

Sustainability Transitions in Urban Water Management: Assessing the Robustness of Institutional Arrangements

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1. Introduction

Urban water management regimes include the physical water storage and distribution infrastructure of a city, as well as the governance arrangements that structure how resources and physical system components are utilized. As such, these regimes can be usefully characterized as coupled natural and human infrastructure systems. To maintain reliable outcomes within these systems under dynamic hydrologic conditions, cities and water utilities can make a variety of policy and management changes, such as raising water rates, implementing conservation measures, and investing in storage infrastructure. When these changes are significant and durable, and when they maintain or improve human standards of living while reducing pressures on the environment, they signal that the system has undergone *a transition toward sustainability* (Garcia et al. 2019; Malekpour, Brown, and de Haan 2015).

Transitioning toward sustainability implies that actors can identify some measure of desirable system performance and make decisions that move the system toward that measure. Performance is influenced by the complex interactions and feedback between the social components of the system (e.g. water users, regulators and other policymakers) and the natural or built infrastructure (e.g. snowpack, reservoirs, etc.). Thus, transitions toward sustainability are triggered by some confluence of natural, built infrastructure, social, economic and political factors. As many urban water management regimes across the globe increasingly face hydrologic stress, it is critical to systematically understand how these factors interact to hasten or inhibit transitions to more sustainable states.

The Robustness of Coupled-Infrastructure Systems framework (Anderies, Janssen, and Ostrom 2004) is one way to organize the often nonlinear and slow-moving forces underlying transitions, and consequently, system sustainability. In this chapter, we apply this framework to demonstrate how interactions among natural, human, and built infrastructure have impacted the performance of urban water systems in three U.S. metropolitan areas: Miami, Las Vegas and Los Angeles.

2. Robustness and Resilience in Urban Water Sustainability

Human and environmental systems are inherently complex. One may influence the other, often with emergent, nonlinear, and irreversible processes (Ostrom 2009; Scheffer et al. 2009). The

concepts of resilience and robustness are commonly used within theories that seek to explain the sustainability of such complex systems. This section highlights the value of these two concepts in relation to the capacity of urban water management systems to maintain adequate and reliable supply in the face of uncertainty and change.

We define *sustainability* as the connection of favored measures of system performance to decision-making processes likely to produce them (Anderies et al. 2013). Within urban water management, sustainability entails preserving the conditions for human well-being without damaging or depleting natural resources for future generations.¹ In other words, water managers make rate-schedules, infrastructure investments, and (re)distributive choices in specific decision-making contexts to attempt to achieve collectively-determined performance goals (Anderies et al. 2013). When some combination of climatic change, development pressure, or physical infrastructure decline threatens actual or future performance, users and managers may collectively change institutions -- defined as their rules and strategies for behavior -- in response (Muneepeerakul and Anderies 2017). Changes may be made to policies or actions assigned to specific actors, as well as to constitutional or collective-action decision processes themselves (Garcia et al. 2019; Ostrom et al. 1994). The decision-making context is often critical to the scope of these alterations of rules, norms, or strategies, and many of the contextual parameters are often difficult to quantify (Anderies et al. 2007; Anderies, Ryan, and Walker 2006).

For a water management regime to transition toward greater sustainability, decision-makers must generate knowledge about these system dynamics and apply it to design the governance institutions and physical infrastructure necessary to achieve or preserve performance (Anderies et al. 2013; Pahl-Wostl 2007). Within this conceptualization, *resilience* refers to the system-level attributes that allow it to bounce back from, or transform in response to, shocks (Carpenter et al. 2001). Resilient systems are often self-organizing and can include attributes such as a high capacity to learn and adapt. Conversely, *robustness* refers to an intentional control process of reducing the sensitivity of a system's outputs to any perturbations from its inputs. The robustness of a system depends on the feedback mechanisms or policies in place, and may allow the system to appear unchanged, based on some standard of performance, even when shocks occur. Distinguishing between resilience and robustness allows us to link the fluidity of systems to the stability required for maintaining a desired level of performance. In other words, the concepts of resilience and robustness help to connect the transformative characteristics and dynamism of complex systems to the types of performance goals and decision-making premises embedded within the concept of sustainability.

Many frameworks used to analyze these types of complex systems attempt to organize and clarify how rules and norms shape human behavior to influence collective action (Anderies, Barreteau, and Brady 2019; McGinnis 2011; Ostrom 1990; Siddiki et al. 2011). The most well-known is the Institutional Analysis and Development (IAD) framework developed by Elinor Ostrom and her colleagues (Ostrom 2011). The IAD focuses on "action situations" in which

¹ <https://www.epa.gov/sustainability/learn-about-sustainability#what>

individuals and organizations collectively address shared-resource problems. Their outcomes are evaluated via “fast feedback” processes that may lead to re-evaluations and adjustments intended to enhance system robustness. However, because the IAD treats the exogenous variables that influence action situations (i.e. biophysical conditions, community attributes, rules-in-use) as static, it fails to account for slower system changes that affect system resilience over time and across multiple action situations (Anderies, Janssen, and Ostrom 2004; Anderies, Barreteau, and Brady 2019; Muneepeerakul and Anderies 2017).

Building on the IAD, the Robustness of Coupled Infrastructure Systems (hereafter, “Robustness”) Framework (Figure 1) was developed to isolate slower-moving system dynamics that evolve over time in a coupled infrastructure system (CIS). Slow feedback, for example, may include changes to sources of water stress, shifts in public awareness of factors underlying droughts or other supply issues, and the effects of higher-level regulations placed on water utilities’ operations. To understand the processes through which these slow feedbacks affect system resilience, the Robustness Framework explicitly attends to the interactions among the various system components.

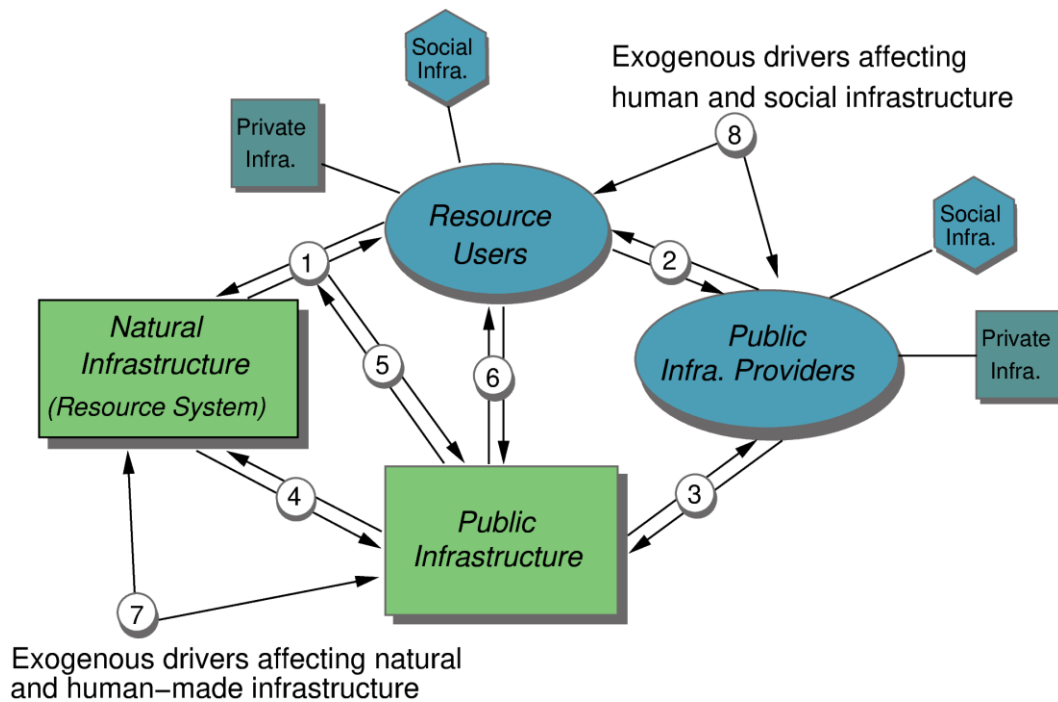


Figure 1: The Robustness of Coupled Infrastructure Systems Framework (adapted from Deslatte et al., Under Review).

In the Robustness Framework, the IAD’s “biophysical components” become the Natural Infrastructure (NI), such as waterways, and “hard” Public Infrastructure (PI), such as reservoirs. The IAD’s “attributes of the community” are regrouped into Resource Users (RU), Public Infrastructure Providers (PIP), and some elements of the “hard” PI (e.g water storage infrastructure or flood control systems). The IAD’s “rules-in-use” are re-grouped as “soft” PI

(such as regulatory processes or bureaucratic culture). The numbered arrows between the components signify flows of information, resources, or authority in the system. Additionally, two types of disturbances are considered within the Robustness Framework: external disturbances such as floods, droughts, and climate change, which act upon the natural and human-made infrastructure (link 7); and socioeconomic (internal) changes such as population growth, economic recessions/depressions, or political shifts that impact resource users and social infrastructure (link 8). Robustness within this framework links the feedback controls that water managers use to preserve system performance -- and thus the hidden fragilities to novel stressors inherent in feedback systems -- to system-level dynamics that characterize resilience. For example, designed feedback (strategies, policies, indicators) aimed at managing high-frequency (inter-annual or inter-decadal) variations in water supply can create fragilities to low-frequency variations (e.g. 100-year floods). Further, such feedback may mask critical performance variation, in turn suppressing learning processes and reducing resilience.

3. Analytic Approach: Periods of Accelerated Change in Three U.S. Cities

In the sections that follow, we draw on the Robustness Framework to better understand the drivers of urban water management transition in three U.S. cities: Las Vegas, Los Angeles, and Miami. External shocks and slow endogenous changes combine to challenge water supply in these cases. City level responses included both incremental changes to existing policies and infrastructures, as well as the creation of new strategies. Applying the Robustness Framework facilitates a better understanding of whether, and why, these responses reduce or increase resilience.

Each of the three selected cities experienced water supply threats and undertook significant water management changes during a similar period, making them useful similar systems to compare (Garcia et al. 2019; Seawright and Gerring 2008). We constrain our analysis for each city to the period of 1991-2014 to hold a variety of factors constant (i.e., economic cycles, national-level regulation and available technology). Guided by existing theories that elucidate drivers of transition in urban water systems (Hughes, Pincetl, and Boone 2013), we collected data on the hydrological, financial, social and institutional conditions of each city and its water utility during the study period. We then analyzed longitudinal trends in these data using a variety of metrics, as described below.

To conceptually map urban water systems using the Robustness Framework, we identify PIPs as the water boards, commissions or councils that develop utility policies for water supply, transmission, distribution and conservation, as well as the regulators or managers who implement and evaluate the policies. The NI consists of the water resources, including surface and groundwater. The primary RUs in each case are municipal water customers that use water in residential, commercial, and industrial applications. The PI comprises both “hard” infrastructure (wellfields, storage reservoirs, pump stations, transmission and distribution mains) and “soft” infrastructure (rules, norms and strategies), which create the circuitry for governing, managing, and enforcing resource constraints.

Characterizing Robust Controls

For each case, we identified one or more periods of accelerated change (PoAC), defined as spans of time when numerous, concentrated management or policy changes occurred (Garcia et al. 2019). Data used to detect these changes include interviews with water utility staff, utility Comprehensive Annual Financial Reports, water supply and demand data, regulatory documents such as consumptive use permits, and media. PoACs may indicate transitions toward more sustainable water use because the system has moved beyond incremental adaptations to disturbances and toward new “pathways” as old ones become untenable (Anderies et al. 2013; Treuer et al. 2017). However, a PoAC does not mean these systems have become more resilient: while feedback processes have prompted clustered water policy changes aimed at meeting some performance goals, systems can become more vulnerable to novel shocks as they increase their robustness (Anderies 2003). As such, we characterize the events comprising the PoACs as “robust controls” that function at the operational level to generate and feed information back throughout the system.

Rules for Governance in Urban Water Regimes

Governance is the process by which rules, norms and strategies for influencing behavior within a policy area are developed, applied, interpreted and reformed (McGinnis 2011). Governance arrangements are shaped by the boundaries of the resource system, the cultural and political attributes of communities, how costs and benefits are divided among users, and the functionality of available monitoring, enforcement and dispute resolution activities (Blomquist, Schlager, and Heikkila 2004; Schlager and Heikkila 2011). Within these arrangements, rules are both the outcomes of prior interactions (via feedback) and the working components of an action situation (Ostrom et al. 1994). Contained in institutional statements, rules constitute the formal basis of *positions*, the *choices* assigned to them, the *scope* of outcomes for which they are responsible, the *information* provided to them, the *aggregation* of decisions into outcomes, and the *payoffs* within action situations (McGinnis 2011).

To characterize the governance arrangements in our three cases, we compiled a subset of institutional statements from state constitutions, statutes, city/county charters and ordinances (for detailed methodology, see Treuer et al. 2017). These statements represent the constitutional-choice level of water governance in each city, which legitimizes the collective-choice procedures for decision-making by PIPs. From this corpus of statements, we identified three types of rules that could be considered either authority, scope or boundary conditions, described below, because of the central role they play in shaping collective actions.

First, *authority conditions* within water utility governing boards pertaining to setting water rates, or how much users pay for water. This authority is typically captured in choice rules, which assign specific actions to positions. Variation in rate-making processes could ultimately influence important decisions about how RUs are informed of needs and how the PI is

maintained, expanded, or depleted. Second, *scope conditions* pertain to the set of outcomes linked to choices and actors. These may include statements which prescribe desirable or avoidable performance outcomes for resource use or address the equity of resource allocation and decision-making processes. Third, we identified the *boundary conditions* for entering and exiting positions on the governing boards of the PIPs. These positions may be appointed by unelected officials, appointed by the elected representatives of the city (the mayor or council), appointed by elected officials outside the jurisdictions (regional or state officials), or directly elected by residents. Different boundary conditions for entering and exiting board positions can shape the incentives of actors and how they interpret the information flows between PIPs and RUs. For instance, RUs may directly appoint (via elections) those who occupy PIP positions, or resource managers within the PIP may be more insulated from RUs when they are appointed by other elected officials. PIP positions that are directly elected may be more responsive to RU's demands or preferences on shorter-term issues, while appointed regulators may be less responsive and more focused on longer-term issues. Thus, variation in the boundary conditions for resource managers/allocators within the PIP may materially affect the quality of information or material flow in the system.

Feedback Through the Natural System

To capture the stress placed on the natural resource system, we calculated the Water Supply Stress Index (WaSSI) for each city over time (McNulty et al. 2007). A composite measure of biophysical and regulatory-driven water stress calculated as total demand divided by total supplies, the WaSSI accounts for water sources available outside of the city's physical boundary as well as legal and infrastructure constraints (Garcia et al. 2019). Water supply is defined as the amount of water that may be legally withdrawn and is accessible to the water provider, making supply a function of water rights/allocations, restrictions, and infrastructure capacity for a respective year (link 4). The supply term captures variations in the NI (e.g. streamflow, link 7) as they are moderated by hard PI (e.g. storage and conveyance). Demand data (annual finished water supply) and supply data were gathered from utility reports and historic water permits. The demand term captures changes in the RU, including the number of resource users and the intensity of their use (link 1).

Feedback Through the Social System

Dynamics between the social components of the framework, the RU and PIP, were examined by compiling a metric of public attention to water issues, defined as "changes in the public's attitude toward [their] resources" (Hughes, Pincetl, and Boone 2013). We measured this via a proxy for issue attention: newspaper coverage of water issues. To gather this data, The major newspaper in each case study city (*Miami Herald*, *Los Angeles Times*, and *Las Vegas Review-Journal*) was queried for the study period using an iteratively-developed set of search terms (for details, see Garcia et al. 2019). Media salience can reflect information flows between the governing body and resource users (link 2), as well as actions taken to co-produce infrastructure (link 6).

We also examined feedback between the PI and PIP itself (link 3) by measuring the change in financial net position of each utility over time. Net position is the sum of a utility's total assets (including capital assets, investments, and cash) minus total liabilities. Net position data were acquired from publicly-available utility financial reports. These data reflect both financial and physical assets and investments, which may be either aggregated components or capacity produced via the “hard” public infrastructure.

4. Empirical Examples: Examining the Robustness of Water Management Regimes

Here, we use the Robustness Framework to depict each case, understand and compare governance arrangements, and explore changes in robust controls in each system that may signal transition. A noteworthy observation is that, in all three cases, PoACs occurred without constitutional level governance reforms, suggesting each systems' adaptive capacity was sufficient to maintain crucial system functions. Additionally, in all three cases, the number of water users grew over the period while the water use per user decreased -- a key metric of system robustness.

Miami

Miami's CIS relies on local groundwater including the Biscayne Aquifer (primary source) and the Floridan Aquifer (backup supply). Surface and groundwater systems in Miami-Dade County are hydraulically connected, and surface water flows are carefully controlled to minimize both flooding and saltwater intrusion, major concerns for this low-lying coastal region (Hughes and White 2014). Human impacts, both local (draining the Everglades for land development) and global (sea level rise) have increased the risk of salt water intrusion.

The Miami-Dade Water & Sewer Department (WASD) emerged from a gradual governance evolution which began in 1972 when Miami-Dade County voters approved the creation of a county-wide water authority (link 6). The City of Miami transferred all city water and sewer properties to the authority in 1975. The authority was abolished in 1983 and absorbed by the county government (link 3), forming the current department. In Miami, WASD provides water to customers in Miami Dade County. The population of resource users grew from 1.9 million in 1990 to 2.6 million in 2014.²

Miami's governance structure features a higher number of scope rules governing collective decision processes than Los Angeles and Las Vegas (Garcia et al. 2019). In this case, the majority of Miami's scope rules applied conservation goals to RUs seeking development permits (link 2), such as regulating landscape-irrigation and use of high-efficiency plumbing fixtures for residential and commercial construction (link 1). Decision-making systems with greater

² <http://www.miamidade.gov/water/library/20-year-water-supply-facilities-work-plan.pdf>

discretion in how to achieve outcomes may enable quicker adjustments to changing environmental and political conditions (Novo and Garrido 2014). However, scope rules embedded in constitutional-choice institutional arrangements (the county charter) can also give these rules more enforcement power or legitimacy. Turning to the boundary conditions, the governance system also features a larger number of formal actors involved in collective-choice decisions. For instance, one actor, the South Florida Water Management District, is a regional body which oversees 16 counties, sets policy priorities, and permits and monitors WASD's use of their primary water source. While WASD is overseen by the elected county Board of Commissioners, SFWMD board members are appointed by the governor. The SFWMD also has distinct boundary conditions (gubernatorial appointment) likely shaping the incentives of its members.

Over the study period, the CIS experienced peak water stress (link 1) at two time periods (1993, 2006), and public attention to water issues (link 2) also peaked twice (2001, 2007). The one-year lag between water stress and public attention is indicative of the types of feedback which may trigger adaptation responses. Financial stress (link 3) peaked a year later in 2008, reflecting a decline in the net position (assets minus liabilities) of the utility. The alignment of water stress, public attention and financial stress within the CIS coincided with a number of changes to robust controls, which we identify as a PoAC (2006-2011): Miami implemented durable irrigation restrictions, rate increases, and conservation surcharges; new leak detection and rebate programs were created; and a water use efficiency plan was adopted. Perhaps the most significant adjustment affecting the robustness of the CIS was the approval by SFWMD of the utility's first consolidated (system-wide) 20-year pumping permit, which extended the utility's planning horizon.

Robustness was also affected by investments in the hard PI (link 3). WASD pumps groundwater from 20 well fields in the Biscayne Aquifer, a shallow porous limestone aquifer. Additionally, four previously abandoned well fields in the Floridan Aquifer have been rehabilitated.³ The utility operates three wastewater treatment plants, each of which have provided reclaimed wastewater since 2007. In 2013, WASD constructed an Aquifer Storage and Recovery pilot project with the capacity to inject 10 Million Gallons per Day (MGD).

In summary, the CIS augmented robust controls (both hard and soft PI) and reduced per-capita resource use. In the WASD service area, per capita water use decreased from 700 L/person/day in 1991 to 510 L/person/day in 2014 (Treuer et al., 2017).

Las Vegas

The Las Vegas CIS relies on the Colorado River as the primary water source. The Colorado River has been in drought since 2000. However, this drought is not just the result of hydrological cycles. Researchers estimate that from one-fourth to one-third of the water deficit is a result of above average temperatures, a trend that is likely to continue (Udall and Overpeck 2017). Some

³ <http://www.miamidade.gov/water/library/20-year-water-supply-facilities-work-plan.pdf>

now refer to this dry period as a period of aridification rather than drought as the drying trend is likely to persist as the climate warms (Overpeck and Udall 2020).

The governance arrangements have been largely stable since the Southern Nevada Water Authority (SNWA) was created by the Nevada Legislature in 1991.⁴ The SNWA is a regional wholesale utility which sells water, sets policy direction, and focuses on regional management; its board is composed of an elected official from each of the seven member utilities. One member utility is the Las Vegas Valley Water District (LVVWD), which was created by the state Legislature in 1947 to replace a private utility and curb groundwater use.⁵ The LVVWD operates at the city-level and services unincorporated areas. Unlike Miami's regional water district, the SNWA cannot impose water restrictions on RUs. Composition of water use has not changed over the study period (Garcia and Islam 2018). However, the population of resource users has grown from 670,000 in 1990 to 1.6 million in 2015.

The institutional structure of the Las Vegas CIS features a higher proportion of choice (or authority) rules specifying the actions assigned to actors - in this case, the Nevada legislature, resource users, the city council and utility. The choice statements assign actions primarily to the PIPs. The institutional statements themselves are less specific than in Miami, and do not specify many outcomes or activities which could produce them. Pertaining to boundary conditions, Clark County Commissioners, who are elected, also serve as the LVVWD Board of Directors, although the Las Vegas City Council oversees rate-making decisions. As with Miami, the countywide election of the PIP reflects some effort to scale representation on the governing board to the broader scope of resource demands. Related to scope conditions, the utility is authorized (via link 3) to provide "reasonably adequate service and facilities" and set rates (link 2) it deems "just and reasonable." Constitutional choice rules can be intended to legitimize the entities involved in collective or operational choice processes, and the Las Vegas CIS appears to do so via formalizing the process whereby residents (resource users) "may" attend any rate-setting hearing and provide evidence for or against a change (link 2).

Over the study period, the CIS experienced elevated water stress (link 1) from 2004-2009, peaking in 2005. Public attention to water issues (link 2) peaked three times (1991, 2003 and 2007) and lagged the increased water stress. Two periods of alignment occurred between water stress and public attention (2003-2004, 2007-2008). Meanwhile, financial stress (link 3) peaked from 2009-2012, reflecting hard PI investments and liabilities incurred. The alignment of water stress and public attention within the CIS coincided with a number of changes to robust controls during its PoAC (2005-2009): Las Vegas implemented durable watering restrictions, landscape codes and golf course water budgets (impacting link 1); it also began incorporating climate change and demand uncertainty into planning processes (links 2 and 3).

Robustness of the CIS was also likely affected by investments in hard PI. The SNWA draws surface water from Lake Mead, a large reservoir on the Colorado River operated by the US

⁴ <https://www.leg.state.nv.us/SpecialActs/67-SNevadaWaterAuthority.html>

⁵ <https://www.leg.state.nv.us/SpecialActs/62-LasVegasValleyWater.html>

Bureau of Reclamation. Las Vegas also benefits from flow regulation provided by upstream reservoirs, including Lake Powell. Las Vegas extracts water from Lake Mead via three intake structures, the third of which was completed in 2015 (link 3) to be used in the event the water levels dropped below the elevation of the existing in-take structures (link 1). In addition, Las Vegas pumps groundwater from a series of wells in the Las Vegas Valley.⁶ LVVWD also uses reclaimed wastewater, both directly and indirectly. LVVWD provides treated wastewater for golf courses, parks and other large-turf facilities requiring irrigation. Additionally, LVVWD discharges treated wastewater back to Lake Mead, where they earn return flow credits allowing additional withdrawals (Garcia and Islam 2018). The risk of surface water reduction increased over this period with declining storage in Lake Mead, but all other water sources remained stable.

Similar to the other cases, the CIS has made both hard and soft PI changes and reduced per-capita resource use. From 1990 to 2015, the per capita water use decreased from 1140 L/person/day to 682 L/person/day.

Los Angeles

Los Angeles relies on a portfolio of surface, groundwater and recycled wastewater. Snowmelt from the Eastern Sierra Nevada Mountains is a significant water source. The snowpack provides natural storage, allowing the system to balance out of phase water demands and precipitation. Snowpack in the Eastern Sierras is projected to decline with warming projected under climate change (Bales, Rice, and Roy 2015). Snowpack also plays an important role in LA's other surface water sources, such as the State Water Project (Johannis et al. 2016). Intensifying wildfire is also changing the nature of CA's watersheds. Wildfire not only alters hydrology (temporarily lowering infiltration and evapotranspiration rates), but impacts water quality by increasing nutrient and metal fluxes (Rust et al. 2018). Los Angeles also depends on water from the Colorado River and is therefore subject to the same drought periods and drying trends described for Las Vegas.

The governance structure of the CIS -- centered around the Los Angeles Department of Water and Power (LADWP) -- is the oldest among the cases, founded in 1902 to end private control of the city's water supply. Pertaining to boundary conditions, the Los Angeles City Council oversees the LADWP Board of Commissioners, who make water-rate decisions (link 2) and are appointed by the mayor. Thus, unelected managers play a larger role in robust control choices. The CIS also displays more complex, multi-level regulatory arrangements. Each of LADWP's water sources has an independent regulatory entity. For example, groundwater is overseen at the basin level, while surface water rights are overseen by the California Department of Water Resources and State Water Resources Control Board, which also set high-level policies and requirements. The LADWP provides water to customers in the city of Los Angeles. The population of resource users has grown from 3.5 million in 1990 to 4.0 million in 2015.

⁶ <https://www.snwa.com/assets/pdf/water-resource-plan-printable-2019.pdf>

The institutional structure of the Los Angeles CIS features more actor types (14) than Miami (10) or Las Vegas (4), and includes an almost equal number of choice and scope rules. The institutional statements governing collective choice processes focus more on adjudication and enforcement of water rights (link 1), with procedural directions aimed at the state court system (link 3). They also spell out specific directives for the LADWP Board of Commissioners to grant water permits and fix rates (link 2), prescribe time and methods of payment (link 6), develop utility assets (link 3), and authorize decisions for “production and delivery” and water as well as conservation (links 1 and 4). Thus, more of the potential pathways for feedback are implicated at the constitutional-choice level, perhaps reflecting the complexity of water rights in the Western U.S. and the diversity of the CIS water supply portfolio.

The LA CIS relies on several types of hard PI to draw from local groundwater (12%), recycled water (2%), imported water from the LA Aqueduct (LAA) (27%), and purchased water from Metropolitan Water District (MWD) (59%).⁷ LADWP has well fields and structures to facilitate recharge across five groundwater basins. Contamination in the San Fernando basin in 2007 led to a reduction in groundwater availability. The city has used reclaimed water for irrigation since 1979, and its capacity for wastewater reuse increased 10 fold over the study period. Los Angeles has two sources of imported surface water: water the city controls from Owens Valley and water purchased from MWD. The city owns diversion licenses on streams in Mono Basin and Owens Valley and moves this water through two parallel aqueducts, collectively known as the LAA. There are no large storage reservoirs on this system, and as a result, deliveries vary substantially with climate cycles (from 67 million cubic meters to 617 million cubic meters between 1980 and 2015, link 7). Purchased water from MWD originates from either the Colorado River or the State Water Project. Water from the Colorado River is conveyed via the Colorado River Aqueduct and benefits from storage on the main stem such as Lakes Mead and Powell. The large scale of storage means deliveries are robust to short term hydrological fluctuations; however, they have been impacted by both changing operational rules and long-term drought. The adoption of the 2006 Consolidated Decree for example, confirmed that California is limited to 5,400 million cubic meters from the Colorado River, reducing MWD supplies available to Los Angeles (link 8). Water from the State Water projects is conveyed from the Sierra Nevada mountains through a network of canals, pumping stations and pipelines, and stored in 34 reservoirs to balance intra- and interannual hydrological variability (LADWP 2015).

Over the study period, the Los Angeles CIS experienced three water stress peaks (link 1) in 1991, 2008 and 2013; two public attention peaks (link 2) in 1991 and 2013; and a financial stress peak (link 3) in 2003. High water stress and public attention aligned in 1991 and again in 2007-2009 during its PoAC (2007-2010). This PoAC featured numerous robust control measures throughout the CIS: durable rate increases (impacting link 1); rebates for turf grass and conservation education programs (production via link 6); piloted stormwater capture and recharge projects (links 3 and 4); and planning for reducing dependence of imported water supplies (links 3 and 4).

⁷ <https://s3-us-west-2.amazonaws.com/ladwp-jtti/wp-content/uploads/sites/3/2019/07/29154703/2018-Briefing-Book-Web-3.pdf>

These intensified efforts allowed Los Angeles to meet state-mandated conservation targets during 2015-2017. From 1990 to 2015, the per capita water use decreased from 655 L/person/day to 432 L/person/day (Garcia et al. 2019).

5. Conclusion

In the three cases above, urban regions facing increased water stress made resource management adjustments to maintain system performance. All three cases experienced external changes, such as sea level rise, aridification, and groundwater contamination, impacting the NI and PI in ways that moved the system closer to the edge of its robust range (link 7). Further, external changes such as federal rulings on interstate water allocations and state-level regulation, imposed new rules on the PIPs (link 8) and challenged the robustness of the systems.

In response, the PIPs invested in changes to PI and NI and altered the rules structuring the interactions between the four key components of these CISs represented in the Robustness Framework. We identify PoACs when a cluster of these alterations are made. Identifying PoACs focuses the analysis on actions taken by the PIP to maintain robustness under changing conditions. The PIPs invested in hard PI (e.g. aquifer storage and recovery in Miami and a new intake structure in Las Vegas), and in recovering lost NI functionality (e.g. groundwater remediation in LA). A range of rule changes -- investments in soft PI -- were also observed, though not at the constitutional level. In all three cases, the PIPs adopted combinations of voluntary and coercive measures to control water demand (link 5 or 6), and modified planning processes intended to increase strategic management of the resource (link 3).

To advance their sustainability, the three cities both reinforced existing feedback loops and adopted new robust controls intended to buffer outputs from changes to inputs. For example, Las Vegas constructed a new deeper Lake Mead in-take structure, strengthening the existing feedback loop involving links 1, 4, and 6. Similarly, leak detection programs in Miami increase efficiency on the margins. In contrast, investments in all three cities to shift the perceptions and behavior of water users through link 6 and to alter planning processes to incorporate uncertainty and climate change through links 1, 2, 3 and 4, alter the structure of the system in ways that create new mechanisms to adapt the system to its environment. New approaches to the built environment can similarly create new mechanisms. For example, Los Angeles's strategy of capturing local stormwater to serve as a supplemental water source, and Miami's piloting of aquifer storage and recovery with reclaimed wastewater, created new opportunities for water management operations. Exploring transitions across Miami, Las Vegas, and Los Angeles illustrates the potential of the Robustness Framework to enable comparison across a diversity of cases and facilitate generalization on the redesign of robust controls as external conditions change.

However, the dynamics of coupled human and environmental systems are often unpredictable. The diversity of institutional arrangements is also a critical component of achieving sustainable

system performance. It remains to be seen if differences in institutionally-induced decision-making processes determine which types of robust controls are needed. However, by examining PoACs through the Robustness Framework, we can better understand how different CISs respond to a set of projected exogenous changes. When their respective PoACs result in sustained system performance, we can identify design elements which may be generalizable to other urban regions facing similar social and climatic pressures. One limitation of our analysis is that the three PoACs observed are fairly recent and each city continues to experience both exogenous and endogenous change. Therefore, it remains unclear if the PoACs, in addition to increasing near term robustness have either increased, or decreased, system resilience.

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