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AN EXAMINATION OF THE IMPACTS OF HURRICANE HARVEY ON WATER UTILITY OPERATIONS AND PLANNING

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BY THE COMMITTEE CONSISTING OF

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Abstract

Hurricane Harvey stalled over Southeast Texas for the better part of a week in August 2017. During that time, the Category 4 storm produced unprecedented amounts of rainfall throughout the region, causing extensive flooding in and around the major metropolitan centers of Houston and Beaumont/Port Arthur. This study seeks to understand how water utilities learn from such flooding events by engaging several utility managers from the area, as well as the control locations of Tampa/St. Petersburg and Pensacola, Florida, in semi-structured interviews focused on the innovations they have implemented since Harvey. Through a comparison of the innovations adopted in Texas to those implemented in Florida, the impact of the storm on water utility operations and planning is examined. Ultimately, it is found that utilities in both states have adopted an array of educational, financial, infrastructural, programmatic, and technological innovations since 2017. However, the reality that those water utilities affected by Hurricane Harvey have implemented more environmental innovations than their unaffected counterparts in Florida suggests that water utilities do in fact learn from flooding events. This finding has important ramifications for sustainability transitions theory and practice, as well as climate resilience efforts.

Keywords: Hurricane Harvey, water utilities, sustainability transitions, innovation, resilience

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Chapter 1: Introduction

Overview

As central actors in water systems, water utilities have significant influence in regard to how these systems transition to a more sustainable or resilient state (Gliedt & Larson, 2018). These sustainability transitions in water systems are most often the results of innovations made or adopted by individual water utilities, which can take many forms. For example, water utility innovations can include hard innovations such as upgrades to infrastructure, as well as soft innovations such as training programs for utility personnel. Additionally, water utility innovations can be precipitated by endogenous factors such as a desire to provide more efficient services, as well as by exogenous factors such as population or economic growth in the areas they serve.

Natural hazards can disrupt water utility operations in dangerous ways, but they also have the potential to provide windows of opportunity for them to innovate. Accordingly, this study seeks to examine how severe flooding events impact the innovations made by water utilities. It does this through the use of semi-structured telephone interviews with 21 water utility managers. Fourteen of these utility managers are from areas in Texas impacted by flooding from Hurricane Harvey in 2017, and the other seven are from the Tampa/St. Petersburg, Florida and Pensacola, Florida areas, which have not recently experienced any major flooding events. Interview questions seek to understand the types of innovations pursued by water utility managers in each location, as well as the factors that aid innovation and the barriers to the innovation process. By comparing the differences between the responses of utility managers from Texas and those of their counterparts from Florida, this study aims to deduce how the experience of severe flooding events impacts innovation and planning processes in water utilities.

This study contributes to a number of prominent domains of scholarship. Primarily, it helps advance sustainability transitions theory (van der Brugge *et al.*, 2005; Loorbach *et al.*, 2017; Sullivan *et al.*, 2017) through its examination of how water utilities innovate after severe flooding events, thereby transforming themselves to a more resilient state. Furthermore, it contributes to the growing academic discourse focused on coastal adaptation (Barnett *et al.*, 2014) by examining how water utilities in coastal regions are altering their practices to overcome the adverse consequences of climate change.

The results of this study can help water utilities become more resilient in the face of current and future climate change. By examining how water utilities learned from a severe flooding event, the project helps establish best practices for other utilities to follow when they face their own shocks in the future. It also illustrates how natural hazards provide a window of opportunity for water utilities to implement new practices and infrastructures, which can help them provide water to their users more efficiently and reliably than ever before.

Insights provided by this study will only become more salient with time. As climate change continues to alter our planet in unprecedented ways (Intergovernmental Panel on Climate Change [IPCC], 2014), natural hazards such as floods and hurricanes will only increase in frequency and magnitude (Emanuel, 2017). Since people rely on the continual supply of safe water provided by utilities, it is of utmost importance that they are able to respond to hazards such as these.

Context

On the night of August 25th, 2017, Hurricane Harvey approached landfall near Port Aransas, Texas as a Category 4 storm (National Oceanic and Atmospheric Administration [NOAA], 2017). Over the next week, Harvey stalled over the Texas coastline, pummeling the region with copious amounts of rainfall. As many as 56 inches of rain, reported in the town of Friendswood, fell in cities across Southeast Texas between August 25th and August 31st, 2017 (NOAA, 2017). This resulted in severe flooding throughout the region, including in the highly-populated Houston and Beaumont metropolitan areas.

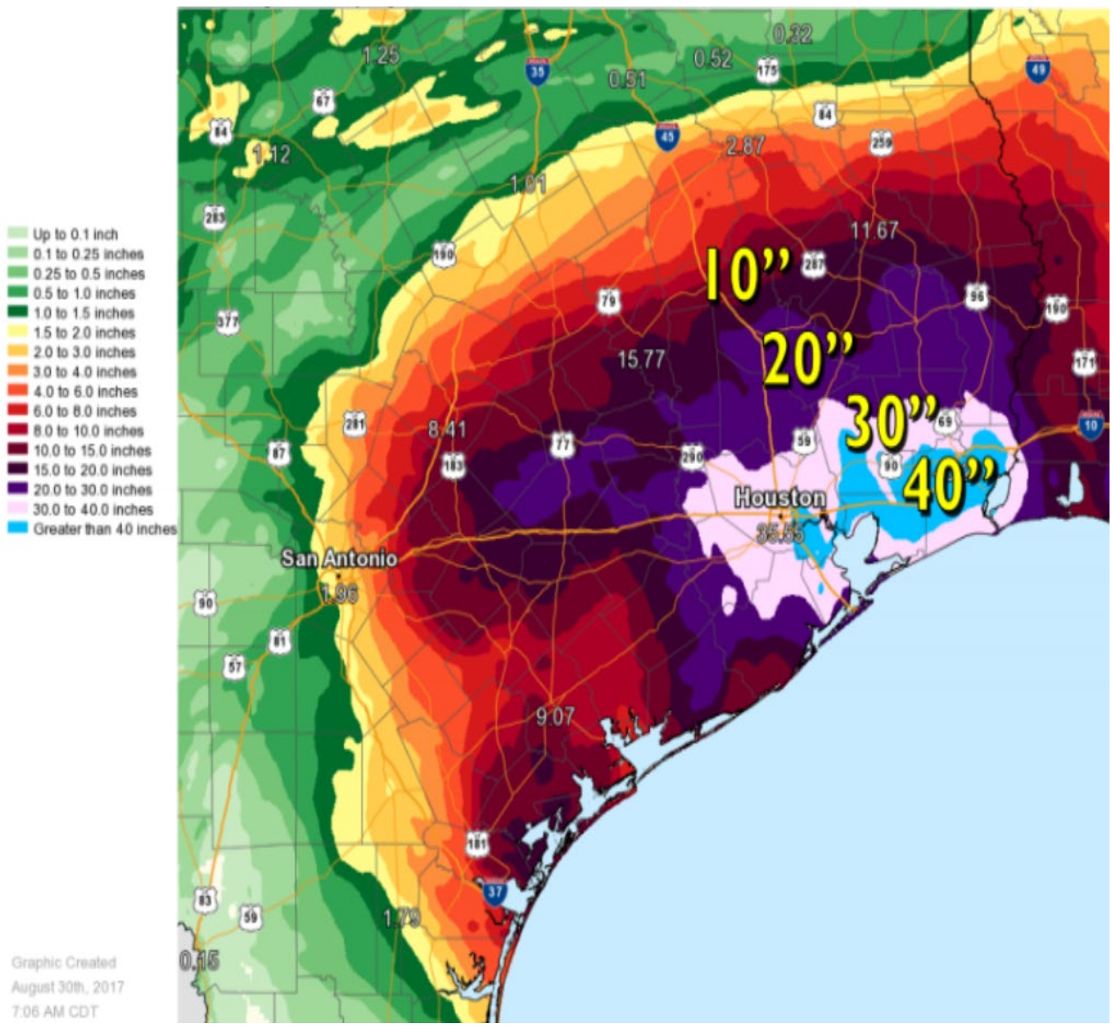

Figure 1 – total Hurricane Harvey rainfall accumulations (NOAA, 2017)

The impacts of the flooding induced by Hurricane Harvey were felt by many actors throughout Southeast Texas, including local water utilities (Force, 2019). These utilities struggled to continue to provide safe drinking water to area residents in the days after the storm, even as their facilities and infrastructure systems were inundated by flood waters and their personnel were forced to confront a challenge the likes of which most of them had never experienced. Once the flood waters receded, local water utilities were able to assess their damage and take the necessary steps to resume normal operations.

This project is focused on the work done by water utilities in Southeast Texas after Hurricane Harvey. It seeks to discern the decisions made by the managers of these utilities in the days, weeks, and months after the storm dissipated and the flood waters retreated. Specifically, it focuses on how these decisions and the managerial processes leading up to them were or were not informed by the experience of Hurricane Harvey. Ultimately, the goal of this study is to examine how water utilities learn from previous flooding events, including how they innovate differently from their counterparts that have not experienced severe flooding in at least the past 25 years. Do they innovate faster, and if so, by how much? What do their innovations tend to look like? For example, do they focus more on improving infrastructure, or on increasing the capacity of their personnel to respond to future hazards? Are water utilities that have recently experienced severe flooding more sustainable and resilient than others that have not?

All of these questions are answered through interviews with water utility managers. Two-thirds of these interviews take place with water professionals from metropolitan Houston, Texas and Beaumont, Texas, as these are major urban centers in Southeast Texas that were significantly impacted by the flooding caused by Hurricane Harvey. In addition, the remaining one-third of the interviews are conducted with water utility managers from metropolitan Tampa/St.

Petersburg, Florida and Pensacola, Florida. These sites were chosen because the areas largely resemble those in Houston and Beaumont due to their status as large coastal population centers along the shores of the Gulf of Mexico. However, the Tampa/St. Petersburg and Pensacola metropolitan areas differ from the Houston and Beaumont areas in that they have not experienced a severe flooding event anywhere near the magnitude of Hurricane Harvey in the last 25 years. To this end, Harvey produced 56 inches of rain in Friendswood, Texas in 2017 (NOAA, 2017), while Hurricane Sally dropped 25 inches in Pensacola in 2020 (NOAA, 2020) and Hurricane Irma yielded no more than 15 inches in the Tampa/St. Petersburg area in 2017 (Cangialosi *et al.*, 2018).

By comparing the interview responses of water utility managers in Texas with those of their counterparts in Florida, this study is able to help understand how experiencing Hurricane Harvey has caused water utilities in Southeast Texas to innovate differently than others. The innovations undertaken by utility managers in Florida provide a baseline against which to compare the innovations undertaken by utility managers in Texas. With a sufficiently large sample size of interviews, the study is able to isolate the impact of Hurricane Harvey on these innovations, and thus answer the research question and sub-questions listed below.

Research Questions

This project seeks to answer the following research question, as well as three sub-questions that fall within its scope:

- How are water utilities learning from previous flooding events?

- What innovations have water utilities impacted by Hurricane Harvey undertaken since the storm to increase their resilience?
- How do the innovations adopted by water utilities affected by Hurricane Harvey differ from those implemented by their counterparts that went unscathed by the event?
- Why is this important for sustainability transitions theory and practice?

Organization of the Study

The remainder of this study is divided into four additional chapters. Chapter Two provides a comprehensive review of the existing academic literature deemed germane to this study, organized into eight thematic domains ranging from broadly relevant to the subject matter at the beginning to precisely relevant to it at the end. Then, Chapter Three gives a detailed overview of the methodology employed to conduct the project. This is followed by Chapter Four, which presents the results of the study, usually in the interviewees' own words. Chapter Five concludes the study by putting its outcomes from Chapter Four into conversation with the scholarship introduced in Chapter Two, as well as answering the project's guiding research question and sub-questions.

Chapter 2: Literature Review

Introduction

The purpose of this chapter is to highlight the breadth and depth of contemporary scholarship pertinent to this study. As such, the following sections discuss the many academic papers that center on at least one facet of the nexus between climate change, urban water systems, innovation, and sustainability transitions. Since this study is primarily focused on distilling the role of Hurricane Harvey in inducing innovation in impacted water utilities across Southeast Texas, extra attention is paid throughout the literature review to both Hurricane Harvey and water governance systems in Texas. It is hoped that doing so will help to more accurately situate this study within its broader topical context.

This literature review aims to be systematic in its scope. For that reason, the popular academic software *Publish or Perish 7* was employed to locate papers for it. The software scoured Google Scholar for any academic articles containing the keywords “water utility” or “water utilities” in their titles, as well as the keywords “innovate,” “innovates,” “innovation,” “innovations,” “innovative,” “adapt,” “adapts,” “adaptation,” “adaptations,” or “adaptive” and "severe weather," "extreme weather," "natural hazard," "natural hazards," "natural disaster," or "natural disasters" anywhere within them. One hundred thirty-six such papers were located on March 24, 2021, although the vast majority were excluded from the analysis because they were focused on tangential topics of research and therefore only included the keywords in manners deemed indirect or unimportant. Ultimately, a few dozen articles were found to be useful for this study and were therefore included in this literature review. The rest of the materials discussed in the literature review were located organically between August 2019 and April 2021, and they were included after being deemed highly relevant to the topic of this study.

The body of this literature review is organized topically from broad to narrow. That is to say that it first examines academic papers that are more generally related to the focus of this study before moving on to consider ones that are increasingly germane to it as the literature review progresses. It is divided into eight sections, titled (a) *Overview of Water Governance and Policies*, (b) *Sustainability of Urban Water Systems*, (c) *Urban Water Transitions*, (d) *Urban Water Innovation*, (e) *Climate Change Preparedness of Urban Water Systems*, (f) *Urban Water Adaptation to Natural Hazards*, (g) *Challenges and Opportunities for Texas Water Systems*, and (h) *Hurricane Harvey and its Impacts on Southeast Texas*, respectively. The literature review then finishes with a brief summary section.

Overview of Water Governance and Policies

From crop irrigation to electricity generation and personal consumption, freshwater plays a myriad of essential roles in society. For this reason, innumerable policies and governance systems exist around the world to ensure its availability and quality in both the short and long term. Consumer confidence is one simple yet important ramification of these regulatory structures, as public perceptions of water quality are often not correlated with its actual quality since individuals tend to base their judgements solely on their water's physical properties (Ochoo *et al.*, 2017). Moreover, actors in water governance must be careful in their choice of strategies and policies since decisions meant to improve access to water at the local scale can precipitate environmental problems at the regional and global scales (Bhaduri *et al.*, 2016).

Political ecology scholars have written extensively about the hydrosocial cycle, a theoretical framework that views the circulation of earth's finite water resources as both a physical and a social process, and therefore as an inherently political one as well (Swyngedouw, 2009). Accordingly, water governance is shaped by power dynamics that cause democratic governance characterized by equitable and inclusive access to water to often be sacrificed in favor of autocratic governance or neoliberal governance, in which the allocation of water is controlled by either socioeconomic elites or the market, respectively (Swyngedouw, 2009). The hydrosocial cycle often functions within discrete spatial areas known as hydrosocial territories (Boelens *et al.*, 2016). One example of a hydrosocial territory exists in southern California, where the surface level of the Salton Sea has dropped significantly since the 1990s because conservation measures intended to provide additional water resources to the cities of Los Angeles and San Diego have led to decreased agricultural runoff into the water body, leaving it as a hydrosocial hinterland (Cantor, 2020).

Systems of water governance can take many forms, and they are influenced by a variety of factors and actors. For example, bureaucratic hierarchies, networks, and markets all have a unique role to play in national water policies, although hybrid systems involving all three are the most adept at solving complex water management challenges (Pahl-Wostl, 2019). Additionally, water governance involves both regulatory and everyday state practice (Ranganathan & Balazs, 2015). The former is based on top-down legislation that sets standards for water systems to meet, while the latter consists of ground level governance that depends greatly on the discretion of individual regulators (Ranganathan & Balazs, 2015). These modes of environmental governance can either remain stable or shift over time, depending on the pertinent physical circumstances, physical and social infrastructures, institutional settings, discourses, agencies, and shock events (Hegger *et al.*, 2020). Moreover, specific actors play key roles in water governance processes. Policy entrepreneurs are bureaucrats who involve themselves throughout the policymaking process in order to shape final water policies (Brouwer & Biermann, 2011). Similarly, community champions are motivated community members in urban water planning who connect water managers with the general population to refine complex ideas and negotiate compromises, thus directly involving stakeholders in the water governance process (Lindsay *et al.*, 2019).

The ways in which water governance is implemented can vary significantly between different countries around the world, with each offering unique insights and opportunities for comparison. China has long relied almost solely on a strict administrative command and control approach to the governance process, although in recent years they have begun to implement more market-based approaches, thus challenging the popular dichotomization of the two strategies as mutually exclusive (Jiang *et al.*, 2020). Additionally, India's national water policy has yielded less successful results than those of many of its continental counterparts because it has been hindered by a lack of integration of its water and environmental policies, significant overlap of responsibilities between different administrative units, and a limited concept of sustainability in its everyday practices (Khan *et al.*, 2019). This shows that water governance must be a highly coordinated effort between actors in order to find success. Similarly, Integrated Water Resources Management (IWRM) has proven to be a poor framework for national water policies in many countries within the Global South such as India since much of their rural populations access water through informal means, illustrating the imperative that water governance take local contexts into account (Shah & van Koppen, 2006). This is exactly what officials in Jordan and Israel are attempting to do as they work to update their mutual 1994 water agreement to better fit their current populations and alternative water sources (Talozi *et al.*, 2019).

No matter how well-intentioned, water policies can fail to produce their desired outcomes even in the Global North. This is certainly true in the United States, where cost-benefit analyses have consistently shown the costs of surface water regulations to outweigh their benefits (Keiser *et al.*, 2019). Moreover, water reform efforts in Australia's Murray-Darling Basin have done little to achieve the environmental improvements in the region that they originally set out to accomplish (Grafton, 2019). This is despite the billions of dollars that have been spent on the reforms since 2007, and the use of these reforms as a blueprint for other countries struggling with water insecurity (Grafton, 2019).

Water services have traditionally been the domain of the public sector, although they have increasingly moved into the hands of private companies over the past few decades as fiscal austerity has taken root in many local governments. Indeed, the fraction of the world's population receiving water from private companies increased from 5% to 12% between 2000 and 2012 (McDonald & Swyngedouw, 2019). However, recent dissatisfaction with the privatization of water services has seen re-municipalization efforts emerge in some cities hoping to improve access to this vital resource for their citizens (McDonald & Swyngedouw, 2019). Perhaps most prominent among them is the grassroots campaign that began in the 2010s for the public provision of water in Barcelona, a city that previously had nearly uninterrupted private organization of its urban water supply and distribution since 1867 (March *et al.*, 2019). Institutional, political, and legal deadlock have stalled this movement for the time being, and the city's water continues to be supplied by a single private entity (March *et al.*, 2019). This information is all relevant to the study's primary research question because it serves as a reminder that water utilities do not act wholly independently. Rather, they are enmeshed in larger systems of water governance, policies, and institutions that play significant roles in how they learn from, and adapt to, flooding events.

Sustainability of Urban Water Systems

Urban water systems are responsible for the storage, treatment, and distribution of water resources for local populations, and are therefore the primary focus of water governance efforts in cities. Unfortunately, many such water systems were originally designed under an assumption of static exogenous conditions, meaning that they were fashioned to provide a continuous supply of clean and safe water to a population of roughly constant size facing unchanging environmental circumstances. This assumption has largely proven false, as urban water systems around the world are now nearing their breaking points due to the extreme challenges posed to them by climate change and rapid urbanization. Accordingly, water system sustainability is becoming an increasingly important area of research that seeks to provide solutions to these wicked problems. To this point, urban water systems have relied heavily on technical answers to their water security questions, although this is not enough (Romano & Akhmouch, 2019). Rather, they must embed these technical solutions in robust institutional frameworks in order to ensure their success (Romano & Akhmouch, 2019).

Past scholarship has suggested a myriad of metrics and frameworks for measuring and assessing the sustainability of urban water systems. One asserts that the most objective criteria for evaluating urban water system sustainability are health and hygiene, supply reliability, economic sustainability of governing institutions, efficiency of supply, and environmental sustainability (Rathnayaka *et al.*, 2016). Another posits that resilient urban water systems are characterized by low supply stress, as well as high supply diversity, water use efficiency, demand diversity, conservation capacity, and augmentation capacity (Gonzales & Ajami, 2017). Similarly, complex socioecological systems such as urban water systems might be assessed with a framework that relates resource units, the resource system, the governance system, and end users (Ostrom, 2009). Such socioecological systems are analogous to the idea of the hydrosocial cycle described previously in that they too consider the myriad ways in which humans interact with the resources they use; however, they differ from it due to their theorization of resources and their governing institutions as being separable (Ostrom, 2009), while the hydrosocial cycle depicts them as inextricable. Innovative technologies that help increase the sustainability of urban water systems can be evaluated on the grounds of environmental, economic, technical, and social performance metrics (Cornejo *et al.*, 2019). The overall sustainability of alternative municipal water supply options can be compared with a framework that includes social, environmental, and economic objectives (Hadjikakou *et al.*, 2019). Finally, urban water security can be operationalized and assessed via a six-step framework that includes understanding the urban water system, creating a working definition of *urban water security*, proposing this working definition to stakeholders, setting up the boundaries and quantification of the assessment framework, normalizing and presenting results, and measuring urban water security (Aboelnga *et al.*, 2019).

Urban water systems constantly face risks that significantly impact their resilience and thus sustainability. In some cases, the prominence of certain risks in the water industry have evolved with time, while in others risks that were significant a decade or more ago remain just as important today. For instance, aging infrastructure was identified as the biggest risk impacting the resilience of water companies in 2005, and it remained so in 2015 (Chalker *et al.*, 2018).

However, a decline in workforce experience and expertise as well as the emergence of cyber risks have begun to significantly plague urban water systems only in more recent years (Chalker *et al.*, 2018).

As managers and directors of water systems and utilities have become more cognizant of the influence that risk has on the sustainability of their operations, they have increasingly turned to explicit risk management strategies (MacGillivray *et al.*, 2006). These efforts have been centered around the idea that identifying system vulnerabilities promptly allows for potential problems to be handled before they can precipitate large-scale system failures (MacGillivray *et al.*, 2006). Thus, the modeling of urban water systems and the particular contexts that they are embedded in has become an essential tool for many water decision-makers (White *et al.*, 2015). Nevertheless, the uncertainty inherent in these models has in some cases curbed their usefulness in the decision-making process (White *et al.*, 2015).

The degree of sustainability that an urban water system achieves is dependent on many additional factors aside from risk. Accordingly, case studies abound that highlight these factors and their impacts on water systems in cities across the globe. For example, the city of Flagstaff, Arizona relies heavily upon external virtual water resources in the form of goods imported from distant locations (Rushforth & Ruddell, 2016). This reliance both increases and decreases the hydro-economic resilience of the city by simultaneously diversifying the geographical locations of the water sources it draws from while also preventing it from producing more of the water it uses locally (Rushforth & Ruddell, 2016). In Italy, public water utilities and smaller water utilities tend to be more efficient than their private and larger counterparts, respectively, which allows them to achieve greater sustainability through decreased consumption of water and energy (Lombardi *et al.*, 2019). Any water system that wishes to improve its resilience and sustainability can do so by focusing intervention efforts at the nexus of the system, the threats facing it, the expected impacts of those threats, and the consequences of those impacts for the population that the system serves (Butler *et al.*, 2016).

Wiek & Larson (2012) argue that to properly evaluate the sustainability of water governance regimes, one must understand not just the impacts of water use, but also what people do with water, and why. Accordingly, they articulate a set of seven holistic principles for sustainable water governance. These seven principles are social-ecological system integrity, resource efficiency & maintenance, livelihood sufficiency & economic opportunity, social-ecological civility & democratic governance, inter-generational & intra-generational equity, interconnectivity from local to global scales, and precaution (mitigation) & adaptability (Wiek & Larson, 2012). In another academic article, they use these principles to appraise the sustainability of the Phoenix, Arizona water governance regime, ultimately finding that even though it is succeeding in some regards, it still faces many issues that are hindering its efforts to supply clean and safe water to its customers in a sustainable manner (Larson *et al.*, 2013). Several of the academic papers highlighted in this section relate to the first research sub-question because they suggest that sustainable urban water systems are characterized by their willingness to innovate to increase their resilience, especially in the face of climatic uncertainty.

Urban Water Transitions

Transitions theory is an emerging field of research within sustainability scholarship. A transition is a shift in a system from one baseline condition to a new one that occurs when the original state of that system becomes untenable, and it can proceed either abruptly or slowly in either a linear or nonlinear fashion (Gleick, 2018). Urban water systems can undergo such transitions to a more sustainable state, and water utilities significantly influence how they do so due to the central role that they play in these water systems (Gliedt & Larson, 2018). Oftentimes, transitions in urban water systems are driven by changes in the urban environment as well as societal dynamics, but the inherent complexity of these underlying processes makes it impossible to neatly explain the occurrence of transitions with linear cause-effect relationships (Rauch *et al.*, 2017).

There exist two primary theoretical models of transitions, and each uniquely encapsulates the way in which they transpire. One is the multi-phase model of transitions, which depicts transitions as S-curves that are each made up of four discrete steps (van der Brugge *et al.*, 2005; Loorbach *et al.*, 2017; Sullivan *et al.*, 2017). First among them is the pre-development phase, which is characterized by an equilibrium where the status quo holds even as new practices start to challenge it (van der Brugge *et al.*, 2005; Sullivan *et al.*, 2017). This is followed by the take-off phase, in which innovation leads to subtle shifts in the system (van der Brugge *et al.*, 2005; Sullivan *et al.*, 2017). Third is the acceleration (or breakthrough) phase, wherein structural changes become more salient as mutually reinforcing innovations accumulate (van der Brugge *et al.*, 2005; Sullivan *et al.*, 2017). Finally, the stabilization phase finalizes the transition as the speed of change decreases and a new equilibrium is reached (van der Brugge *et al.*, 2005; Sullivan *et al.*, 2017).

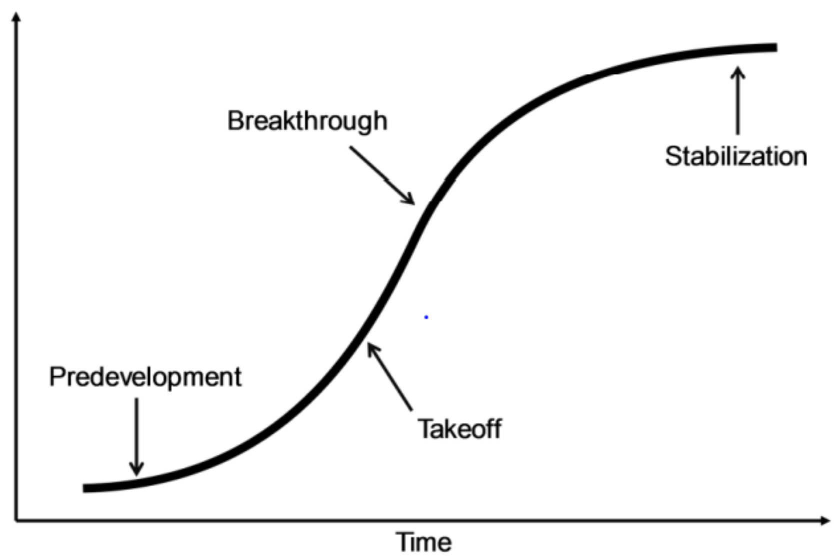

Figure 2 – multi-phase model of transitions (Sullivan *et al.*, 2017)

The other most widely used model for understanding transitions is the multi-level model. This model focuses less on the precise steps by which transitions play out, and more on the contexts and actors which enable them. The macro-level of the model is known as the landscape, which consists of large-scale contextual factors such as the politics, cultures, and economies in which the system is embedded (van der Brugge *et al.*, 2005; Loorbach *et al.*, 2017). Below this is the meso-level of the model, known as the regime, which is made up of the dominant institutions, rules, and norms that allow the system to function properly (van der Brugge *et al.*, 2005; Loorbach *et al.*, 2017). At the base, or micro-level, of the model are niches, which include the individual actors, innovative technologies, and local practices that can provide alternatives to those found in the regime (van der Brugge *et al.*, 2005; Loorbach *et al.*, 2017). According to the multi-level model, transitions occur as a form of punctuated equilibrium in which the regime usually upholds the status quo (van der Brugge *et al.*, 2005; Loorbach *et al.*, 2017). However, every so often a window of opportunity opens and allows niche innovations to destabilize the regime, upending dominant practices in favor of novel alternatives (van der Brugge *et al.*, 2005;

Loorbach *et al.*, 2017). Often this window of opportunity results from a shock to the system which occurs at the landscape level (van der Brugge *et al.*, 2005; Loorbach *et al.*, 2017).

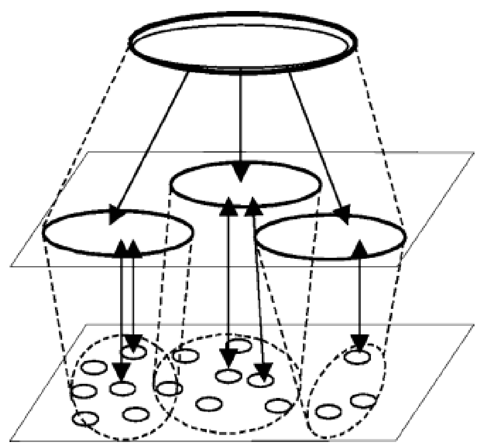

Figure 3 – multi-level model of transitions (van der Brugge *et al.*, 2005)

Even though the exact causes of sustainability transitions in urban water systems are difficult to conclusively establish, a number of factors are known to support and facilitate these transitions. Cross-boundary interactions between stakeholders are one such factor, as they allow for ideas to be shared and implemented to help propel transitions forward (Wen *et al.*, 2015). A few personal characteristics also influence how supportive individual stakeholders are of urban water sustainability transitions, including how supportive the stakeholders are of pro-environmental actions, the degree of trust they have in local and federal government, the magnitude of their perceived social responsibility, the amount of relevant procedural knowledge that they possess, and the number of socioeconomic resources that they have access to (White *et al.*, 2019). Finally, effective science-policy interfaces can foster sustainability transitions in urban water systems, which require compelling water narratives, cross-sectoral collaboration, co-production of knowledge, experiential evidence-based learning, strategic use of trusted scientists, strong networks, and business generated from science-based innovation (Dunn *et al.*, 2017).

Government regulations are unmatched in their ability to impact the degree of success of urban water transitions. Public policy can aid transitions by destabilizing existing conditions and therefore opening windows of opportunity for new technologies and ideas to take hold (Edmondson *et al.*, 2019). Conversely, it can stifle transitions by empowering the dominant water regime and thus reinforcing the status quo, effectively preventing niche ideas and practices from ever taking off (Edmondson *et al.*, 2019). Policy processes also have a significant effect on urban water transitions, as they determine why certain policies come into being while others do not (Kern & Rogge, 2018). Thus, any efforts to cultivate regulations that create favorable conditions for urban water transitions must focus on the policymaking process.

A number of American cities have undergone urban water transitions in the 20th and 21st centuries. Los Angeles provides an illustrative example, a megacity that has historically relied almost solely upon imported water from the Sierra Nevada and the Colorado River to quench its exceptional thirst (Hughes *et al.*, 2013). Recognizing the vulnerability inherent in being so heavily dependent on distant water sources, Los Angeles has since the 1990s both tapped into local groundwater and implemented extensive water conservation measures that have reduced per capita demand by roughly 30% from its peak in the 1980s (Hughes *et al.*, 2013). The southwestern cities of Denver, Las Vegas, and Phoenix have similarly transitioned to being more water sensitive since they all depend on the Colorado River for water, a waterway which has long faced exhaustion and is now being stressed further by the effects of climate change and population growth (Sullivan *et al.*, 2017). Thus, this section is directly relevant to the final research sub-question for this study, as it illustrates what conditions are favorable for inducing sustainability transitions in urban water systems, as well as what these transitions most frequently look like.

Urban Water Innovation

Innovation is the lifeblood of urban water sustainability transitions, as water systems and utilities that innovate on a regular basis are far more likely than their less ambitious counterparts to implement new technologies and practices that make them more sustainable and resilient (Loredo *et al.*, 2019). Motivations for water utilities that choose to innovate span economic, environmental, and social reasons including spurring economic growth, maintaining an adequate water supply for future generations, and complying with governmental regulations, respectively (Widener *et al.*, 2016). Furthermore, a direct relationship exists between the innovativeness of a water utility and the number of dynamic capabilities (organizational and institutional factors important for innovation) it possesses, while indirect relationships exist between the utility's innovativeness and the size and income of the population it serves, as well as the educational backgrounds of its decision-makers (Widener *et al.*, 2016). Additional factors that influence innovation in an urban water system include its institutional environment, its natural-physical environment, various characteristics of its innovators, and the attributes of the particular innovation (Spiller *et al.*, 2015).

A host of other factors influence how innovative particular urban water systems become. Ownership structure certainly plays a role, as private water utilities tend to be more innovative than their public counterparts due to their search for profit in a market environment, although public utilities tend to do better at achieving sustainability goals (Lieberherr & Truffer, 2015). Collaborative governance also impacts innovation since it facilitates shared understanding among an array of actors (Kallis *et al.*, 2009). Adaptive capacities ranging from skilled staff to good asset management foster innovation because they allow water systems to reorganize, learn, and successfully adapt to stresses (Mullin & Kirchhoff, 2019). Lastly, governmental regulation of the water sector plays an important role in innovation, but depending on the specific regulations, it can either support or inhibit the creation and implementation of new technologies (Sherman *et al.*, 2020).

As previously mentioned, dynamic capabilities have the capacity to affect the degree to which urban water systems innovate; in reality, they are perhaps the single most significant factor influencing the innovation process. Lieberherr & Truffer (2015) define dynamic capabilities as "organizational and strategic routines that enable organizations to create, evolve, and recombine resources (ranging from physical assets to competences such as specific skills) to generate new value-creating strategies and even change the market." Simply, they are the practices that allow organizations to respond to exogenous opportunities and threats, and they are frequently used by firms of all types to gain a competitive advantage (Ambrosini & Bowman, 2009). The importance of dynamic capabilities to water system innovation is highlighted by the existence of a strong positive correlation between the number of dynamic capabilities and innovations in Oklahoma water utilities (Hartman *et al.*, 2017).

The innovation process has been theorized to unfold in five successive steps (Spiller *et al.*, 2015). It begins with *agenda setting*, which occurs when decision-makers in urban water systems realize that they need to make a change in their processes or assets to improve system performance (Spiller *et al.*, 2015). Then, these decision-makers determine which potential innovation to pursue in the *choice between alternatives* step (Spiller *et al.*, 2015). This is followed by the *re-innovation/restructuring* phase of innovation, in which available options or possibly the system itself is redefined to fit the specific context of the immediate situation (Spiller *et al.*, 2015). Afterward comes *diffusion*, in which the decision-makers decide how to best disseminate their innovation (Spiller *et al.*, 2015). Finally, the new innovation loses its novelty and becomes part of the water system's regular routine during the *routinization* phase (Spiller *et al.*, 2015).

Urban water system innovations can take many forms. Perhaps the most readily recognizable of them are technological innovations, which involve changes to the physical assets of a system. For example, some regional water systems choose to invest heavily in automated monitoring and control systems which help increase the reliability, resilience, and sustainability of those systems (Bradshaw *et al.*, 2011). Many urban water systems focus instead on financial innovations in order to incentivize water conservation behaviors amongst their customers, as well as shield themselves from unforeseen financial hardships. When a handful of water utilities in California began including energy costs in their customers' bills, total domestic water use decreased by 3% and indoor domestic water use decreased by 24% (Escriva-Bou *et al.*, 2015). In addition, numerous water utilities are embracing increasing-block tariffs as a means for encouraging their customers to save water while also ensuring that they are allotted a sufficient quantity to meet their needs (Boyle, 2014).

Forward-thinking programs, plans, and collaborations can also constitute innovations in urban water systems. Potable water reuse systems are beginning to gain traction as an innovative solution to water shortages, although they often struggle to gain the public's acceptance (Harris-Lovett *et al.*, 2015). Sustainable Urban Water Management (SUWM) practices reduce the strain on conventional water infrastructure by mimicking natural principles (Esmail & Suleiman, 2020). In turn, Water Safety Plans (WSPs) help improve the processes and practices meant to ensure water quality and safety (Roeger & Tavares, 2018). Finally, collaborative relationships amongst water utilities and governing agencies aid in the proliferation of fresh ideas and the sharing of resources and expertise during emergency situations (Hughes & Pincetl, 2014; Jalba *et* *al.*, 2014). This section, then, is germane to this study's research question and sub-questions since it both suggests what the innovation process may look like in water utilities across Southeast Texas and the Gulf Coast of Florida, as well as foreshadows what these innovations may consist of.

Climate Change Preparedness of Urban Water Systems

Today the effects of climate change are ubiquitous. From increased droughts to stronger hurricanes and even expanded transmission of some infectious diseases, people and systems around the world are being forced to adapt to unprecedented environmental stresses. Water systems are no exception, and they will have to continue innovating their infrastructures and practices in order to provide a sufficient supply of clean and safe water to their customers into perpetuity. Climate change preparedness efforts are therefore invaluable capabilities that water systems ought to undertake sooner rather than later, and in an iterative fashion.

Currently, climate adaptation planning and implementation appears to be seriously lacking in both urban water systems and more generally in the cities they serve. One recent study examined the effectiveness of climate adaptation planning in 59 highly populated coastal cities across the globe (Olazabal & de Gopegui, 2021). Of the 53 metrics used to assess climate preparedness, the cities were on average proficient in just 20.4 of them, and only Baltimore and Los Angeles were proficient in more than 30 (Olazabal & Ruiz de Gopegui, 2021). Furthermore, a typology was created to rank cities based on their degree of maturity in climate mitigation planning, and its categories, from most mature to least, consisted of *advanced*, *maturing emergent*, *faltering emergent*, and *laggard*, respectively. (Foss & Howard, 2015). When applied to 15 municipalities in the Dallas-Fort Worth metroplex, another major metropolitan region in Texas with similar governance systems to those of the Houston area, seven were found to be laggards and six were labeled as faltering emergent, while only two and zero were described as maturing emergent or advanced, respectively (Foss & Howard, 2015). More specific to urban water systems themselves, only 30% of Canadian water utility officials were found in 2015 to be aware of the possible impacts of climate change on water utilities, while 65% had not conducted climate change vulnerability assessments and 56% did not have operational plans to address climate change impacts (Brettle *et al.*, 2015).

Even though many urban water systems are woefully underprepared to respond to the myriad challenges posed by climate change, those that have already begun climate adaptation planning efforts can provide valuable insights into best practices for other systems to follow. For example, a significant number of water managers are implementing climate projection and assessment information into the day-to-day operations of their systems, and a lot of them have stressed the importance of educational, training, and support materials to the success of their adaptation programs (Raucher *et al.*, 2018). Moreover, water utility planners in Wuhan, China have started consulting their staff and stakeholders before investing in climate resilience strategies in order get input on which options are best from those who will be most significantly affected by them (Yang & Zhu, 2017). Finally, water managers in Addis Ababa and Adama, Ethiopia have implemented climate-resilient water safety planning into their systems, and they have found that prioritizing events which pose a higher risk of contaminating drinking water supplies can optimize water quality monitoring processes (van den Berg *et al.*, 2019). Therefore, these articles are highly relevant to this study's research question and first & second sub-questions. This is because they highlight the various degrees to which climate change plays a role in the planning processes of different urban water systems.

Urban Water Adaptation to Natural Hazards

As previously mentioned, one of the most significant challenges posed to urban water systems by climate change is the increased frequency and severity of natural hazards (Diaz & Yeh, 2014). Among others, these hazards include drought, flooding, hurricanes, and even outbreaks of disease. Despite the threat that such disasters pose to water systems, they have the potential to precipitate innovation and even sustainability transitions in them. These innovations and transitions can either be proactive in nature if taken in preparation for future natural hazards, or they can be reactive if taken in response to past ones.

Severe drought is one natural hazard which is exacerbated by climate change and which can force a system to innovate to more efficiently meet customer water demand (Berbel & Esteban, 2019). The innovations and other adaptive measures taken by urban water systems in response to drought are diverse and can involve actions meant to assess, monitor, and respond to risk; reduce water consumption; or increase water supply (Gasbarro *et al.*, 2016). Of all the different forms of innovation, financial innovations seem to have been given the most attention in the academic literature focused on water system drought response. For instance, increasing block tariffs are a popular innovation in locations where single water utilities have monopolies because they provide an incentive for end users to conserve water during droughts by limiting their consumption to only what they need (Lu *et al.*, 2019). Novel forms of insurance can also protect urban water systems from the negative ramifications of drought, as multi-year insurance contracts that cover long-term water shortages offer better financial performance than their counterparts that cover those of any duration (Guzman *et al.*, 2020). Additionally, the formation of a mutual of water utilities located in diverse locations combined with reinsurance coverage can significantly reduce the cost of risk management for member systems during widespread droughts (Baum & Characklis, 2020). Lastly, a water utility's financial vulnerability to drought is often minimized more through the use of third-party index insurance contracts than through that of self-insurance (Zeff & Characklis, 2013).

Hurricanes and their resultant flooding are also expected to become more frequent and severe with continued climate change. Fortunately, having previous experience with these natural hazards can increase resilience to them, as the percentage of individual households in Florida who were highly prepared for hurricanes was 2% greater the year after an active hurricane season than during each of the two years preceding it (Baker, 2011). Furthermore, water managers and other public officials who implement the use of GIS to visualize the extent of potential future flooding and open lines of communication with other local economic sectors in advance of possible flood events can proactively make their water systems more resilient to these hazards (Allen *et al.*, 2019). However, a wide array of stakeholders should be given the opportunity to input their opinions before flood risk management efforts are undertaken by urban water systems in coastal cities, as personal waterbody meanings have the capacity to impact which innovations individuals prefer (Quinn *et al.*, 2019).

The COVID-19 pandemic is a natural hazard that has gripped the world for more than a year at this point, and accordingly a proliferation of scholarship has focused on the ways in which urban water systems may choose to innovate to protect their customers and employees from disease outbreaks. For example, utilities can implement multi-barrier treatment processes for wastewater and stagger working hours for their essential employees to ensure that workers are endangered neither by the water supplies nor the coworkers that they work in close proximity to (Gude & Muire, 2021; Berglund *et al.*, 2021). Moreover, they may test for viruses in wastewater or establish mutual aid agreements with other nearby water utilities for sharing employees and supplies so as to protect the safety of their customers during such outbreaks (Berglund *et al.*, 2021; Gude & Muire, 2021). Finally, water utilities can order extra supplies in advance of outbreaks and postpone capital projects until after them in order to protect their operations from supply chain issues and financial hardships wrought by the outbreaks, respectively (Spearing *et al.*, 2021). This section's discussion of water system responses to various natural hazards thus supports the idea embodied in this study's research question and sub-questions that such events can catalyze significant changes in water utility practices and processes.

Challenges and Opportunities for Texas Water Systems

As both the second most populated state in America and one that will continue to face increased incidences of severe droughts, hurricanes, and floods due to climate change, it is of the utmost importance that water systems across Texas be highly resilient moving forward. Therefore, it would be valuable to have at least an elemental understanding of the key stakeholders, challenges, and opportunities that are currently influencing these systems within the Lone Star State. Accordingly, the primary state-level water governance agencies in Texas are the Texas Water Development Board (TWDB), which plans and finances water projects across the state, the Texas Commission on Environmental Quality (TCEQ), which provides surface water rights permits to Texas water systems, and the Texas Parks and Wildlife Department

(TPWD), which protects the state's wildlife and its habitats (Wurbs, 2015). In addition, groundwater conservation districts are responsible for managing Texas' groundwater, while 19 river authorities are tasked with managing and developing the water resources of the state's major river basins (Wurbs, 2015). Lastly, Texas is home to 16 regional water planning zones that cover the state, as well as 30 aquifers that underlay a combined total of 80% of its area; these aquifers supply 80% of their pumped water to agricultural irrigation and another 15% of it to municipalities (Wurbs, 2015).

Texas water systems are currently facing a unique set of both challenges and opportunities in their pursuit of providing their customers with a continuous supply of clean and safe water. Groundwater depletion is one of their most prominent challenges, as statewide median aquifer water levels dropped 22 meters between the 1930s and the 2000s (Chaudhuri & Ale, 2014). Evaporation of surface water is another major hurdle that Texas water systems are beginning to encounter, as total long-term evaporation from the 3,415 reservoirs in the Texas water rights permit system is predicted to be 7.53 billion cubic meters per year, which is equivalent to 61% of the total agricultural, or 126% of the total municipal, water use in the state in 2010 (Wurbs & Ayala, 2014). However, many water systems in Texas are well equipped to alter their practices in order to meet these pressing challenges. For example, the city of Lubbock could increase its use of reclaimed water and water conservation measures in order to reduce its dangerous overreliance on the Ogallala Aquifer, while the city of San Antonio could implement low impact development technologies to collect some of its 32 inches of annual precipitation and use it for agricultural irrigation (Daher *et al.*, 2019). Furthermore, innovations such as the widespread shift to drought-tolerant corn could reduce agricultural water consumption throughout Texas, thus leaving more for municipal purposes in the state (Hao *et al.*, 2015).

Through its overview of the regulatory and environmental contexts that Texas water systems are enmeshed, this domain of literature provides valuable insight into the research questions listed before. This is because they paint a precise picture of the specific factors that most impact their innovation processes.

Hurricane Harvey and its Impacts on Southeast Texas

The damage wrought by Hurricane Harvey and its resultant flooding in 2017 was unprecedented in Houston and throughout Southeast Texas, and it shone a spotlight on the many substantial threats to the sustainability of both the city and the region. Indeed, flooding due to the heavy precipitation that pelted the Houston area as Hurricane Harvey stalled over it for the better part of a week was responsible for 57 of the 70 casualties directly attributable to the storm, as well as roughly $11 billion in losses (Touma *et al.*, 2019). Poor planning played a role in this devastation, as 9.6% of Houston's current urban development is located within the 100-year floodplain, and this percentage will only increase as sea levels rise and Houston continues to grow (Kim & Newman, 2019). Moreover, emergency planning in Harris County, Texas, where Houston is located, is based on an outdated definition of 100-year storms as ones that produce at least 13 inches of precipitation within a 24-hour period (Blackburn, 2018). Experts estimate that today that figure is actually somewhere between 15 and 19 inches (Blackburn, 2018).

A substantial amount of empirical evidence suggests that the severity of Hurricane Harvey was increased by climate change. For example, one study estimates that the return period of the extreme rainfall totals observed during Hurricane Harvey is greater than 9,000 years in the Houston area, but that climate change made this precipitation 15% more intense and three times more likely to occur than would otherwise have been the case (van Oldenborgh *et al.*, 2017). Another asserts that climate change was responsible for increasing the total rainfall accumulation in Houston during the storm by 37% (Risser & Wehner, 2017). Still one more study posits that the annual probability of observing precipitation totals in Texas of Hurricane Harvey's magnitude was 1% for the period from 1981 to 2000 but that that probability will increase to 18% for the period from 2081 to 2100, including a 6% probability in 2017 (Emanuel, 2017).

Perhaps the most unfortunate aspect of the destruction caused by Hurricane Harvey in Southeast Texas is that it did not impact all demographic groups equally, thus begging questions of environmental justice. Fittingly, the city of Houston has been the epicenter of the environmental justice movement ever since 1979, when the landmark class action lawsuit *Bean vs. Southwestern Waste Management, Inc.* became the first one to ever challenge the siting of a waste facility under civil rights law (Bullard, 2008). The flood extent due to Hurricane Harvey in different Houston census tracts was significantly and positively correlated with the proportion of Blacks and Hispanics living in these areas, but negatively correlated with the share of Asians and Whites residing there (Chakraborty *et al.*, 2019a). Furthermore, a statistically significant positive relationship has been found between census tract flood extent and the percentage of disabled individuals living within the areas (Chakraborty *et al.*, 2019b). Finally, the share of people experiencing socioeconomic deprivation within various census tracts was positively and significantly associated with flood extent within those areas, as well (Chakraborty *et al.*, 2019a). Ultimately, this section depicts the severity of Hurricane Harvey's impacts on Southeast Texas. This is relevant to the research question and sub-questions guiding this study since the storm made clear the vulnerabilities of the region's many water systems, and thus their imperative to innovate and become more resilient.

Summary

This chapter has highlighted a meaningful subsection of today's academic scholarship located at the intersection of climate change, urban water systems, innovation, and sustainability transitions theory. It began by providing a broad analysis of water governance practices and water system sustainability efforts, before shifting its focus toward the ways in which urban water systems innovate and transition toward more sustainable states. The chapter then discussed how urban water systems are currently preparing for climate change and adapting to natural hazards. Finally, it examined the current state of water governance in Texas and the impacts of Hurricane Harvey on the state. Ultimately, it is hoped that this study will bring all of these theoretical domains together in a novel way by identifying the role of Hurricane Harvey in precipitating innovation in Texas water utilities that could cause them to undergo sustainability transitions.

Chapter 3: Methodology

Introduction

As can be gleaned from the previously stated research questions, the primary objective of this study was to understand the extent to which water utilities in Southeast Texas learned from the severe flooding caused by Hurricane Harvey throughout the region in 2017. Evidence of such learning exists, as the innovations undertaken by the impacted utilities since then have different attributes than those implemented by the utilities in other locations not affected by the storm. As such, this study took a qualitative form in which several semi-structured interviews were conducted with water utility managers in coastal regions of both Texas and Florida, and the answers given by the two groups of officials were compared. The rest of this chapter contains the following sections: (a) *Selection of Participants*, which explains how potential participants were identified and recruited; (b) *Instrumentation*, which details the formatting of the participant interviews; (c) *Data Collection*, which describes the processes for designing and conducting these interviews; and (d) *Data Analysis*, which discusses how the interviews were analyzed, thus allowing conclusions to be drawn. This is followed by a short summary section.

Selection of Participants

In order to be eligible to participate in this study, individuals had to hold senior management status in water utilities located in metropolitan Houston, Texas; Beaumont/Port Arthur, Texas; Tampa/St. Petersburg, Florida; or Pensacola, Florida. Furthermore, participants from Texas had to supervise utilities serving municipalities that had received some non-zero amount of rainfall from Hurricane Harvey between August 25th, 2017 and August 31st, 2017. The rationale behind these criteria was simple. Since this study sought to distill the impacts of Hurricane Harvey on water system innovation, it required two groups of water utility managers whose responses to interview questions could be compared: an experimental group of managers from Southeast Texas whose water systems were affected by the storm, and a control group of their counterparts in other locations that went untouched by it. Tampa/St. Petersburg and Pensacola, Florida were chosen as control locations due to their relatively unique positions as major American metropolitan regions that regularly confront hurricanes, but which have not experienced severe flooding in the aftermath of one in the past 25 years.

The names and contact information of potential study participants were identified over a period of several months beginning in August 2019. In February 2020, a comprehensive database of water utility managers from Texas was obtained from an official with the Texas Water Development Board. This list of phone numbers and email addresses for thousands of water professionals from across the state was then sorted by county, and contact information for those individuals from the following counties of focus was copied over to an Excel spreadsheet:

- Austin County, Texas
- Brazoria County, Texas
- Chambers County, Texas
- Fort Bend County, Texas
- Galveston County, Texas
- Hardin County, Texas
- Harris County, Texas
- Jasper County, Texas
- Jefferson County, Texas

- Liberty County, Texas
- Montgomery County, Texas
- Orange County, Texas
- Victoria County, Texas
- Waller County, Texas

To procure the contact information of eligible water utility managers from Florida, the cities and towns that comprise the Tampa/St. Petersburg and Pensacola metropolitan areas were first identified. Afterward, Internet searches were conducted in order to locate the webpages of the water utilities that serve these municipalities, from which the names, email addresses, and phone numbers of their managers were culled. Finally, this information was transferred to an Excel spreadsheet identical to the one containing information for Texas contacts. All of the individuals in Florida who were identified as potential study participants came from one of the following counties:

- Escambia County, Florida
- Hernando County, Florida
- Hillsborough County, Florida
- Pasco County, Florida
- Pinellas County, Florida
- Santa Rosa County, Florida

Once the two Excel spreadsheets were completed, the water utility managers whose contact information had been compiled were contacted and asked to agree to take part in a single semi-structured telephone interview. This was done by first sending an email explaining the background and purpose of the study to every email address that had been found. Approximately one to two weeks after these initial emails were sent, water utility managers who did not respond to the email and whose phone numbers had been located were called. These calls were used for essentially the same purpose as the emails, explaining the purpose and background of the study. All water managers who explicitly agreed or declined to take part in the study at any point had their responses recorded immediately and were not contacted again. Managers who had yet to definitively agree or decline to be interviewed continued to be contacted periodically via email or phone call. These attempts to contact them continued until they made an explicit decision as to whether or not to be interviewed. In some cases, additional participants were recruited via a snowball sampling technique in which water utility managers who had already been interviewed were asked to provide contact information for other nearby managers who may have been interested in participating in the study.

A total of 21 water utility managers ultimately participated in the study. 14 of them were from Texas, including ten from the Houston area and four from the Beaumont/Port Arthur region. The remaining seven participants were from Florida, of which six were from metropolitan Tampa/St. Peterburg while one was from the Pensacola area. Since the sampling procedures used to identify these participants were exhaustive, it is likely that they are representative of the general population of water utility managers in their areas, and therefore that the conclusions drawn from their interviews are not biased by any sampling errors.

Instrumentation

The primary instruments for data collection employed by this study were semi-structured interviews with participating water utility managers. Each interview was conducted over the phone and lasted roughly an hour to an hour and a half. Only one participant was interviewed at a time, and each participant took part in just a single interview. Due to scheduling constraints, one participant requested to forego a formal interview in favor of answering the 43 interview questions electronically. This request was granted, and a copy of the interview guide was emailed to this participant to be filled out at his convenience and then returned. Interview questions covered the following topics:

- The age of the water utility's infrastructure
- The current quality of the water utility's infrastructure
- The timeline that the water utility is following to update its infrastructure
- The water utility's vulnerability to various risks such as flooding, drought, personnel, changes in demand, etc.
- The mechanisms used by the utility to track water supply
- Disaster contingency funds put in place by the water utility
- Incentives for the water utility to innovate, such as regulations, sustainability, economics, stakeholder pressure, etc.
- The water utility's access to external resources, including financial and expertise
- The water utility's internal knowledge creation and learning mechanisms, such as professional certifications
- Barriers to innovation for the water utility
- The water utility's experiences with, and responses to, hurricanes such as Harvey

Semi-structured interviews were used to collect data for this study because of their flexible nature. Indeed, this open-ended format of questioning is popular among academics for data collection because it is "well suited for the exploration of the perceptions and opinions of respondents regarding complex and sometimes sensitive issues and enable[s] probing for more information and clarification of answers" (Barriball & While, 1994). Moreover, semi-structured interviews, although more time consuming, provide greater depth in the data they produce than close-ended surveys (Creswell, 2004). The 43 interview questions provided a framework for the interviews and ensured that every topic which needed to be considered would at least be touched upon. Discussion was not limited to just these subjects, however, as many interview questions were used as catalysts for further open-ended dialogue with water utility managers about topics that they considered to be pertinent. Thus, the use of semi-structured interviews allowed the interviewer to guide discussion without preventing the interviewees from providing the most robust data possible.

Data Collection

The process of data collection for this study began with the creation of an interview guide during late summer and early autumn of 2019. As previously mentioned, the interview guide contains the 43 scripted interview questions that were used to guide discussions with water utility managers from Texas and Florida. Many of these questions were derived from an earlier study that focused on water utility innovation in response to drought in Oklahoma (Hartman *et al.*, 2017), although they were contextualized and augmented with new inquiries to better fit the focus of this project. Afterward, an email script and a phone script to be used when contacting potential study participants were written, and all three materials were submitted to the Institutional Review Board (IRB) at the University of Oklahoma. The IRB approved the study in autumn 2019, which allowed the recruitment of participants to commence.

Study participants were selected according to the process described previously. Once an individual had elected to take part in the study, he or she was emailed a consent form to be completed and signed, which explained both the project and participant expectations in greater detail. Upon receiving the finished consent form from the participant, a date and time for the phone interview were agreed upon. If a particularly long period of time elapsed between the completion of the consent form and the interview, a reminder email was sent to the water manager the day before the appointment.

At the agreed upon time, the participant was called for the interview and any last-minute questions that he or she had regarding the study were answered. If he or she had agreed in his or her consent form to have the interview audio recorded, then the entire phone call was documented on two separate recorders to ensure that no data would be lost in the event that one failed. In the instances where permission for audio recording had not been given, detailed notes were taken by the interviewer throughout the call. All answers to questions involving Likert scales were marked down by the interviewer, and the participant was thanked for his or her time and efforts at the end of the phone call. Once the call was completed, all audio recordings, notes, and answers to Likert scale questions were uploaded to a secure centralized location for future use, along with the participant's signed consent form. A few times, a persistent scheduling conflict prevented a traditional interview from being conducted with a participant. In those cases, a blank interview guide was emailed to him or her to be filled out and submitted electronically, and, once received, these answers were uploaded to the same location as the other audio recordings and call notes. Each of the 21 interviews took place between June and December 2020.

All recorded interview audio was transcribed in the late winter and early spring of 2021. This was done by hand, with the interviewer listening to the phone calls and writing out what was said by both him and the participants. In a few instances where audio quality was exceptionally poor and the interviewer could not discern what was said even after multiple times listening to it, an ellipsis was added to the transcript at the appropriate location to denote this fact. Each of the interview transcripts was then uploaded to the centralized location storing the other data sources.

Data Analysis

After all the audio from the interviews was transcribed, the final transcripts and call notes were uploaded into the qualitative research software MAXQDA in the spring of 2021. At this point, the interview transcripts were read in an iterative fashion in order to analyze the data present within them. This was done through the use of an inductive coding technique similar to the one described by Gioia *et al.* (2012). The first time the transcripts were read, a "1st-order analysis" was conducted in which the exact terms used by participating water utility managers were strictly adhered to for generating codes, and little attempt was made to distill themes (Gioia *et al.*, 2012). A large number of codes thus resulted from this analysis, which then required pruning. This was done the second time the transcripts were read, as thematically similar codes were combined into broader "aggregate" themes (Gioia *et al.*, 2012). Every time the transcripts were reread from that point forward, they were checked to ensure that the previously coded themes seemed to fit the data, as well as to look for other themes that were previously missed. By the time the iterative coding process was completed, a total of 1,811 different codes belonging to 20 distinct thematic categories had been located in the 21 interviews. These themes included the following:

- Personal information of the participant
- General information about the utility
- Prominent stakeholders
- Utility vulnerabilities
- Efforts to reduce utility vulnerabilities
- Barriers to utility innovation
- Tactics to overcome barriers to utility innovation
- Specific examples of utility innovations
- Factors aiding utility innovation
- Disaster mechanisms put in place by the utility
- Resources & capabilities available to the utility
- Strategic plans made by the utility
- Utility motivations for making strategic plans
- Advance utility preparations for hurricanes
- Hurricane damage suffered by the utility
- Disruptions caused at the utility by hurricanes
- Backup systems used by the utility during/after hurricanes
- Utility recovery efforts after hurricanes
- Lessons learned by the utility from past hurricanes

- Previous disasters faced by the utility

Bias was controlled for during the coding process through the extensive employment of accepted intra-coder reliability techniques. Intra-coder reliability can be defined as "the level of coding agreement of one coder between different points of time" (Silvis, 2020, p. 92). Accordingly, interview transcripts were coded for themes iteratively, with a minimum time period of 14 days elapsing between each reread of the same transcript (Schreier, 2012). Thus, the reliability and validity of the data were ensured even though only one person was involved in the coding process because he was able to observe the same themes in the data at different points in time.

Once a consensus was reached regarding which themes were present in the data, it was ascertained which ones were the most salient. This was done by comparing themes across interviews to see which ones were brought up by the most water utility managers. It was assumed that the themes brought up by the most managers were the ones that were most strongly influencing the innovation and planning processes of water utilities. Finally, the study was completed by comparing the themes most frequently discussed by water utility managers in Texas to those most frequently discussed by water utility managers in Florida. By comparing and contrasting these themes, the study was able to examine the degree to which experiencing Hurricane Harvey has caused water utilities in Southeast Texas to innovate differently than their counterparts in other locations that have not experienced any severe flooding in the last 25 years.

Summary

This chapter detailed the various methods used to conduct this study from beginning to end. Water utility managers from metropolitan Houston, Texas; Beaumont/Port Arthur, Texas; Tampa/St. Petersburg, Florida; and Pensacola, Florida were recruited to take part in the study. Those who agreed to do so participated in semi-structured interviews regarding the ways in which their water systems have innovated after facing natural hazards. These interviews were audio recorded and transcribed, and the resulting transcripts were analyzed for key themes. Finally, the answers given by water professionals in Texas were compared to those provided by their counterparts in Florida in order to deduce the attributable effects of Hurricane Harvey on water system innovation. The results of the study are presented in the following chapter.

Chapter 4: Results

Introduction

The purpose of this study was to provide insight into the extent to which water utilities impacted by Hurricane Harvey in 2017 have innovated relative to their unaffected peers. Innovation has previously been defined as "the creation and implementation of new or adapted institutional and technological changes that generate value and enhance water system sustainability" (Hartman *et al.*, 2017), and this definition was the one that guided this project. This chapter seeks to help answer that question by providing an overview of the most salient and frequently discussed innovations adopted by participating water systems across Southeast Texas and the Gulf Coast of Florida. Many patterns emerged from the interview data as to the kinds of innovations that water utilities in each site have adopted in the years since the storm, and, accordingly, the rest of this chapter is organized to reflect those thematic similarities. Thus, it is divided into the following sections: (a) *Educational Innovations*, (b) *Financial Innovations*, (c) *Infrastructural Innovations*, (d) *Programmatic Innovations*, (e) *Technological Innovations*, and (f) *Environmental Innovations*. The chapter is then wrapped up with a brief summary section.

Educational Innovations

When asked to enumerate all the innovations that their systems had previously implemented, various water managers in both Texas and Florida cited ones focused on education. Educational innovations can improve the performance of a water system by teaching its employees fresh skills or augmenting their existing ones. They can also enhance the environmental sustainability or financial viability of the system by demonstrating to its customers practices for conserving water or the imperative of raising rates, respectively. In this way, educational innovations are unique in that they can target individuals either working for a water system or purchasing water from it, and they most often take the form of training classes, meetings, or educational materials.

One particular water manager from Florida's Tampa Bay region stressed the importance to his system of continuing education for its staff due to its ability to both foster inventive new ideas and improve upon old ones. Interviewee F7 stated that in the future, his water system will be "continuing the training and classes. In doing so, I feel like we create more ideas and ways to improve on what we've already developed" (Interview F7). Similarly, an operator of large water systems in Southeast Texas discussed the benefits of the informal training that occurs when his employees learn new tasks for themselves:

> Well, I guess it's kind of innovative to self-learn a lot of these tasks. So let's just say electrical. Instead of having to find an electrician, you can kind of figure it out yourself. So in a way, that's kind of innovative. The treatment aspect of things, we are a water treatment business as well. So know how to treat something and how to be innovative, especially for the future, because a lot of people are having to switch to filters. And it's important to know how to work those filter systems. And there's many routes of treatment, so it's important to know. (Interview T7)

In this way, water systems benefit when their staff members learn new tasks informally. This is because doing so can prevent the leaders of the system from having to locate (and pay) outside professionals to perform simple tasks, as well as familiarize the employees of the system with emerging technologies in the industry that will only become more prevalent in the future.

Not only do water systems benefit by educating their staff members, but also by educating their customers. Doing so can serve various ends such as teaching the public to conserve water or making it more likely to accept rate increases. In turn, the systems themselves are able to become more environmentally sustainable, financially viable, and physically resilient.

For example, training customers to use less water increases the amount of freshwater available to other people and organisms, and encouraging consumers to approve rate increases provides utilities more with which to update their infrastructure. Thus, water systems that invest in public education tend to ultimately reap multifaceted benefits from doing do.

One such educational innovation directed at the public was described by a water manager from Texas who mentioned that "they actually send letters out to the top five users in each system to let them know, 'Hey, you're kind of bucking the average there'" (Interview T1). The goal of this initiative is to let the largest consumers know that they are using atypical quantities of water in hopes that the recognition of this fact will spur them to be more cognizant of their water use moving forward. Another educational innovation detailed by a different water official in Texas involved relabeling the term *maintenance*. Although this change in language seemed trivial at first, it ultimately increased his customers' willingness to pay more to keep their infrastructure functioning at a high level well into the future.

> Our number one thing that we did is we retrained all of our clients to stop referring to what everybody else calls maintenance, we don't call it maintenance. The M word is not allowed in our shop. It's called asset reliability services. And the reason we made such a big deal about that is because a Municipal Utility District (MUD), when they put in a water system, they're spending $3 million. It's an asset, and they expect it to be reliable. So we started getting them to understand. And we found out that through referring to it as an asset reliability, they were more apt to understand that it costs money to do maintenance on an asset than if you just said maintenance. So that was a big deal. And everybody laughed at it at first, but now it has gotten to be a pretty big buzzword in the industry. And we now have clients that are willing to spend money on maintaining their assets, because they realize they've got to last for 40, 50, 60 years. (Interview T2)

This simple change in terminology increased the collective willingness of customers to pay to maintain their water system because they began to view it as something that added value to their lives. In turn, the water utility had more financial resources to be able to harden its infrastructure, thus increasing its resilience to future hurricanes and flood events.

These responses gathered from water managers in Texas and Florida regarding the financial innovations adopted by their utilities directly relate to the research questions guiding the study. Although the similar nature of many of the innovations implemented in the two states makes it difficult to discern how water utilities are specifically learning from past flooding events, it can be observed that those undertaken in Texas include informally training employees, educating customers on their water use, and relabeling routine maintenance to make it easier to fund. These innovations are similar to the formal employee training discussed by a water manager from Florida, and this is important for sustainability transitions theory because it shows that water systems across Southeast Texas are actively implementing niche financial innovations to make themselves more resilient and less vulnerable to natural hazards.

Financial Innovations

During the course of their interviews, many water utility managers in Florida and Texas also described financial innovations that their systems had undertaken. These innovations took an array of different forms, but for the most part they had similar goals. The first objective was to ensure the financial viability of systems in the face of future uncertainties, and the second was to incentivize their customers to conserve more water. Therefore, the financial innovations highlighted by water utility managers sought to increase both the economic and environmental sustainability of their respective systems.

Interviewee T7, a water professional from Southeast Texas, explained how the uncertainty of future conditions can render financial planning a difficult prospect for any water system.

> I guess it's really hard to come up with an innovative budget plan, especially because you never know what could happen from month to month, maybe even week to week. You may have to repair something, put something here, take something out. So it's really hard to implement that. (Interview T7)

Uncertainty is a barrier to budgeting because one cannot precisely predict when equipment will need to be repaired or replaced. Accordingly, the costs to do so can put a strain on system finances when they do inevitably arise if they were not previously budgeted for, which is often the case. Many water systems which recognize this fact have responded with innovative financial practices to ensure that unanticipated expenses do not compromise their economic viability. One such tactic was articulated by a water manager who works extensively with MUDs in Texas.

> So, in the MUD district, their revenue comes from the selling of the water and the wastewater services, right? So they have their monthly rate, and then they actually have taxes at the end of the year for maintenance and debt service. So they'll tack on based on the property value. And then they'll just keep, of course they have to operate and have to pay as things keep going, but then they'll try to save at least six months to a year of cash in the bank so when they have big projects that come up, or unexpected emergencies. (Interview T1)

By implementing additional taxes and having up to a year's worth of revenues on hand at all times, this water system is able to respond immediately whenever a significant unexpected cost arises, thus ensuring its financial health and resilience. This sentiment was echoed by another water utility professional from Texas whose system similarly saves a percentage of its regular income in order to have contingency funds available to be used in the event of a disaster or other unforeseen expense.

> That's inside the annual budget discipline process, you create where you're directing your monthly revenues from your customers, and how you split it up and take some of that money and put it in a savings account, essentially, or reserve. (Interview T11)

Safety concerns due to the ongoing COVID-19 pandemic have fundamentally altered many of the most common practices employed by water systems. One of these changes has been the replacement of traditional in-person meetings with virtual ones in order to prevent spread of the disease among participants. This shift to online communication has also had the co-benefit of saving water systems substantial amounts of money that traditionally fund the travel expenses for the members of their staff that attend such events. For this reason, at least one water manager from Texas expects to retain the innovation of virtual meetings even after the pandemic ends.

> COVID's put a hold on a lot of our face to face meetings and I think that in the future, online classes will be the way people go because we save a considerable amount of funds, especially on my lower level employees, for them to get some education by just going online and studying. (Interview T5)

Aside from using them to improve their own economic resilience, water utilities and systems also deploy financial innovations to incentivize their customers to conserve water. This, in turn, increases the ability of the systems to effectively respond to the challenges posed by water shortages and droughts, should they emerge. Multiple water managers from Texas mentioned in their interviews that their systems had adopted such financial innovations meant to promote water conservation by their customers. For example, Interviewee T13 stated that his system was in the process of implementing a rebate program wherein customers could substantially reduce their water bills by consuming smaller quantities of the resource. Moreover, Interviewee T1 explained the increasing block tariff that his utility had recently adopted, saying that "the board put rate structures together where the more water you use, it goes up exponentially. First 10,000 gallons is this, next 10,000 it's going to be a higher rate" (Interview T1). Increasing block tariffs are an increasingly popular conservation mechanism in which the cost per unit of water increases as the volume of consumption increases, therefore encouraging customers to limit the total amount of water that they use while simultaneously allowing them a fixed volume at a base rate.

These financial innovations elucidated by this project help answer its guiding research questions. Water utilities impacted by Hurricane Harvey have responded with innovations such as novel budget plans, contingency funds, virtual meetings, rebate programs, and increasing block tariffs. By contrast, the only financial innovation mentioned by a manager from Florida was a new billing system implemented by the utility in Pensacola (Interview F3). This points to Hurricane Harvey possibly playing a large role in the adoption of financial innovations, suggesting that the storm opened a window of opportunity for utilities there to begin a transition in this domain.

Infrastructural Innovations

Another domain in which water systems in coastal Texas and Florida are innovating is that of their infrastructure. Large numbers of water managers from both states spoke extensively throughout their interviews of the ways in which they have recently updated the physical equipment that collectively forms their systems. Generally, these infrastructural innovations fell into one of two categories: system expansion and new equipment. The former group of innovations included new large-scale items such as utility buildings, storage basins, and water mains that allow systems to produce greater volumes of water and distribute it to more people. By contrast, the latter consisted of small-scale supplies such as new lift stations, backup electric generators, and disinfection agents that aid the everyday functions of a water system.

Frequently, the impetus for innovations involving water system expansion was population growth. When cities expand and new buildings are constructed, utilities are forced to build additional water storage and distribution infrastructure to accommodate that growth. This idea was succinctly articulated by a particular water manager from a rapidly growing community near Tampa/St. Petersburg, Florida whose system is currently focused on “supply and getting the supply to where we know the growth is going to occur" (Interview F4). Other times, water distribution systems are rebuilt not because they need to sustain a growing population, but rather because they are old and deteriorating with age. Indeed, dilapidated pipes were the reason a consultant convinced the representatives of a small water utility in Texas to install an entirely new distribution system, thus improving the quality of their water and reducing losses due to leaks.

> I think everything we wanted to do, we got done, which is extremely rare in a large system that you'd fix, not only a brand new distribution system, but that you get from the meter to the houses that service line. That's almost never done in a project. And we got that done. And with these houses all being that old, 50 or 60-year-old service lines with various natures and various leaks. So this way, we could kind of get that all taken care of and brought to a modern standard in one shot, to where nobody should have any water quality issues in that whole area due to some kind of corroding service line, for example. We have all brand-new PVC stuff that's properly buried, installed, and their water quality is probably as good or better than any major city in the country right now. (Interview T11)

The leader of another water system in Southeast Texas discussed the unique challenge that required his organization to construct a new surface water plant.

> So we're going to have the surface water go to more parts of the city. Just as a background, the reason that the surface plant was built was because of groundwater subsidence. The state mandated that groundwater use be cut back by like 30% by 2015, and then 60% by 2025. And that's for this area, because in Houston there's been so much groundwater pumpage that there's a lot of land subsidence. So they're building surface plants down in this area in order to alleviate groundwater. (Interview T4)

This interviewee went on to note that this innovation has been highly successful, as it has cut his community's consumption of groundwater in half in only a handful of years (Interview T4). In fact, it has been so successful that they are currently working to expand the plant, which will allow them to send surface water "to more areas of the city" (Interview T4).

In addition to expanding and rebuilding their systems, many water managers from Texas and Florida discussed innovations that consisted of purchasing new supplies and equipment to help their systems run in more efficient and resilient manners. For example, managers in both states mentioned that their utilities were in the process of installing permanent new electric generators (Interviews T4 & F3). While the system in Texas was doing so to be able to run a newly built water plant in the event of a power outage, its counterpart in Pensacola was instead making the decision because recent population growth in the area had rendered its reliance on portable generators insufficient (Interviews T4 & F3). This reality was made clear during a recent storm that knocked out power throughout the region served by the utility (Interview F3). As the system's employees attempted to deploy their portable generators to return functionality to all their lift stations, they were met with heavy vehicle traffic that greatly slowed their response time (Interview F3). It was then that they decided to install permanent auxiliary generators at all their lift stations to avoid this delay in the future.

While a few of the innovations described by water system managers in this study focused on providing electricity to lift stations during power outages, others involved constructing new lift stations altogether. Specifically, this innovation was being implemented by a water system in Southeast Texas as a means of ameliorating the severe sewer backups that had previously plagued it during flood events.

> So when the sewer water backs up just due to many miles, 35 miles of sewer pipe leaks and breaks and people doing the wrong thing, draining their yard or what have you, we have two neighborhoods that actually experience backing up during flooding or when it's heavy rain. So what we're looking at doing is putting in small neighborhood lift stations which actually pick that water up and force it directly to a lift station. And yeah, so that would be an innovation: putting in neighborhood lift stations, specifically geared to provide relief to people. (Interview T8)

This wasn't the only innovation that the system had devised to deal with this problem. It had also previously added flappers to individual service lines so that the sewer would not back up into private residences.

> Another innovation we've done is add a flapper on their sewage on their service line to where they can flush a couple times. And you can't wash clothes or something, but we put a four-inch flapper on there where the sewer, as it backs up, it has a little bit of pressure on it, it can actually blow out towards their home. We don't want that. So we've put flappers on these ends of the lines and before the main, and it's helped people be able to get a few flushes in as the system charges before it comes back down. And that's kind of innovative. (Interview T8)

Perhaps the most unique infrastructural innovations adopted by water managers in Florida and Texas were those that they engineered themselves to overcome challenges specific to their systems. One example comes from a system in Texas that recently found itself facing an estimated $500,000 to $750,000 bill to fix an odor problem along a three mile stretch of its sewer main. Rather than paying this sum to have the problem fixed for them, the system's leaders instead decided to come up with their own solution. Eventually, they were able to fashion a lasting remedy involving an exhaust fan, a curved metal structure, a carbon filter, and some odor neutralizing agent for a relatively paltry $5,000 (Interview T3). Another unique infrastructural innovation was implemented by a different water system in Southeast Texas to inexpensively handle its residual waste, which is any nonhazardous industrial waste (Pennsylvania Department of Environmental Protection), as described by a consultant who helped with the project:

> And so we also came up with a very innovative way to handle the residuals that come off the backwash. You're allowed in Texas to dispose of the residuals on your own land, as long as it doesn't go to other neighboring properties. And we were able to invent a little spray bar off the side of the water plant, off the chain link fence where we zip tied the PVC line, drilled holes in it, and whenever the backwash kicks on, it just sprays out onto the vacant lot next door that they own. And there's no having to handle it, contend with permitting and plant infrastructure to deal with the backwash. It has some low levels of arsenic and iron and things which are all allowed for that kind of discharge. They're not toxic. And so it's a low cost, no maintenance type of handling of your residual management. And that's because residual management can become a large part of a budget for water treatment if you don't have something that's like this. (Interview T11)

The infrastructural innovations articulated throughout this section together provide some answers to the research questions posed at the outset of this study. Water utilities that faced adverse consequences from Hurricane Harvey have adopted innovations including a new water distribution system, permanent new electric generators, new lift stations, new sewer line flappers, and homemade infrastructures for handling unpleasant odors and residual waste. Such innovations suggest that these utilities have learned from the storm and are collectively attempting to scale up their innovations in order to make the water regime more resilient moving forward.

Programmatic Innovations

Another category of innovations that water systems in both Texas and Florida are adopting is that of programmatic innovations. Depending on their precise nature, these innovations sometimes require specific infrastructures or technologies to be in place before they can be implemented. However, they are all process-based, which is why they are included here as a distinct class of innovations, separate from their infrastructural and technological counterparts. Programmatic innovations were widely discussed by water professionals across both study locations, illustrating their importance throughout the industry. They take many unique forms across different utilities, but by far the most popular programmatic innovations mentioned by study participants were water reclamation/reuse programs and water treatment programs.

Of the 21 individuals who were asked about innovations for this study, nine of them described water reclamation/reuse programs that their systems had put in place. Such programs treat wastewater and then use it again for some other purpose, thus conserving the freshwater resources that would have otherwise been exploited. An example of this kind of innovation was detailed by the manager of a water system in the Tampa/St. Petersburg region of Florida.

> Oh, an innovation here in the county? I gotta say, our reclaimed water storage capacity is pretty unique to our county. There's not a lot of utilities out there that have up to 700 million gallons of reclaimed water storage. I think that's a pretty unique thing for us. And, we reuse at least 90% of our reclaimed water. So that's kind of an innovation and a success story, all at once. (Interview F6)

Another water manager from Florida's Tampa/St. Petersburg region similarly boasted about his system's reclaimed water program, noting that 80% of its recycled water is regularly reused for beneficial purposes, while only 20% of it is ultimately disposed of in the environment (Interview F1). He then went on to explain the context in which this innovation was adopted, saying that it was put in place in the 1990s and driven primarily by statewide regulations intended to alleviate the water scarcity that was at that time prevalent throughout Florida.

Even if not intended to provide water to be reused for other purposes, inventive water treatment programs were another common innovation amongst water utility managers in Florida and Texas. They were referenced by a total of five utility managers across the two states, and they served a variety of unique purposes. For example, one water system in Texas implemented a new water treatment program after repeated water quality violations.

> Well, I mean the fact that we pretty quickly got a complete treatment scheme in place. It's in a single footprint plant. We were able to completely take away their iron and manganese secondary violation problems and also their primary constituent problems of arsenic down to non-detect and do it in a way that that is long-term functioning, doesn't have to be replaced. The media and such doesn't have to be replaced. It's good every 15 or 20 years. So it's long-term viability without a lot of tending to. (Interview T11)

Another water system, this one in Tampa/St. Petersburg, Florida, is actively seeking out alternative disinfecting agents to chlorine due to concerns regarding the environmental and health impacts of the chemical.

> Were there other ideas for innovations? We're always looking at things. And some things we do, some things we don't do. For example, we're looking at disinfection alternatives to chlorine, which emits gaseous chlorine. And ozone, we're not going to consider that. Bleach, we're going to consider, and we might even consider on-site generation. But we

> look at the technology. I know a lot of people use ozone. We didn't think it was right for us. (Interview F4)

Similarly, the director of a water system in Southeast Texas views the day-to-day operations and maintenance of his wastewater treatment program as their own set of informal innovations (Interview T3). This is due to the fact that the treatment program makes use of microorganisms and, accordingly, his employees are constantly adjusting their environmental conditions to maximize their productivity.

Accordingly, these programmatic innovations adopted throughout Texas and Florida provide insight into this study's research questions. Programmatic innovations undertaken by water systems that faced Hurricane Harvey primarily include water reclamation/reuse programs and water treatment programs. However, the fact that their counterparts in Florida implemented largely the same innovations indicates that these innovations were not a direct result of the storm. This fact is important for sustainability transitions research because it strongly suggests that water systems that face future hazards will not respond with significant programmatic innovations, possibly because of the laborious efforts required to design and implement them.

Technological Innovations

By far, the largest group of innovations discussed by water managers in this study was that of technological innovations. Indeed, 17 of the 21 water professionals who were interviewed mentioned at least one technological innovation that their utility had recently implemented, including five of the seven from Florida and 12 of the 14 from Texas. In total, 38 technological innovations were described, and their defining characteristic was the use of computers or other automated equipment to generate, process, or interpret data about specific water systems to aid decision-making by their operators. Specific innovations within this category varied between water systems, but four were especially prevalent: smart meters, geographic information systems (GIS), satellite leak detection, and supervisory control and data acquisition (SCADA) systems.

Smart meters constituted a plurality of the technological innovations cited by participants in this study, as five water systems in Florida and nine in Texas had adopted them over the past few years. This form of metering infrastructure tracks volumetric and temporal trends in the water consumption of individual customers, thus providing water utilities with extensive data in real time as to where their water is going and when. Such data is useful because it can quickly alert both water systems and their customers of unsustainable consumption patterns, allowing them to remedy the situation more quickly than was previously possible. Several of the water managers who participated in this study attested to the benefits of smart meters, including this one from Southeast Texas.

> We have been selling a bunch of smart meters lately, and that's big because now customers can see in real time their water usage. It used to be they had to wait until the monthly bill came out, and by the time the bill came out they already had used the water and they didn't understand why their bill was so much. Now a smart meter actually sends them a text message that says, "Hey, don't know if you realize this or not, but you used a lot of water today. Did you mean to?" because a lot of times what happens is the customer has a leak and they don't know about it. (Interview T2)

Another water utility manager in Texas shared this enthusiasm for the benefits of the speed with which smart meters generate consumption data.

> Smart meters with waterflow measurement and reporting capabilities? Yeah, that's interesting. You know, smart meters are, I think, the wave of the future. I think more and more we're gonna have smart meters that are gonna be able to tell when somebody is using too much water or not. Be more real time instead of, you know, two months later somebody gets a bill for a high amount and they call up and say, "Hey, why did I have such a high water bill?" And so if we could find that information a lot quicker with the smart meter and be able to flag, you know, certain things, that would be somewhat important. (Interview T4)

Yet another water manager in Texas appreciated smart meters not only for their ability to provide fast and accurate data, but also for their tendency to foster meaningful interactions with it.

> What made smart meters successful? Their universal ability to connect. I mean, they're connected to the Internet. So you can see, you can create all kinds of data, links, and graphs and stuff. So that's what's made it successful is the fact that it's all connected with each customer. (Interview T6)

While smart meters were nearly universally praised by those whose systems had put them to use, they are not perfect. The manager of one water system near Tampa/St. Petersburg, Florida described a public relations hurdle that the technology initially created for his organization, although he was quick to note that this problem did not last.

> So we implemented smart meters within the last five years to help with tracking water loss, as well as to create an accurate billing system. We had inundated meters in the ground that were very old, and it was time to take that next step as far as industry standards go, and we did that. And I would say for the first year, the biggest obstacle was dealing with public relations. As I'm sure you know, with a newer meter there's a misconception out there that a newer meter will lower your bill. That's actually quite the opposite. So we were able to more accurately track water, so people's bills went up. And we did get some negative feedback from the public, of course, but that has since kind of trickled off. And it's actually, I think the public appreciates it more so because we're able to, from a computer, determine if they've got a problem on their side of their meter in their home, if they've got a leak. We're able to help them out in solving problems. (Interview F7)

Another technological innovation that was widely discussed by water utility managers from Florida and Texas was their systems' employment of geographic information systems (GIS). GIS is a computerized mapping tool that allows users to visualize and analyze spatial data. Four of the professionals interviewed for this study discussed the ways in which their water systems had utilized GIS, including three in Florida and one in Texas. Primarily, systems used this tool to track the locations of their physical infrastructures, as well as record the current conditions of these assets. This fact was discussed at length by the manager of a water system in Tampa/St. Petersburg, Florida.

> And one of them is our GIS team here. Our guys that do that are not highly trained GIS analysts or technicians. They basically just figure it out themselves. These are guys that got a bunch of GPS backpack units and started collecting data, and they have been able to drop all that into our GIS system, not only with the backpack units, but also we got the Collector app. And they're collecting all the infrastructure, all the data, populating all of the maps to be able to take into all of our CAD drawings and develop a robust GIS system, where all of our information is in that mapping program. So that we can easily pull that information when we need it, especially if you're out in the field and you want to know something about a valve, or hydrant, or some pipe and know what condition it's in. You can get that information from the system. (Interview F6)

The locational information of equipment provided by GIS can also have environmental benefits, a topic which was brought up by another water manager in Tampa/St. Petersburg, Florida.

> I would also say our GIS mapping system, mapping all of our water mains and valves based on feedback from crews out in the field…With our GIS mapping system, with our maps being accurate and our valves being where they are shown on the map, we would, in a roundabout way, be able to save water. If we were to have a major water main break, our guys would be able to respond and shut those valves off and stop the leak, saving tens of thousands if not hundreds of thousands of gallons of water. (Interview F7)

Satellite leak detection systems were another one of the most popular technological innovations discussed by water utility managers in this study. These systems use aerial images from sensors on satellites to determine the precise locations of significant leaks in water mains, and they have been adopted by five of the systems operated by participants in this study. Four of those systems are in Southeast Texas, compared to one in the Tampa/St. Petersburg area of Florida. The benefits to water systems of using satellite leak detection to quickly locate and remedy large-scale water losses from their pipes are twofold. First, doing so contributes to the environmental sustainability of the systems by reducing the amount of water that they need to produce to sufficiently serve their customers. Moreover, adopting the technology augments the financial sustainability of the systems by decreasing the amount of water they distribute that does not, in turn, generate revenue. One water manager from the Tampa/St. Petersburg region of Florida gave a detailed description of his organization's satellite leak detection program.

> We do a satellite leak detection program using a company called Utilis. This company has been one of the firms that has been part of the team that has been trying to find water on Mars. So their satellite technology and their software signature is that they find, so like if there's chlorine in the water or something like that they can kind of decipher that, which is why they're useful leak detection. So they do the satellite run over a certain area, and then, through the signature of the water that they find, they're able to run it through some algorithms or whatever, however they do it. And they can tell if it's your municipality or your county or if it's your actual water supply that's showing up in that area. And then they can determine where the leak is, and then they actually have boots on the ground techniques that they're able to go down and get a lot closer to where the actual leak is coming from. (Interview F6)

A water professional in Texas who talked about his system's satellite leak detection system mentioned that he regularly uses the data from it to generate a water accountability report. This has been beneficial because "the board can see every month their accountability, if they're losing water through leaks," which then "kind of forces their hand to make repairs" (Interview T1). In this way, satellite leak detection allows water systems to make repairs to their infrastructure that save both resources and revenues much faster than they were previously able to.

The final technological innovation that was widely common among water utilities managed by study participants was that of supervisory control and data acquisition (SCADA) systems. SCADA systems allow users to monitor and control field equipment virtually from a remote location, which is especially important to large technical systems like water utilities that are comprised of huge numbers of interconnected individual pieces of equipment. Four water system managers cited their SCADA systems as technological innovations during interviews, all of whom were from Texas. One of them discussed the benefits that his system anticipates receiving once its SCADA system is fully implemented, mentioning that it will "send out a signal that'll say if something's going on with the water plant…It'll basically notify you on your phone what's going on" (Interview T7). Another water manager from Texas discussed his utility's SCADA system while also taking the time to touch on the barriers that some utilities, particularly smaller ones with fewer financial resources, may face when trying to acquire such technology.

> We developed a SCADA system for data acquisition only. It doesn't operate anything. Visual information…And then on the SCADA system, it's all the same barriers with it. There's quite a bit of upfront cost, and I had to figure out how to cut those costs, and I designed, worked with people, and did my own type of little SCADA system. So, I guess the people, the governing body understanding the importance of being able to see data, trend data, and make decisions off of those trends. (Interview T14)

In terms of answering the study's research questions, many of the innovations implemented by water utilities impacted by Hurricane Harvey are technological ones. These overwhelmingly include, but are not limited to, smart meters, GIS, satellite leak detection, and SCADA systems. The technological innovations described by water managers in Florida largely fell into the same four categories, which means it is unlikely that these innovations can be directly attributed to the experience of the storm. However, the sheer number of technological innovations adopted by water utilities in Southeast Texas after Hurricane Harvey is extremely important for sustainability transitions theory because it highlights how heavily many water systems rely on incremental, technocentric innovations to become more sustainable, as opposed to more diverse portfolios of radical innovations.

Environmental Innovations

Finally, a number of the water professionals who were interviewed for this study identified environmental innovations as being important to their utilities. Environmental innovations are defined by their existence at the nexus between water systems and the natural environment. Accordingly, all of the ones described by participating water managers fell into one of two categories. The first consists of those innovations intended to reduce the negative impacts that water system operations have on the environment. Conversely, the second is made up of those meant to increase the resilience of water systems to natural hazards and other environmental challenges. Particularly salient among the latter group of environmental innovations were those precipitated by the damage that Hurricane Harvey inflicted throughout Southeast Texas. In total, five water professionals across Texas and Florida enumerated 10 distinct environmental innovations.

Among the environmental innovations adopted by water systems to reduce their environmental footprints, the use of solar energy was the most popular. For example, the manager of a water utility in Tampa/St. Petersburg, Florida that had recently begun using solar power maintained that the decision to do so was rooted in the system's commitment to becoming more sustainable by expanding its energy portfolio to more clean sources (Interview F1). Similarly, one of his counterparts in Texas hoped to invest in solar panels in the near future, although this project was at that point on hold for financial reasons.

> Yeah, when we were doing that wastewater project for the conversion of the aeration basins, the pumps, we wanted to implement solar technology out here for just our little campus. And it was determined that the payback would be too long, even though I didn't think it was all that long. So that was a money thing. (Interview T10)

Although that water system in Texas had yet to implement solar panels, it had reduced its energy consumption substantially by upgrading some of its old equipment to a more energy-efficient version. The manager of the system spoke about this change and its financial co-benefit to the utility.

> We applied for and got a grant for more energy efficient blowers at our wastewater treatment facilities. That was a good thing, but that's hardly innovating. But it is taking advantage of a system, and our processes work a little better now. It didn't save water. But it did save energy consumption costs for wastewater treatment, which those can be a big drag on a municipality. We anticipated that we save about $110,000 a month in energy costs. (Interview T10)

Additionally, the system hopes to make its future facilities more sustainable by designing them with Leadership in Energy & Environmental Design (LEED) standards in mind, as LEED is the premier green building certification program in the world.

> We have a policy for LEED facilities. We don't want to achieve LEED status necessarily, but we want to implement LEED techniques when constructing facilities, so that's good. It's basically like doing everything in accordance with LEED except get the plaque, right? (Interview T10)

The six remaining environmental innovations discussed by water utility managers for this study were all intended to increase the resilience of their systems to hurricanes and other natural threats. Accordingly, five of the six were undertaken by systems in Southeast Texas that were directly impacted by Hurricane Harvey, and which hoped to reduce their vulnerability to future storms of equal or greater magnitude. The other one was a resiliency plan being implemented by a system in coastal Florida with particularly vulnerable assets. Even though this system has not faced a severe hurricane in recent years, its manager knows that investing in precautionary measures now could save substantial money in the future.

The resiliency plan that was described as an innovation by a water utility manager from Tampa/St. Petersburg, Florida is currently in the process of being carried out. It is expected to cost between $100,000 and $200,000 in total, although the water manager who was interviewed estimated that it could ultimately save his system millions of dollars if a particularly strong hurricane makes landfall in the area. This is due to the fact that many of the system's facilities are located in floodplains and are therefore highly vulnerable to even minimal storm surge. Thus, the leadership of the water system has been working to save money and fill out grant applications to fund the rest of the project, and they hope that doing so will spur the municipality they serve to make its own resiliency plan as soon as possible (Interview F1).

Almost all of the environmental innovations adopted by Texas water systems in the wake of Hurricane Harvey relied on physical means of protecting their most valuable assets from flooding. One of the more common examples of this involved elevating critical equipment so that it would be out of the reach of even the highest floodwaters in the future. This idea was discussed by a water manager from the Houston area.

> Some districts have decided to take all of their electrical components and mount them up in the air on pedestals that are 10 feet high in the air, thinking that they would, if it happens again, the flooding would not affect their electrical components. I don't know if that is a good strategy because I don't know if Harvey's the worst one that we're ever going to see. And how high do you go? Is 10 feet high enough? Is 12 feet high enough? I don't know. The way that we look at it is Harvey was a once in a lifetime event. We don't have any data to suggest that Harvey is going to happen again. So we have reconstructed everything to the best we can. (Interview T2)

A similar technique was employed by another water professional in the area whose system was working to protect its operator's control building.

> Well, we are starting to put things up in the air like I mentioned. I don't have a choice. I mean, it's crazy to think I'm building an operator's control building four feet in the air, but that's what I'm doing. (Interview T8)

In addition to placing valuable assets at higher elevations, another popular approach to protecting important water system equipment was to physically surround it with protective infrastructure.

> This is nuts. We're looking at possibly spending approximately $100,000 on a dam that protects our water plant administration building. It's a two acre, we have like about a two acre site here of admin facilities and a water plant. So we're looking at possibly purchasing a dam that covers all that. (Interview T8)

This approach was echoed by a different Texas water manager with a similar goal.

> Some utilities have purchased, there are some companies out there that are making fences that basically, I don't know how to describe this, but they go around your facility. And as the storm comes, the top of the fence has got a buoy on it, and it raises the fence up as the water level rises. So it floats on top of the water, and they claim that it can keep the water from coming into the facility. (Interview T2)

Not all of the environmental innovations triggered by Hurricane Harvey were physical in nature, however. For example, a water professional working with a small system in Southeast Texas discussed the unique approach that his organization came up with to protect its assets during future emergencies.

> They trained up an additional set of local volunteers that are customers and board members to be able to know how things work operationally. And, not that they're the certified operator, but they can. Let's say the road is impassable. They are able to by phone communicate to a cell phone to the operator, they can take instruction, and they can deal with some of the stuff at the water plant that they have to just if he couldn't get there. And they decided they needed to do that as a result of this event. They didn't have to contend with it this time. But they were, they realized, like the power line can be down across the road and you can't get in. If there's a single road in here, we can't get somebody in here. We might need to have some of those locals that are living here make sure the chlorinator is working or whatever else once they get power going. Or the operator may be so strung out with various water systems he's all contracted with he just can't get there. So they basically have trained up additional local volunteers to help operate the water system in an emergency. (Interview T11)

Unlike all the previous categories of innovations discussed throughout this chapter, the environmental ones show clear evidence that water utilities are learning from previous flooding events. This is because in addition to those innovations intended to reduce the environmental footprints of water utilities in both Texas and Florida, many resilience-focused innovations were mentioned only by water utility managers from Southeast Texas. These included elevating valuable assets, constructing dams and fences around vital utility buildings and equipment, and training local volunteers to run systems in the event of an emergency. Only one resilience-centered innovation was mentioned by a water manager from Florida, making it extremely likely that these innovations were a direct response to Hurricane Harvey. This fact shows just how important shock events are for opening windows of opportunity for innovation that contributes to sustainability transitions.

Summary

This chapter highlighted the many innovations that water utilities in the metropolitan regions of Houston, Texas; Beaumont/Port Arthur, Texas; Tampa/St. Petersburg, Florida; and Pensacola, Florida have adopted since Hurricane Harvey made landfall in August of 2017. These included educational innovations targeted at both water system employees and customers, financial innovations meant to increase system solvency and water conservation, and infrastructural innovations that physically expanded systems or provided them with new equipment. They also included programmatic innovations such as water reuse and wastewater treatment programs; technological innovations such as smart meters, GIS, satellite leak detection, and SCADA systems; and environmental innovations such as green technologies and those that make the systems more resilient and therefore less vulnerable to natural hazards. Whenever possible, these innovations were detailed using direct quotes from the water managers who implemented them, as it was assumed that their words were the most apt to provide insight into their thinking. In this way, it is hoped that this study granted its participants with a substantial degree of sovereignty over the data they provided.

The following tables provide a brief glimpse at the quantitative results of this study that have hitherto been neglected in favor of their qualitative counterparts. Although this numerical data does not provide the same depth or richness of insight into water utility decision-making processes as the interview answers previously highlighted, some valuable insights can still be gleaned from it. For this reason, a succinct discussion of these quantitative results is warranted.

Innovation Type	Total Texas Innovations	Texas Innovations Per Utility	Total Florida Innovations	Florida Innovations Per Utility
Educational	8	0.571	2	0.286
Financial	5	0.357	1	0.143
Infrastructural	8	0.571	2	0.286
Programmatic	11	0.786	6	0.857
Technological	26	1.857	12	1.714
Environmental	8	0.571	2	0.286
Total	66	4.714	25	3.571

Table 1 – categorical innovations by study location

Table 1 depicts the total number of innovations within each category adopted by water utilities in Texas and Florida, as well as the mean number of innovations of each type implemented per utility in each state. Overall, the utilities in Texas whose managers were interviewed for this study have innovated at a higher rate than those in Florida in the time since Hurricane Harvey made landfall in August of 2017. This can be observed since Texas water systems have adopted more innovations per utility than Florida systems in five of the six innovation categories identified. Furthermore, Texas systems have implemented, on average, 1.143 more innovations per utility than Florida systems. It is important to recognize this information because it shows that water utilities are in fact learning from previous flooding events. Simply, water utilities that were caught in the path of Hurricane Harvey as it stalled over Southeast Texas for the better part of a week have responded in the years since by innovating at a faster rate than those located in the control locations of Tampa/St. Petersburg and Pensacola, Florida, with the hopes of increasing their resilience against future natural hazards.

Interviewee	Six-Day Rainfall Total	Innovations
T8	60.58”	6
T5	60.58”	3
T13	49.94”	8
T9	47.35”	5
T14	45.10”	6
T7	40.00”	5
T6	37.64”	2
T2	35.09”	5
T4	35.08”	7
T1	32.65”	7
T12	30.27”	1
T10	27.07”	5
T3	25.07”	2
T11	15.60”	4

Table 2 – number of innovations per Texas utility with Hurricane Harvey rainfall totals

Similarly, Table 2 depicts the total number of innovations adopted by each water utility in Texas whose manager participated in this project, as well as the total amount of rain that fell in the community it serves between August 25th and August 31st, 2017 (NOAA, 2017). Early in this study, it was hypothesized that those utilities which experienced the most rainfall during Hurricane Harvey would implement the most innovations after it. However, this does not appear to be the case. This might be due to the fact that the severe damage inflicted by Hurricane Harvey received so much national and international attention that even those water utilities who did not receive as much rainfall from it were forced to recognize the necessity of innovating afterward to reduce their vulnerability to future hazards.

Chapter 5: Conclusion

Introduction

The final chapter will provide a holistic overview of everything that has been discussed to this point, with a particular focus on both the theoretical and practical implications of the results of the study. Consequently, the rest of the chapter is organized into five sections. First, (a) *Summary of the Study* provides a broad synopsis of the project, while (b) *Discussion of the Findings* interprets its results as they relate to the existing academic literature. This is followed by (c) *Implications for Practice*, which suggests some ways in which stakeholders of urban water systems may choose to apply the results of the study in the real world, and (d) *Recommendations for Further Research*, which outlines a few ideas for extending the project in future scholarship. Finally, the entire study is wrapped up with a quick summary section.

Summary of the Study

The purpose of this study was to examine how severe flooding events impact the innovativeness of urban water utilities. More specifically, it was designed to investigate what innovations those Texas utilities impacted by Hurricane Harvey in 2017 have adopted in the years since the storm, and then to compare these innovations to the ones implemented over the same time period by their unaffected counterparts in Florida. In this way, the study aimed to understand the impact of Hurricane Harvey on the types of innovations undertaken by the water systems directly affected by its flooding. Ultimately, it was hoped that by examining how some water utilities learned from a severe flooding event in the past, the project would help establish a precedent for other utilities to follow when they face their own shocks in the future.

The goals of this study were particularly important for a couple of reasons. First, natural hazards such as floods and hurricanes are expected to increase in frequency and magnitude as climate change continues to alter the earth in unprecedented ways (Emanuel, 2017). Since people rely on the continual supply of safe water provided by utilities, it is of utmost importance that those utilities most vulnerable to hazards such as these are able to respond in an appropriate manner. Moreover, the innovations made by individual water utilities in response to disasters have the ability to precipitate sustainability transitions in water systems. These transitions can make the systems more resilient to future shocks, so it is vital to understand the conditions that are most likely to foster them.

With these goals in mind, the study sought to answer the following research question, as well as three sub-questions that fell within its scope:

- How are water utilities learning from previous flooding events?
    - What innovations have water utilities impacted by Hurricane Harvey undertaken since the storm to increase their resilience?
    - How do the innovations adopted by water utilities affected by Hurricane Harvey differ from those implemented by their counterparts that went unscathed by the event?
    - Why is this important for sustainability transitions theory and practice?

Ultimately, each of the innovations discussed by water utility managers in Texas and Florida fell into one of six categories. Educational innovations included a diverse set of employee training programs and customer education initiatives, while financial innovations consisted of various contingency funds and novel rate structures. Additionally, infrastructural innovations encompassed system expansions and new equipment purchases, and programmatic innovations comprised of water reclamation/reuse programs and water treatment programs. Finally, technological innovations included smart meters, GIS, satellite leak detection, and SCADA systems, while environmental innovations encompassed green technologies and practices, as well as resilience-focused projects. Among the innovations intended to increase the resilience of water systems to natural hazards was a subset of innovations notable for being adopted by utilities in Texas as a direct response to Hurricane Harvey.

Discussion of the Findings

For the most part, the results of this study confirm the findings of the existing innovation scholarship focused on urban water utilities and systems. Indeed, previous researchers have investigated the conditions under which water systems innovate, the characteristics of the innovations they implement, and the barriers that sometimes hinder their innovation processes. Within this plethora of academic literature, multiple studies have described past innovations adopted by water systems, which primarily fell within the domain of each of the six innovation categories elucidated by this project. The existence of this scholarship with similar findings therefore lends credence to the legitimacy of the results of this study.

To start, much academic literature points out that it is common practice for urban water systems to implement educational innovations, especially as a response to climatic events. For example, Gasbarro *et al.* mention that when water systems face droughts, they frequently respond either by augmenting their existing water supply with previously untapped sources or by teaching their customers to conserve more water (2016). The latter option tends to be the cheaper one, and therefore it is often the first of the two to be adopted by water systems when drought strikes. Moreover, a recent study on the relative success of various financial and educational mechanisms meant to reduce demand among customers of a drought-stricken United Kingdom water utility finds that the most effective and long-lasting technique for doing so is to regularly tell each customer how much water he or she consumes relative to his or her neighbors (Lu *et al.*, 2019). This tactic thus employs perceived peer pressure to encourage high water users to reduce their consumption, although it can sometimes backfire and convince low water users that they are free to use more of the resource without negative environmental consequences (Lu *et al.*, 2019).

These findings on the prevalence of educational innovations in the water utility industry are largely reflected by this study. In all, 10 educational innovations were discussed by water managers during their interviews, half of which were directed toward their customers as opposed to their employees. Particularly germane among these innovations was the practice of sending letters to the top five water users in the Texas system managed by Interviewee T1 to make them aware that they were "kind of bucking the average there." This was especially smart because by limiting these alerts to only the top water users, this utility was presumably able to avoid the aforementioned pitfall of giving low water users an excuse to consume more (Lu *et al.*, 2019). However, it should be acknowledged that very little consideration is given in the academic literature to educational innovations made by water systems to enhance the skills of their employees. This most likely does not mean that the water systems interviewed for this study were exceptional for doing so. Rather, it presumably signifies that these training and continuing education programs are common enough that they are not frequently viewed as innovative, and for that reason they did not show up in the systematic literature review conducted for this study. Thus, the academic literature seems to support this study's finding in regard to the research questions that water utilities exhibit learning from natural hazards by implementing educational innovations that help their customers to conserve water, thus allowing them to transition to a more sustainable state.

The academic literature also suggests that financial innovations like those elucidated by this study are commonplace in the water utility industry. Furthermore, the scholarship has largely found the factors that foster these innovations to be nearly identical to those discovered here, namely the twin imperatives of ensuring the continued economic and environmental sustainability of the systems. Therefore, it seems to confirm the finding in this study that the adoption of financial innovations is a valuable means of increasing revenues and conserving water, which helps answer the study's research questions. Among the most studied financial innovations intended to keep water systems solvent in times of unforeseen economic hardships are contingency funds and drought surcharges. Contingency funds are created when water systems consistently save a portion of their revenues to be used in the future when revenues drop or expenses rise for unexpected reasons (Zeff & Characklis, 2013). They are thus a powerful tool for increasing the financial viability of water systems, although correctly predicting just how much money to save or preserving these funds for their intended uses can often prove challenging. Drought surcharges, in turn, are rate increases that utilities implement when water use restrictions are in place, thus recuperating diminished revenues from reduced water sales (Zeff & Characklis, 2013). This tactic, however, can sometimes prove infeasible since rate increases tend to be unpopular among the customers paying them.

In terms of financial innovations, which incentivize water system customers to consume less of the resource, increasing block tariffs seem to have received the most attention in the academic literature. This rate structure charges more per unit of water the more water is used, thus encouraging customers to hold their consumption below specific thresholds (Diaz & Yeh, 2014). Increasing block tariffs have been growing in popularity around the world, with prominent studies documenting their effects in locations as diverse as North Carolina and the United Kingdom (Zeff & Characklis, 2013; Lu *et al.*, 2019). Indeed, a two-tiered increasing block tariff adopted by the Los Angeles Department of Water & Power in the 1990s is a significant reason why the city's overall water use has declined over the last 30 years, even as its population has grown by 1.2 million (Hughes *et al.*, 2013).

Of these three prominent financial innovations described in the literature, two were discussed by water managers that participated in this study. Water managers T1 & T11 from Texas explained how their systems relied on contingency funds to help them overcome surprise economic hurdles, with the former also mentioning that his utility had recently implemented an increasing block tariff to encourage its customers to save water. These similarities between prior scholarship and the results of this study point to the legitimacy of the findings presented in the previous chapter. However, none of the participating water professionals in this study talked about drought surcharges. This fact is unsurprising since the study's four locations of focus all receive substantial annual precipitation and therefore rarely deal with drought; they are, as one participant put it, "blessed in water. [They]'re water rich in th[ose] part[s] of the country" (Interview T8). Thus, this discrepancy does not diminish the quality nor the robustness of the findings of this project.

Although infrastructural innovations as defined by this study were one of the more popular categories of innovations among participating water utilities, they have received relatively little attention in the academic literature. Nevertheless, where they do show up, infrastructural innovations are frequently described as a critical means both for decreasing the vulnerability of water systems to climate change-induced hazards, as well as for reducing the water consumption of their customers. For instance, increasing water storage capacity can make systems more resilient to drought by expanding their supply when the resource is otherwise scarce in the immediate area (Gasbarro *et al.*, 2016). Further, constructing emergency generators with on-site fuel storage allows utilities to operate continuously during extreme weather events even if power is lost for an extended period of time (Diaz & Yeh, 2014). With regard to reducing the water demand of end users, low-flow fixtures and appliances are an extremely popular and effective infrastructural innovation, as they can decrease total water consumption by up to 30% (Diaz & Yeh, 2014). In fact, alongside the increasing block tariff discussed previously, a low-flow campaign was a pivotal part of the 1990s conservation program that has seen the net water use of the city of Los Angeles decrease over the last three decades, even as the city has continued to grow (Hughes *et al.*, 2013). This academic literature therefore validates the finding that infrastructural innovations can be a powerful signal of learning by water utilities that have experienced natural hazards, which is especially important when considering the first research question.

While many of the water managers interviewed for this study chose to adopt similar infrastructural innovations to those discussed most extensively in the literature, they sometimes had quite different motivations for doing so. Interviewees F4 from Tampa/St. Petersburg, Florida & T4 from Texas, for example, both mentioned expanding the storage capacities of their systems, but they chose to do so in order to deal with population growth and groundwater subsidence, respectively. Furthermore, participants from both sites highlighted installing new electric generators, although the one from Pensacola did so to ameliorate the negative consequences of population growth rather than to keep his system running during severe weather events (Interviews T4 & F3). These infrastructural innovations uncovered in this study, then, largely reflect the findings of previous scholarship in their forms but not their catalysts. Interestingly, none of the water professionals who participated in this study described employing low-flow fixtures and appliances to reduce the water demand of their customers. This is most likely because such water efficient equipment is now the norm and therefore no longer viewed as an innovation. As one study participant put it, "you cannot buy an inefficient water system now. You can't buy an inefficient HVAC system. No architect is going to design you a building with an inefficient air conditioning system in it, you know what I mean?" (Interview T10).

Out of the six categories of water utility innovations identified in this project, programmatic ones appear to have been the least studied in contemporary scholarship. To this end, only a few academic papers were found which discuss innovations of this nature in any meaningful way. One of them theorizes that potable water reuse programs must obtain three forms of legitimacy before they can be accepted by the public: pragmatic legitimacy, moral legitimacy, and cognitive legitimacy (Harris-Lovett *et al.*, 2015). Another explains how a newfound willingness to put recycled wastewater and stormwater to use for productive ends has helped Los Angeles shift away from its long history of relying almost solely on imported water in favor of water independence (Hughes *et al.*, 2013). This lack of focus on programmatic innovations, just like the results of this study, appears to suggest that such innovations are not a commonplace response to natural hazards, which helps to answer the primary research question.

Perhaps this dearth of academic literature regarding programmatic innovations in urban water systems is due to their abstract nature being incompatible with most people's visualizations of innovations as tangible, primarily technological, items. Regardless, many of the water managers who participated in this study mentioned that their systems had adopted programmatic innovations in the past, the majority of which were either water reclamation/reuse programs or novel water treatment processes. The fact that representatives of eight different water systems across coastal Texas and Florida highlighted their water reclamation programs implies that such projects are quickly gaining legitimacy in the eyes of the public, and that they will continue to play an increasingly significant role in the transition toward sustainable water consumption. Additionally, the regularity with which these professionals touted their water treatment schemes as programmatic innovations illustrates the unsung importance of the practice to everyday utility operations, even if it has not yet been thoroughly examined in the literature.

Recent scholarship seems to demonstrate that the great popularity of technological innovations among those water systems whose managers participated in this study is indicative of a larger trend. Indeed, one survey of 38 Oklahoma water utilities impacted by severe drought finds that over 80% of the innovations they have implemented in the years since are "infrastructure-based" rather than "institutional," meaning that more than four in five of their innovations have involved changing physical technologies and equipment as opposed to immaterial processes and practices (Hartman *et al.*, 2017). This considerable reliance on technological innovations specifically, and all tangible ones more generally, might be explained by their compatibility with the observation that innovations are adopted at higher rates when they provide a competitive advantage, are consistent with existing organizational capabilities, are easy to trial, and have outcomes which are easily observed (Spiller *et al.*, 2015). It is far simpler to measure, for example, how much water smart meters save than how much more efficient a new employee training program makes a utility.

Many such technological innovations, then, have been explored in the academic literature. One such example comes from an article examining the reliability of a United

Kingdom regional water supply system which ultimately finds that the utility invests most heavily in automated monitoring and control systems when attempting to minimize risk (Bradshaw *et al.*, 2011). Moreover, the use of leakage control technologies are posited in another paper as a critical adaptation measure for utilities confronted by climate change-induced water scarcity (Gasbarro *et al.*, 2016). Finally, smart meters are praised in a third study not only for their ability to save water by quickly identifying probable leaks, but also for their ability to educate customers and utilities alike by generating real-time consumption data (Diaz & Yeh, 2014). Accordingly, the academic literature supports this project's finding that the implementation of technological innovations is perhaps the most common response to natural hazards by impacted water utilities. This is important for sustainability transitions practice because it means that these innovations are the ones that are most likely to be scaled up and to destabilize the existing water regime, possibly precipitating a full sustainability transition.

As mentioned in the previous chapter, this enthusiasm for technological innovations on the part of urban water systems was mirrored in the findings of this study. By far the most discussed such innovations by participating utility representatives were smart meters, GIS, satellite leak detection, and SCADA systems. To this end, each of these four technological innovations was described by at least four different utility managers across Texas and both Tampa/St. Petersburg & Pensacola, Florida, with smart meters being reported by a whopping 15 of the total 21 participants. These high numbers of reported technological innovations, both in this study and among the wider academic scholarship, are important to note for a couple of reasons. First, they highlight the reality that at this point, hard innovation is more important to water systems than soft innovation. This trend will likely continue for the foreseeable future, as illustrated by the Texas water manager who enthusiastically described smart meters as "the wave of the future," which will have significant ramifications for water utility operations and planning for a long time to come (Interview T4). The seeming ubiquity of technological innovations among water systems is also important to consider because it begs the question of whether these systems are becoming too technocratic in their approaches to climate resilience. After all, what good are these innovations, ultimately, if the social context in which they are embedded is not also considered?

Finally, the rise of climate change as a central societal issue over the past few decades has been accompanied by an abundance of contemporary scholarship on environmental innovations in urban water systems. Just like those described by the participating water managers in this study, the environmental innovations discussed in the literature can largely be divided into two categories: environmental innovations meant to curb the ecological impact of water utility operations, as well as resilience-focused innovations intended to reduce the vulnerability of water utilities to natural hazards and other ecological challenges. In terms of the former group, most of the suggested innovations involve mitigation of system greenhouse gas emissions, primarily through fuel diversification (Gasbarro *et al.*, 2016). Simply, water systems would be more environmentally sustainable if they emitted less carbon into the atmosphere by replacing at least some of their consumption of fossil fuels with that of clean energy sources like solar and wind. With regard to the latter group, an array of resilience-centered innovations have been encouraged, ranging from creating resiliency plans to upgrading flood-protection facilities and from elevating valuable plants and equipment to erecting hard storm surge barriers such as levees, dams, and sea walls (Gasbarro *et al.*, 2016; Diaz & Yeh, 2014). Thus, the existing scholarship relates to the research questions guiding this study by showing that many water utilities, similarly to the ones discussed throughout this study, learn from natural hazards by implementing an array of resilience-focused innovations at a disproportionately higher rate than their counterparts that have not recently faced any such events.

These environmental innovations examined in the academic literature are startlingly similar to those adopted by the water systems interviewed for this study. For instance, two water managers, one each from Texas and Tampa/St. Petersburg, Florida, mentioned during their interviews that they had either recently begun using solar power or were hoping to do so in the near future in order to make their utilities more sustainable. Furthermore, a participant from the Tampa Bay area of Florida spoke extensively about the importance to his system of creating a resiliency plan in the immediate future due to its low-lying location along the Gulf Coast and its resultant vulnerability to hurricane-induced flooding and storm surge. Finally, a handful of the water managers from Texas whose systems had suffered severe damage from Hurricane Harvey talked about the engineering-based solutions their utilities had come up with to increase their resilience to flooding from future hurricanes. These included elevating electrical components and control buildings so they would be out of the reach of floodwaters, as well as constructing dams and fences around utility facilities to prevent water from breaching them in the first place in the event of another hurricane or similar flood event. The strong parallels between the environmental innovations overviewed in the academic literature and those elucidated in this study, then, suggest that most of the interviewed utilities in Florida and, particularly, Texas are at the forefront of innovation and best practices. They are learning from past severe weather events and responding by putting in place many of today's most revolutionary ideas for environmental innovation.

The answer to the research question posed at the outset of this study, then, is that water utilities are learning from previous flooding events by implementing innovations that are primarily physical in nature and intended to protect their facilities and infrastructures from future floodwaters, thus allowing them to continuously operate during and immediately after natural hazards. Both water utilities in Southeast Texas which were impacted by Hurricane Harvey in 2017 and their counterparts along Florida's Gulf Coast which have not faced a severe flood event in at least the past 25 years have adopted largely comparable innovations to one another in the domains of educational, financial, infrastructural, programmatic, technological, and environmental innovations, with the primary goal of increasing their sustainability. However, a distinct difference exists between the two groups of utilities in terms of their resilience-centered innovations. The utilities in Texas have in some cases elevated critical equipment and constructed protective dams and fencing around their facilities in anticipation of future storms. One has even gone so far as to train a local group of volunteers to run the water system in the event of an emergency which prevents its operator from being able to access it. By contrast, only one utility in the Tampa/St. Petersburg metropolitan region in Florida has even begun to contemplate possible innovations to increase its resilience, as it is considering the creation of a resiliency plan in the imminent future. This stark difference in the approaches to resilience between those water utilities which were damaged by Hurricane Harvey and those which were not points to the fact that utilities do learn from external shocks such as severe weather events. Accordingly, the lessons that they have learned can, and should, be heeded by other coastal utilities which may be themselves vulnerable to hurricanes and other major flood events. That way, they can take a proactive approach to climate resilience which will protect not only their assets, but ultimately their customers who depend on them for a continuous supply of clean and safe drinking water.

These findings are important for sustainability transitions theory and practice because they provide evidence that Hurricane Harvey may have been a catalyzing event that pushed water systems across Southeast Texas into the take-off phase of a sustainability transition. Due to the long-term nature (25-50 years) of transitions (van der Brugge *et al.*, 2005), it is nearly impossible at this point to ascertain whether the resilience-focused innovations undertaken by utilities after the storm amounted to the first steps in a longer process, or simply one-time changes. However, the finding that utilities in Texas have adopted such innovations at a much higher rate than their counterparts in coastal Florida suggests that the damage inflicted by Harvey opened a window of opportunity for a transition to begin. If this opportunity is actively and properly managed by the relevant stakeholders, then the niche innovations elucidated by this study can be scaled up to destabilize the existing water regime, and systemic change can occur.

Sullivan *et al.* (2017) note that the shift of a system from the pre-development phase of a sustainability transition to the take-off phase is "often accompanied and catalyzed" by critical events that threaten the status quo. Hurricane Harvey was possibly such a critical event, as it brilliantly highlighted the inadequacy of resilience efforts to that point by water systems across Southeast Texas. In response, the managers of these systems implemented an array of new innovations to protect their assets from future hazards, from elevating critical equipment to constructing physical flood barriers and even training local volunteers to operate a utility in the event of an emergency. The widespread adoption of such innovations by utilities impacted by Hurricane Harvey relative to the dearth of them implemented by their unaffected counterparts in coastal Florida suggests that water systems in Southeast Texas may have entered the take-off phase of a sustainability transition. Nonetheless, the technocratic nature of the majority of these resilience-centered innovations implies that even if a transition is indeed underway, the systems undergoing it are still far from moving into the acceleration and stabilization phases. This is because during past transitions in both the Netherlands and cities across the western United States, these latter phases have been characterized by the shift away from technocratic approaches to resilience and toward integral and participatory ones with a greater focus on the ecological functions and values of water (van der Brugge *et al.*, 2005; Sullivan *et al.*, 2017).

Thus, the findings of this study provide support for many of the theoretical principles of sustainability transitions. The possibility that Hurricane Harvey catalyzed a transition in water systems across Southeast Texas illustrates the non-linearity of transitions (Loorbach *et al.*, 2017), as the region's utilities remained in the pre-development phase for an extended period of time before this shock event coaxed them into the take-off phase. Moreover, the adoption of resilience-focused innovations by utilities throughout the region after the storm highlights the multilevel dynamics of transitions (Loorbach *et al.*, 2017) since a landscape event opened a window of opportunity for niche innovations to take hold, which will now attempt to scale up and destabilize the dominant water regime. However, it is currently too early in the transition to locate any evidence to support the principle of emergence (Loorbach *et al.*, 2017), as this requires the chaotic change of a transition to stabilize into a new status quo, something that will not happen until the fourth and final phase of the transition. Furthermore, the principles of coevolution and variation & selection (Loorbach *et al.*, 2017) are not within the scope of this study, as the former requires a wider focus on social and institutional changes in addition to system innovation, while the latter requires a longitudinal view of experimentation in innovation.

In terms of sustainability transitions practice, the results of this study are important for a couple reasons. First, they indicate that water systems in Southeast Texas may be on the cusp of a sustainability transition. This knowledge is valuable because it ought to encourage these utilities to continue to innovate, as well as push local decision-makers such as lawmakers and utility leadership to foster an environment in which innovation can flourish. That way, these water systems can become more resilient to future threats, thus making them more dependable for their customers, even in the worst of circumstances. More broadly, these results indicate that shock events can catalyze sustainability transitions in urban water systems. Armed with this knowledge, water managers whose systems face hazards in the future can use the recovery process as an opportunity to update their technologies and practices so that they too can become more sustainable and resilient.

Implications for Practice

The results of this study highlight the reality that there are several concrete steps which climate-vulnerable water utilities can take to increase their resilience to natural hazards. These include elevating valuable assets so that they are not submerged during large-scale flood events, as well as constructing protective dams around low-lying facilities and equipment to prevent them from being breached by floodwaters in the first place. Additionally, vulnerable utilities may choose to adopt resiliency plans and implement redundancies in both equipment and personnel so that they are prepared to handle severe weather-induced failures without being forced to temporarily cease operations. Moreover, the fact that many water utilities in Texas have put these innovations in place in the immediate aftermath of Hurricane Harvey illustrates that natural hazards provide a window of opportunity for utilities to increase their resilience by investing in adaptations during the rebuilding process. Other utilities thus have a blueprint to follow if they are ever faced with extreme weather events themselves. They may instead choose to adopt these innovations prior to experiencing any natural hazards, however. Such a proactive approach to resilience would be expensive in the short-term, although it would ultimately save utilities money in the long-term, as well as protect their assets and customers from unnecessary hardship.

These lessons are particularly valuable for three groups of stakeholders. The first, and perhaps most germane, is the senior management groups of individual water utilities, as they are the ones who have the decision-making capabilities necessary to implement resilience-focused innovations. By heeding the information resulting from this study, these individuals ought to understand that climate change will almost inevitably pose acute negative ramifications for the operations of their water systems at some point in the future. Thus, it would be wise for them to invest in adaptive innovations like the ones described in this project sooner rather than later.

In addition, the findings of this study are worthwhile for policymakers. These people are tasked with protecting the safety and wellbeing of their constituents, so it is vital that they understand that climatic events such as hurricanes pose a very real threat to the water supply of the communities which they represent. Thus, they can use this knowledge during the legislative process by implementing minimum standards for water utility protections against the effects of natural hazards, thus ensuring improved safety and consistency of drinking water for all. Finally, the results of this study are relevant for the general public as well. If the lay population can come to recognize that severe weather events can jeopardize their drinking water, perhaps they will be more likely to approve rate increases or tax hikes to protect this invaluable resource.

Recommendations for Further Research

The premise of this study could be extended a few different ways in future research. First, another study could be conducted to see how other types of utilities learn from natural hazards.

Although water utilities were the focus of this project, they are not the only ones that provide critical resources to the general population. Thus, it is vital to gain a better understanding of the ways in which gas or electric utilities, for example, innovate after being subjected to severe weather events.

Another way in which this research could be built upon is to examine the role that socioeconomic status plays in urban water system innovation. Time and time again throughout this study, water managers remarked that a lack of funding was the biggest barrier to innovation for their systems. Furthermore, it seemed as if the water utilities located in bigger and wealthier (and whiter) communities with larger tax bases were able to implement more innovations than their counterparts in smaller and more blue collar municipalities. Everyone deserves access to safe and dependable water no matter where they live or how much wealth they possess, so it is essential to illuminate the potential relationship between socioeconomic status and innovation in urban water systems so that these possible disparities can be addressed.

New research stemming from this project could also focus on the impact of managed retreat on water utility operations. *Managed retreat* refers to the physical relocation of people or assets as a proactive adaptation strategy to the most severe effects of climate change (Mach & Siders, 2021). Unlike previous climate-induced relocation efforts, however, it emphasizes the imperative of explicitly gauging the values that underlie the decision whether or not to relocate in order to make the process more equitable and desirable for all. Thus, future studies could investigate how the relocation of people away from hazard-prone locations such as Southeast Texas impacts the ability of local utilities to continue to provide water to dwindling populations.

Finally, the focus of this study could be broadened with another project meant to distill whether public or private water systems innovate more. Each type of water system has its own benefits, with public ones generally providing greater access to water at a lower cost to consumers and private ones often being more efficient in their operations. Accordingly, the debate over the relative benefits of each business model could benefit from a comprehensive examination of the rate of innovation in each. This information could ultimately help clarify whether public or private water systems are more beneficial to end consumers.

Summary

This study has contributed to both the innovation literature and the sustainability transitions literature by elucidating how water utilities in Southeast Texas have learned from the severe flooding across the region caused by Hurricane Harvey in August of 2017. By comparing how these impacted utilities have innovated in the years since the storm relative to their unaffected counterparts in coastal Florida, it has been established that while both groups of utilities have adopted many similar educational, financial, infrastructural, programmatic, technological, and environmental innovations, many of the utilities in Texas are unique in their implementation of resilience-centered innovations. This reality implies both that water systems learn from extreme weather events and that such natural hazards provide windows of opportunity for utilities to innovate and transition to more sustainable states. Such conclusions are valuable for water systems themselves, policymakers, and the general public, all of which have unique roles of various sizes to play in future urban water climate resilience efforts.

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