand management programs and prevents the need to increase rates (Figures 5e-f). Slowing rate increases does not affect demand sensitivity in Phoenix and Scottsdale significantly (Figure 5g), but intuitively, decreases rate sensitivity.

However, this trade-off between reliability and citizen burdens is not one-for-one. For each city, there are ϵ_j values that decrease rate sensitivity with minimal impact on reliability (e.g., $\epsilon_3 = 0.3$ for Scottsdale). Rate-setting institutional costs, though, can be detrimental for citizen burden metrics. When $\epsilon_3 \in [0.25, 0.45]$, Phoenix experiences higher rates because Phoenix was slow to increase rates during the 2010-2020 period, leaving them with more debt by 2024 and therefore, in need of a larger rate increase to cover shock-induced investments (Figure 5g). For Queen Creek, $\epsilon_3 \in [0.5, 0.7]$ forces partial investments before the groundwater crisis, which then requires higher demand cuts when they run out of credits (Figure 5h).

4.2.2 Institutional Flexibility

Varying the response elasticity, λ_j, did not significantly alter reliability or the ending demand when institutional costs, ϵ_j, are kept at their baseline no-costs level. This is likely because the CAP shock and Queen Creek's groundwater crisis are at high enough magnitudes to produce error that exceeds Δe_j, leaving no concern for partial response when $\epsilon_j = 0$. However, when these high magnitude events occur, adding flexibility to rate-making (lowering λ_3), can decrease the ending rates sensitivity (Figure 6b) by lowering the immediate rate increase, which can temporarily hurt the debt service goal but allows the PIP to gradually raise rates as the operational context evolves. Lowering λ_3

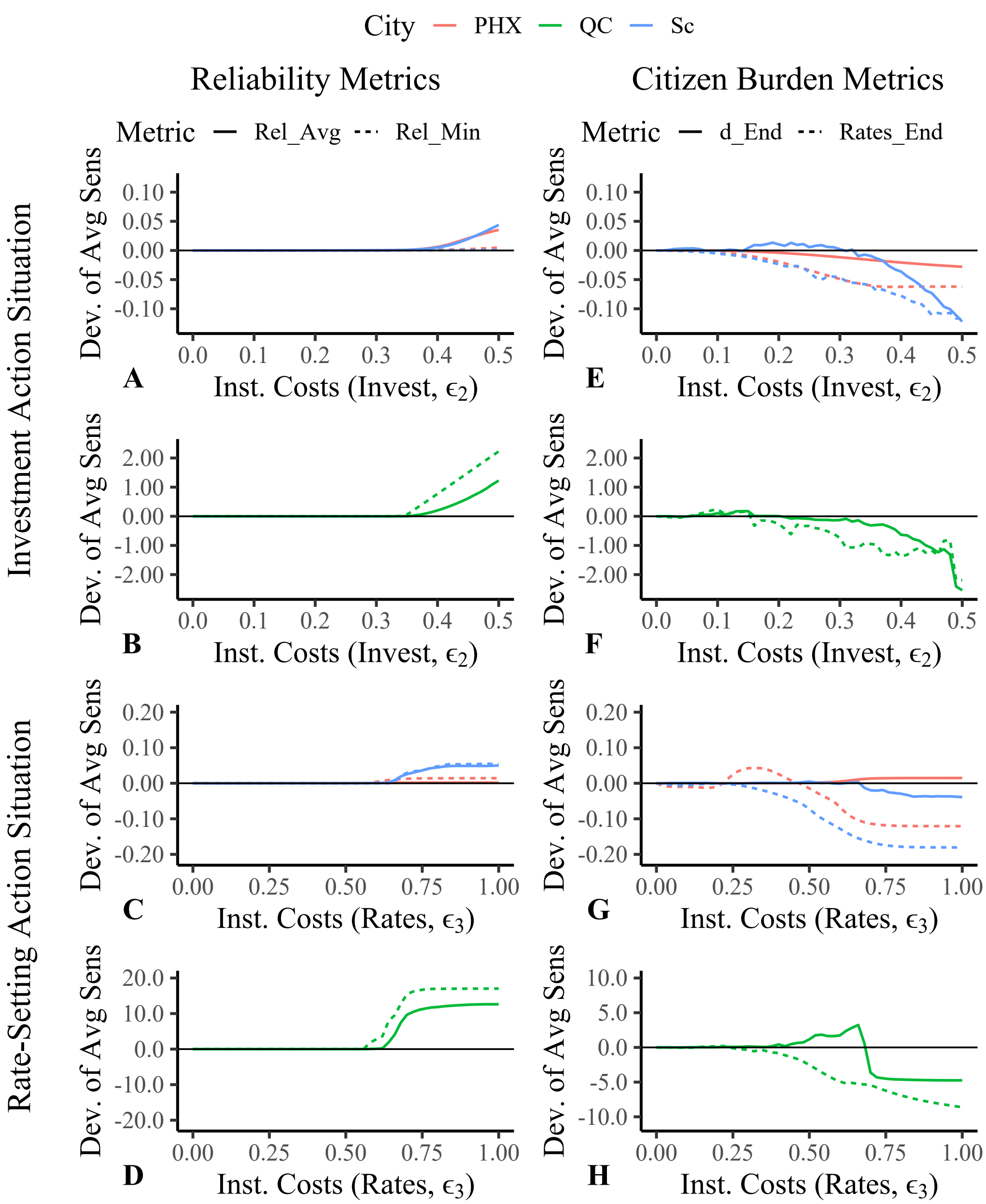

Figure 5. Sensitivity analysis results for varying institutional costs in investment (ϵ_2) and rate-making (ϵ_3) for each city. Sensitivity of each performance metric is presented on the y axis by the deviation of the average sensitivity from the average sensitivity associated with the baseline setting ($\epsilon_{2,3} = 0$) over all CAP shock magnitudes where $s < -0.6$ for Phoenix and Scottsdale and $s > -0.2$ for Queen Creek.

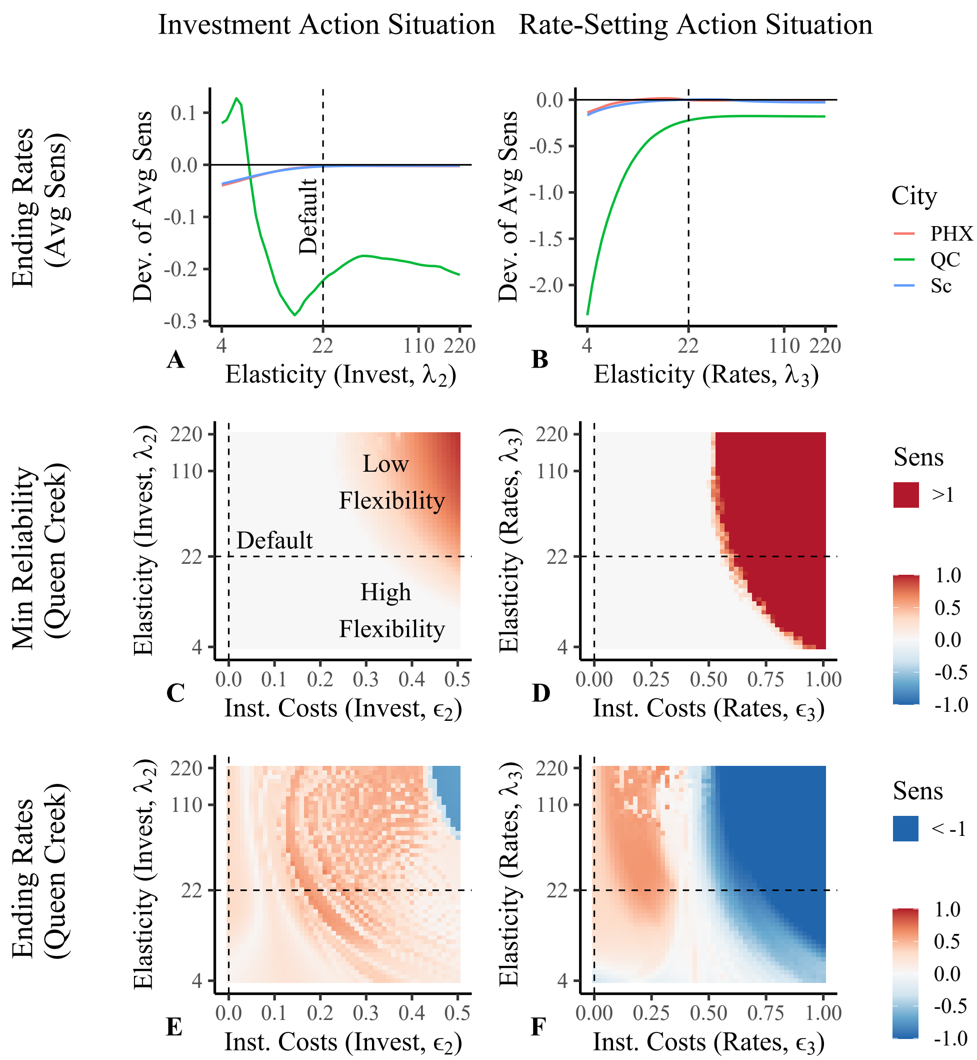

Figure 6. Sensitivity analysis results for varying institutional flexibility in investment (λ_2) and rate-making (λ_3) for each city. First, (a-b) the deviation of the average sensitivity of ending rates from the baseline setting ($\lambda_{2,3} = 22$) over all CAP shock magnitudes where $s < -0.6$ for Phoenix and Scottsdale and $s > -0.2$ for Queen Creek. Then, the sensitivity of minimum reliability (c-d) and ending rates (e-f) at the Tier 3 CAP shock ($s = -0.284$) given variation in institutional costs (ϵ) and flexibility (λ) in both action situations.

also allows the PIP to lower rates because the partial response region (Δe_j) exists on both sides of ϵ_j. Queen Creek's rates sensitivity curve for the investment action situation does turn positive when $\lambda_2 < 6$ because the partial investments caused by high flexibility ultimately sum up to a higher revenue need (Figure 6a).

Additionally, we investigate the interactive effect of λ_j with varying ϵ_j, keeping $s = -0.284$ (Tier 3 shortage). At this level, Phoenix and Scottsdale have sufficient operational capacity to buffer the shock, but Queen Creek must take investment action (Figure 4). In each action situation for Queen Creek, the slowing effect of institutional costs on reliability can be overcome with added flexibility (Figures 6c,d), which add needed partial responses when the action threshold would otherwise preclude the PIP from responding. On the other hand, adding flexibility to low-costs rate-setting situations (e.g., $\epsilon_3 \in [0, 0.25]$) can ease the ending rate pressure through gradual rate increases (Figure 6f). There are complex interactions between investment and rate-making where partial responses may increase overall investment and revenue needs in the long-term (especially at the borders of the color regions in Figures 6e,f), but complete investigation of this interactive effect is beyond the scope of our initial study.

5 Discussion

Our application of the UWIIM yields three important takeaways regarding the interaction of operational and political-economic feedback in the response of coupled infrastructure systems to changing environmental inflows.

5.1 The Inescapable Role of Redundant Operational Capacity

Even though political-economic features, like institutions, can influence the way an urban water system responds to environmental changes, the operational capacity and in particular, the presence of redundancy, sets the bandwidth of disturbance that the system can tolerate *before* requiring political-economic action. Redundancy is a well-established feature of robust systems (Anderies & Janssen, 2013; Biggs et al., 2012), and our baseline analysis of the PMA cities before institutional friction variation highlights the need to clarify the operational context before investigating political-economic considerations.

In the PMA case, the presence of non-CAP supplies, SRP water and groundwater, defined the range of CAP shortage cities could manage before requiring additional investments and rate increases, and in the current PMA management context, this is a prominent focus. Phoenix, for instance, has invested in flexible delivery system infrastructure to ensure that they can use their additional SRP water throughout their service area. The non-renewable nature of groundwater, though, has placed Scottsdale in a more sensitive position, assuming they can distribute the groundwater throughout their service area, to buffer CAP shocks. In our scenarios, large CAP shocks beyond the D-SEIS shortage sharing option force Scottsdale to ultimately use up their groundwater credits within thirty years, which would then require more serious action, potentially including major demand cuts. Queen Creek is groundwater dependent, but they are pursuing alternative renewable water sources to achieve this needed redundancy (ADWR, 2022b).

5.2 CIS Robustness & Political-Economic Feedback

When the system's operational capacity cannot tolerate a disturbance, political-economic action is necessary. Given our critical infrastructure systems, like urban water, face an uncertain future in the Anthropocene (Chester et al., 2019), analysis must consider the multiple layers of governance, including, as presented here, the differing roles of operational and political-economic feedback. The UWIIM demonstrates the potential to weave political-economic considerations into the dynamics of human-water systems.

One political-economic consideration elevated by this manuscript is the dynamic implication of institutional friction (Jones & Baumgartner, 2005a) on CIS sensitivity to environmental shocks. Across all cities examined, adding institutional costs tended to increase the sensitivity of supply reliability when the shock necessitated political-economic action (otherwise, the existing operational capacity was able to cope), but our analysis points to city-specific ways that this complex relationship between institutional costs and operational context behaves. For instance, Phoenix and Scottsdale's higher operational capacity allowed them to maintain reliability when faced with low-to-moderate institutional costs (5a), but Queen Creek's immediate pressure to keep up with rising population, move away from CAGRD, and find alternative sources before it ran out of groundwater credits, necessitated major early action, making it more sensitive to anything in the institutional context that slowed the response. In fact, high institutional costs in rate-setting decisions, created a demand curtailment trap, identified in other socio-hydrologic studies of urban water systems (Rachunok & Fletcher, 2023; Kenney, 2014) where the city must continually cut demand to ration supply, but then loses potential revenue to support needed investments.

While institutional costs can make reliability more sensitive, they can benefit potentially competing objectives relating to externalities of investments like the rates or demand pressure placed on ratepayers. In fact, consideration of such externalities is likely one of the main reasons such institutional costs exist in the decision-making process (Deslatte et al, in press). Such performance-vulnerability trade-offs are a feature of complex social-ecological systems (Anderies et al., 2007; Homayounfar et al., 2018), and incorporating institutional information processing into human-water system models is a promising way to make these trade-offs apparent in the system's dynamics rather than serving as static decision parameters manipulated exogenously by the modeler.

5.3 The Interactive Effect of Institutional Flexibility

Even if political-economic actors are aware of the institutional costs associated with taking action, institutions often fail to specify exactly how an actor should respond to a particular problem, perhaps even providing conflicting direction. These situations can be termed "institutional voids" (Mesdaghi et al., 2022), and we attempt to capture their dynamic role through the response elasticity parameter.

For all cities, adding flexibility did not impact reliability significantly when there are no institutional costs, but, particularly when added to rate-setting decisions, flexibility can ease the burden placed on ratepayers. It generates partial rate increases that may temporarily violate debt coverage goals but decrease the rate burden over time if reliability is sufficiently managed and more shocks do not occur. Proportional control is often associated with abrupt, over-responsive action (Rodriguez et al., 2011), and our findings demonstrate that institutional flexibility can be conceptualized as a potentially helpful *integral* element to the control scheme to encourage a smoother response to sudden supply shocks. Additionally, when a system must deal with high institutional costs to taking major action, adding flexibility can improve reliability and rate pressure by opening up opportunities for much needed partial responses. We emphasize that this complex interaction between institutional costs, flexibility, and operating capacity speaks to the importance of considering institutional friction in the analysis of coupled infrastructure sytems.

5.4 Limitations & Opportunities

The UWIIM offers multiple opportunities for additional research on the relationship between operational and political economic feedback in human-water systems. Our focus on institutional friction bridges policy process theory with human-water systems, but additional policy process concepts can be investigated. Other iterations can consider competition between belief systems from the Advocacy Coalition Framework (Weible et al., 2018), richer institutional characteristics with the Institutional Grammar Tool (Siddiki et al., 2019), or the way actor participation in multiple action situations creates institutional cost spillovers with the Ecology of Games Framework (Berardo & Lubell, 2019). Once actor heterogeneity is considered, an agent-based model may be a more effective tool than our aggregate dynamical system.

The study did not consider the interaction effects between institutional friction and other institutional design parameters like goals (e.g., debt service coverage ratio) and choice constraints (e.g., maximum annual rate increase allowed). Analysis of these concerns, particularly the selection of supply and financial goals, may benefit from the risk of failure threshold choice analysis performed by multiple water resource models (Trindade et al., 2020; Zeff et al., 2016; Palmer & Characklis, 2009).

Finally, even though the UWIIM is not designed to be a decision support or predictive model, we defined the PMA cities to reflect the critical ways they vary in their operational capacity. We do not account for the complex firming contracts the cities may have to weather additional CAP shortages and any sudden water transfers from actors that have unused portions of their CAP allocation. Additionally, we do not incorporate new water sources like importing desalinated water.

Political-economic feedback provides a valuable opportunity for human-water systems modelers to enrich their understanding of information processing in complex social systems like cities and deepen the interdisciplinary ethos of socio-hydrology with insight from fields like policy process theory. In the Anthropocene, it is no longer sufficient to treat the political-economic processes that govern a CIS as exogenous parameters or endogenous rational entities that can be modeled in the same way as a pipe network. The UWIIM is one attempt to operationalize political-economic and operational feedback in a coupled infrastructure systems model, and we encourage adding additional considerations or the development of alternative models to further this much needed discussion.

Open Research Section

This version of the Urban Water Infrastructure Investment Model (UWIIM), written in Julia, all output data generated from model runs, and the R scripts used to create the published figures, will be published and made available on GitHub and HydroShare repositories once review comments are incorporated.

All data used to define parameters and initial conditions for the studied cases were calculated from publicly available databases (Supporting Information), which can be obtained from the citations noted in-text.

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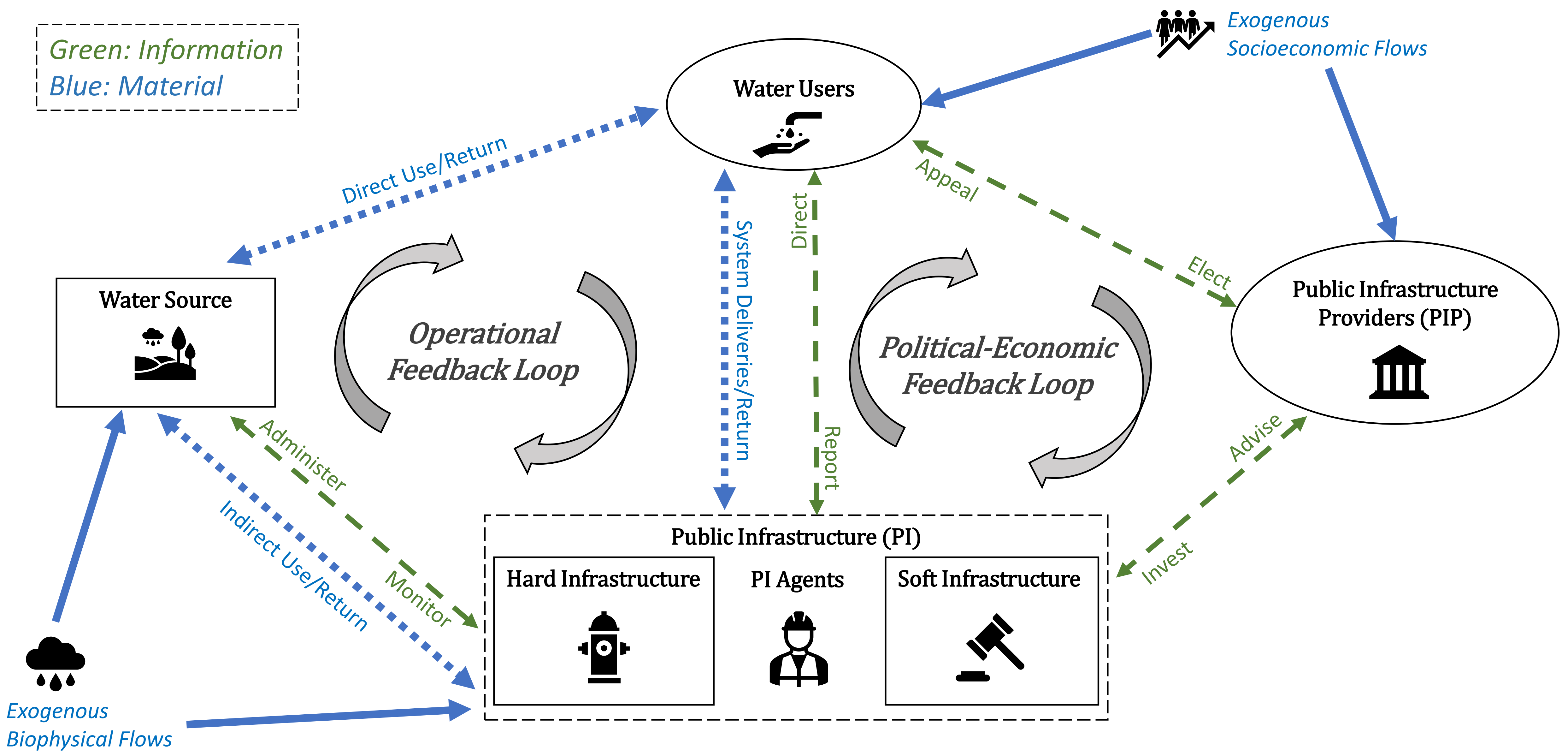
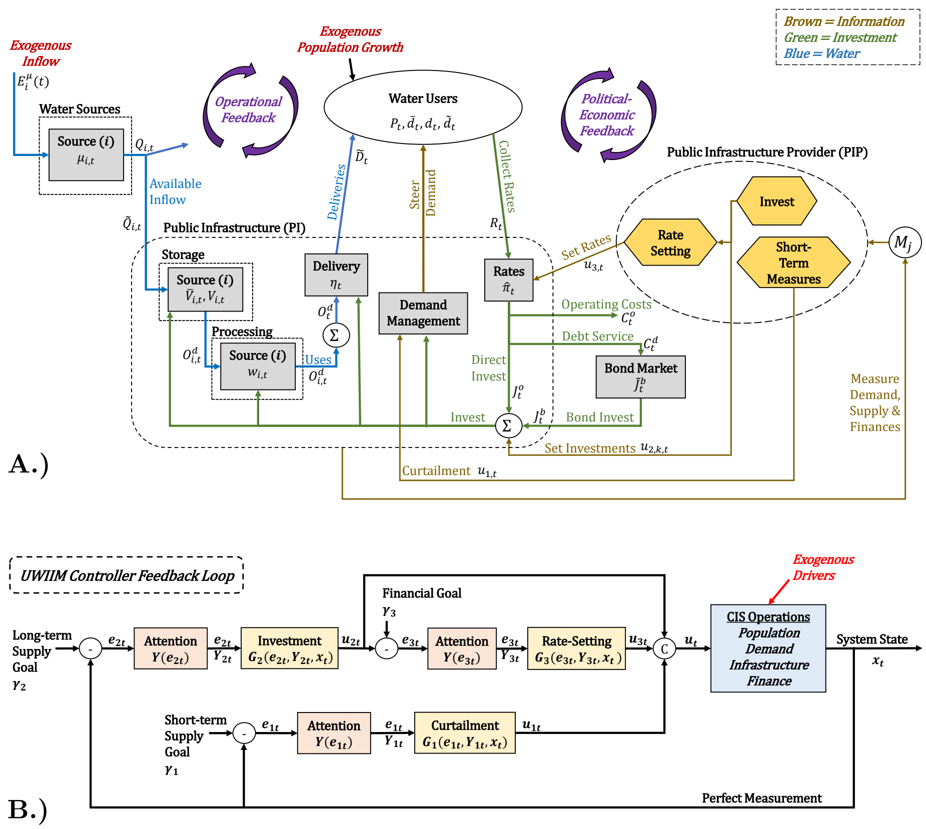
Figure 1.



Green: Information
Blue: Material
Water Users
Exogenous
Socioeconomic Flows
Direct Use/Return
System Deliveries/Return
Direct
Report
Appeal
Elect
Water Source
Operational
Feedback Loop
Political-Economic
Feedback Loop
Public Infrastructure
Providers (PIP)
Administer
Monitor
Indirect Use/Return
Advise
Invest
Public Infrastructure (PI)
Hard Infrastructure
PI Agents
Soft Infrastructure
Exogenous
Biophysical Flows

Figure 2.



Brown = Information
Green = Investment
Blue = Water
Exogenous Inflow
Exogenous Population Growth
Operational Feedback
Political-Economic Feedback
Water Users
Water Sources
Source (i)
Available Inflow
Public Infrastructure (PI)
Public Infrastructure Provider (PIP)
Storage
Processing
Delivery
Deliveries
Steer Demand
Collect Rates
Demand Management
Rates
Invest
Rate Setting
Short-Term Measures
Set Rates
Operating Costs
Debt Service
Bond Market
Direct Invest
Bond Invest
Uses
Set Investments
Curtailment
Measure Demand, Supply & Finances
A.)
UWIIM Controller Feedback Loop
Exogenous Drivers
Long-term Supply Goal
Financial Goal
Attention
Investment
Rate-Setting
CIS Operations
Population
Demand
Infrastructure
Finance
System State
Short-term Supply Goal
Curtailment
Perfect Measurement
B.)

Figure 3.

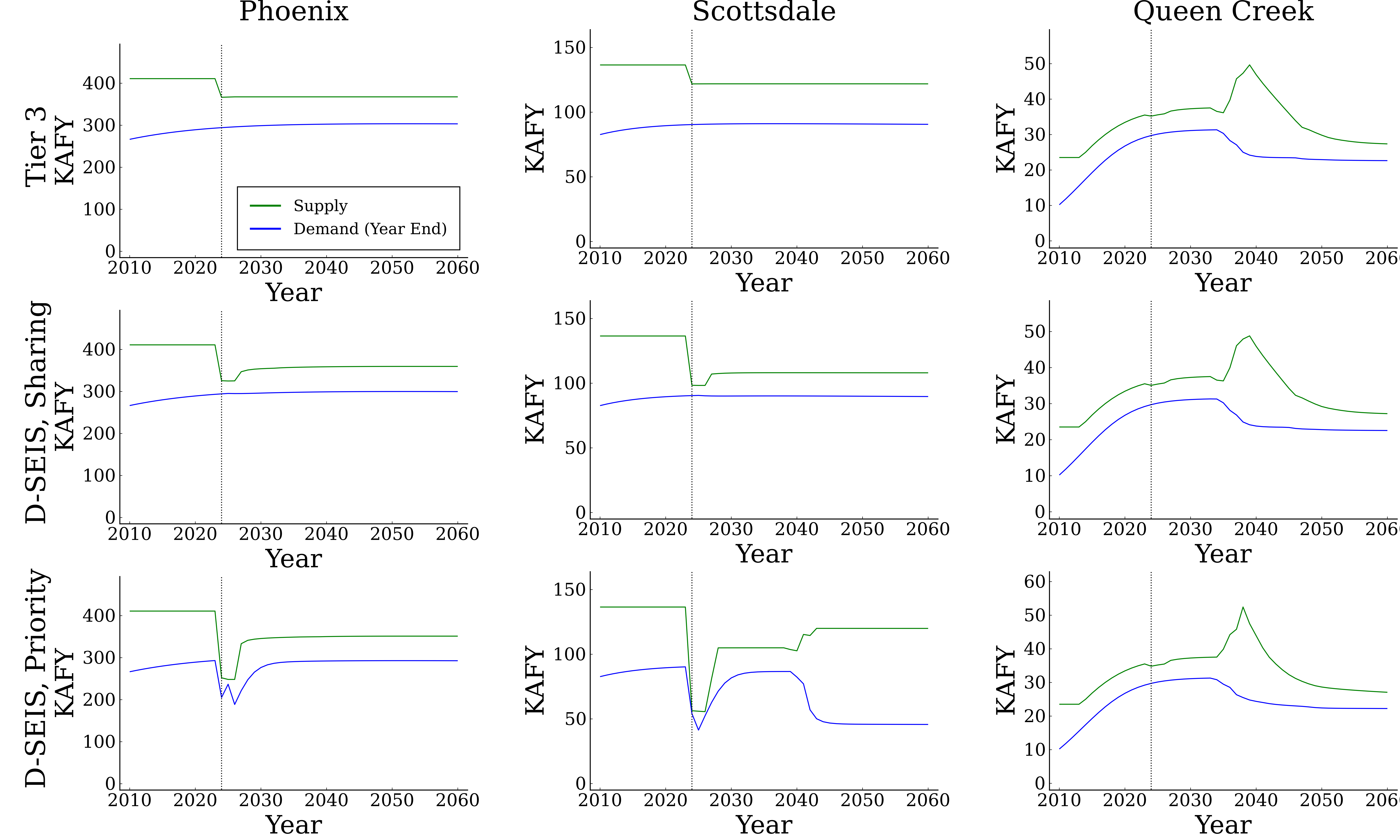

Phoenix
Scottsdale
Queen Creek
Tier 3
D-SEIS, Sharing
D-SEIS, Priority
KAFY
Year
Supply
Demand (Year End)

Figure 4.

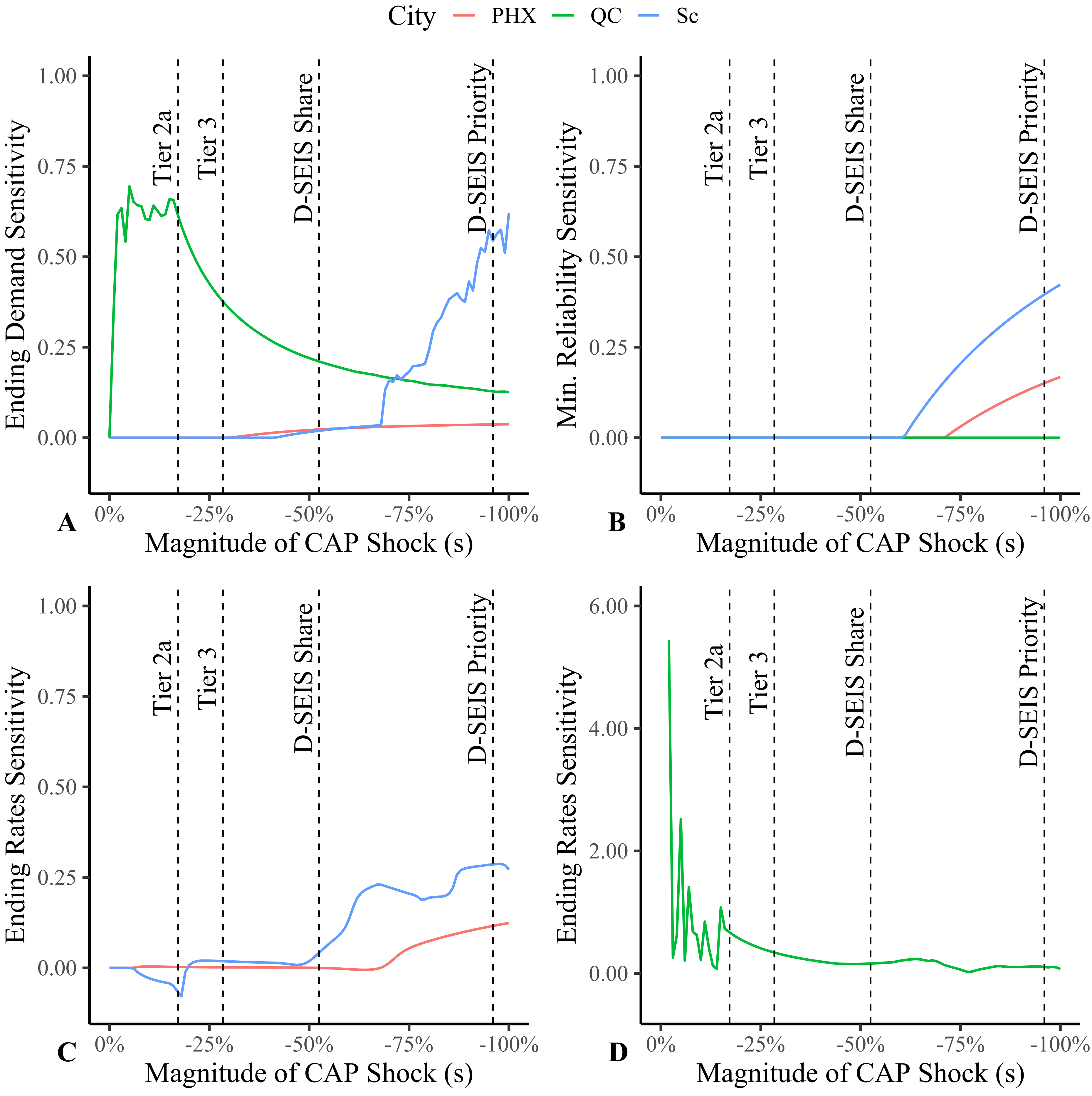

City
PHX
QC
Sc
Ending Demand Sensitivity
Min. Reliability Sensitivity
Ending Rates Sensitivity
Ending Rates Sensitivity
Tier 2a
Tier 3
D-SEIS Share
D-SEIS Priority
1.00
0.75
0.50
0.25
0.00
6.00
4.00
2.00
0%
-25%
-50%
-75%
-100%
A
B
C
D
Magnitude of CAP Shock (s)

Figure 5.

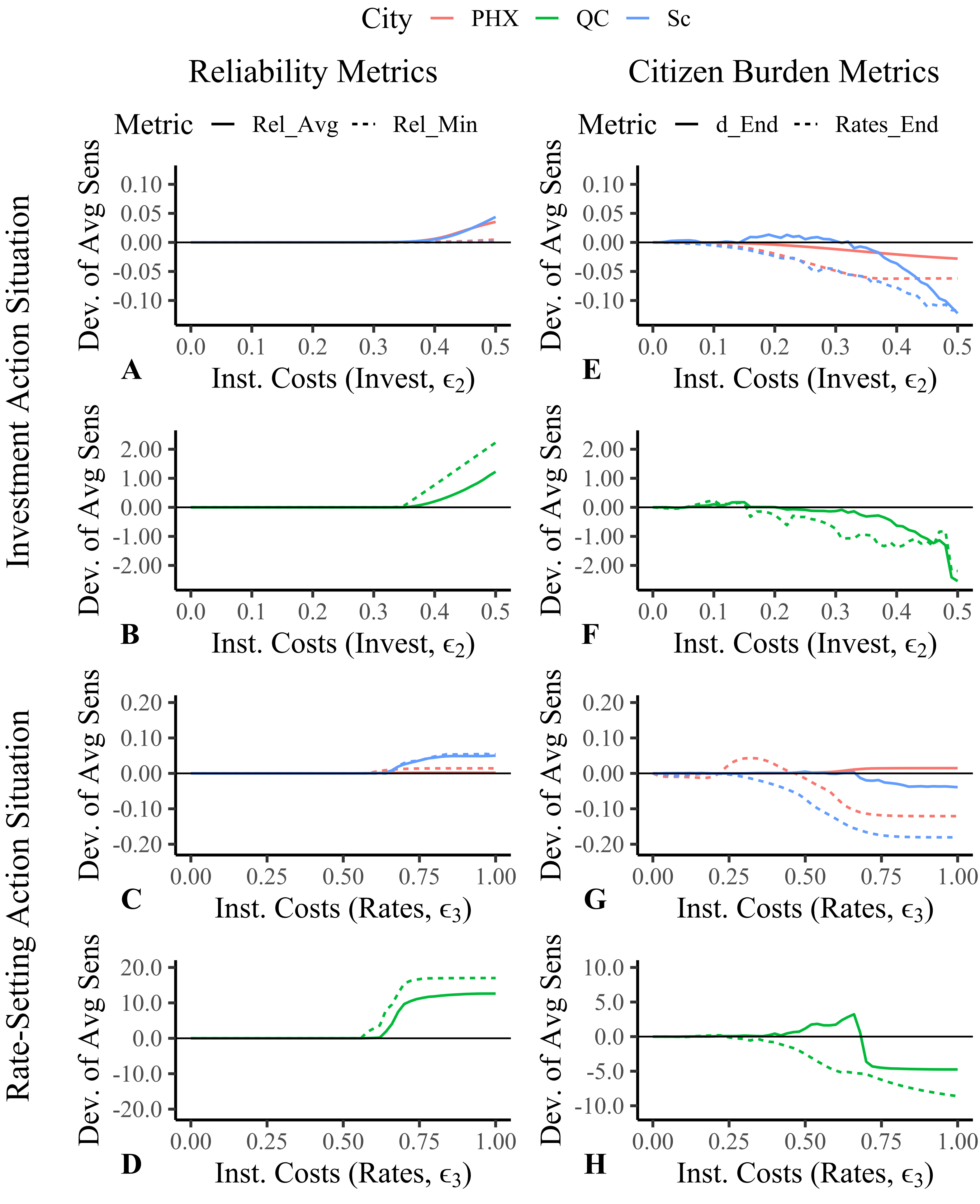
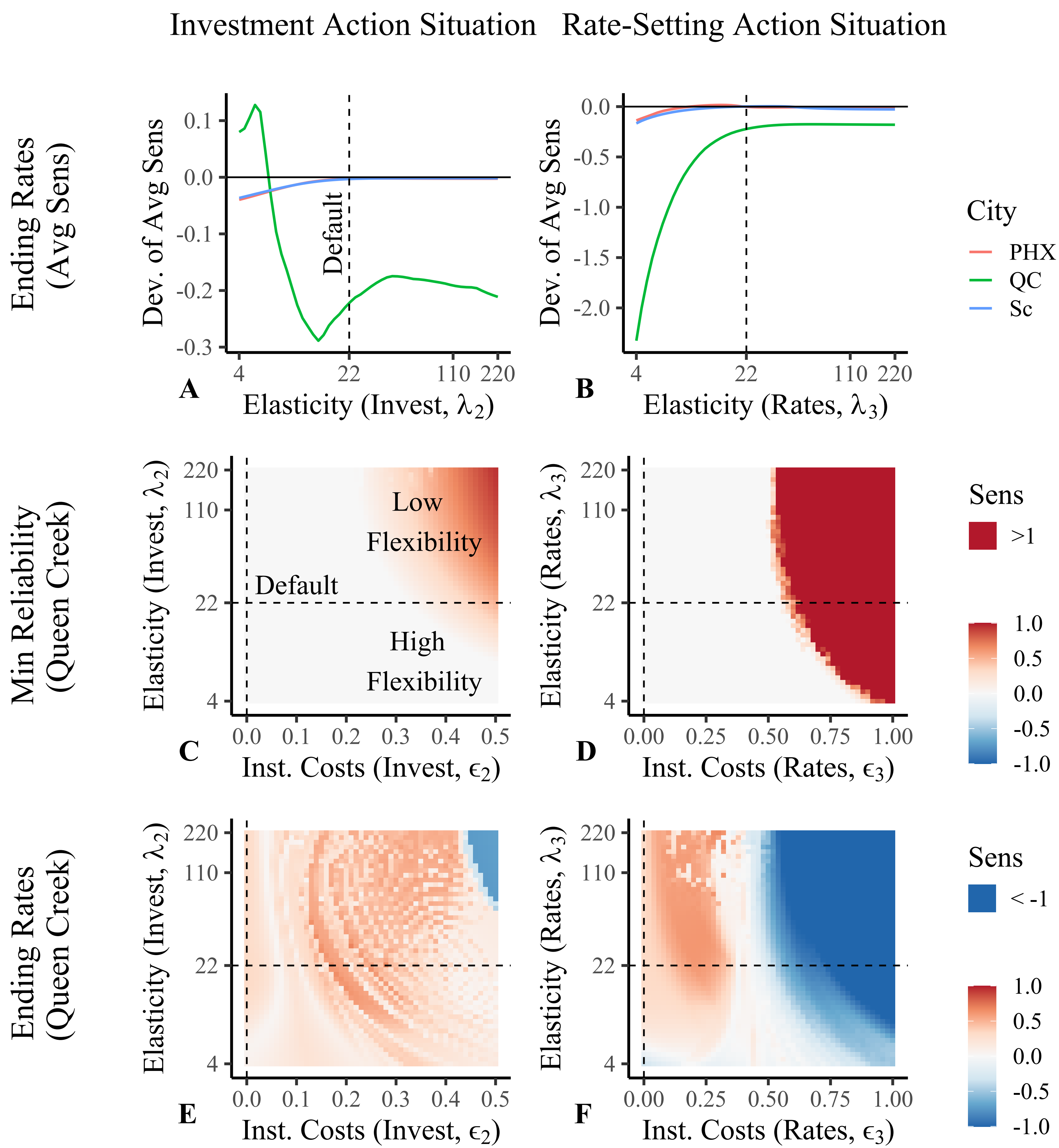

City PHX QC Sc
Reliability Metrics
Citizen Burden Metrics
Metric Rel_Avg Rel_Min
Metric d_End Rates_End
Investment Action Situation
Rate-Setting Action Situation
Dev. of Avg Sens
A
B
C
D
E
F
G
H
Inst. Costs (Invest, ϵ2)
Inst. Costs (Rates, ϵ3)

Figure 6.



Investment Action Situation
Rate-Setting Action Situation
Ending Rates (Avg Sens)
Min Reliability (Queen Creek)
Ending Rates (Queen Creek)
Dev. of Avg Sens
Default
Elasticity (Invest, λ2)
Elasticity (Rates, λ3)
City
PHX
QC
Sc
Low Flexibility
High Flexibility
Inst. Costs (Invest, ϵ2)
Inst. Costs (Rates, ϵ3)
Sens
>1
< -1
A
B
C
D
E
F