JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

AMERICAN WATER RESOURCES ASSOCIATION

Marshaling Adaptive Capacities within an Adaptive Management Framework to Enhance the Resiliency of Wastewater Systems

Cristina A. Mullin and Christine J. Kirchhoff

Research Impact Statement: Wastewater systems with many diverse adaptive capacities and managers that deploy those capacities within an adaptive management framework are more resilient to storms.

ABSTRACT: We assess adaptive capacity and adaptive management as measures of wastewater (WW) system resiliency using data from interviews with WW system managers (hereafter managers) impacted by past storms. Results suggest the most resilient WW systems are those with high adaptive capacities that employ an adaptive management approach to make ongoing adaptation investments over time. Greater amounts of generic adaptive capacities (i.e., skilled staff and good leadership) help smooth both day-to-day and emergency operations and provide a foundation for adaptive management. In turn, adaptive management helps managers both build more generic adaptive capacities, and develop and employ greater amounts and diversity of specific adaptive capacities (i.e., soft and/or hard adaptations) that are especially important for enhancing and sustaining resiliency. Adaptive management also enables managers to better understand their system's vulnerabilities, how those vulnerabilities change over time, and what specific actions may reduce those vulnerabilities. Finally, our work suggests WW system resilience critically depends on the capacities of the human systems for building resilience as much as or more so than relying only on physical infrastructure resilience. Our work contributes to filling an important gap in the literature by advancing our understanding of the human dimensions of infrastructure resilience and has practical implications for advancing resilience in the WW sector.

(KEYWORDS: climate variability/change; planning; flooding; precipitation; wastewater management; organizational learning; resilience; adaptive capacity.)

INTRODUCTION

While wastewater (WW) systems provide invaluable societal services and are critical to public and environmental health, economic vitality, and national security (Guikema et al. 2015), they are sensitive to extreme winds, precipitation, and flooding. Past storms including Alfred, Sandy, and Irene exposed these sensitivities inflicting billions of dollars in damage to WW infrastructure in the Northeastern United States (U.S.) (Baylis et al. 2016). Changes in the economy, aging infrastructure, and an uncertain regulatory environment exacerbate these vulnerabilities as does accelerated sea level rise and more frequent extreme precipitation expected with climate change (Horton et al. 2014; Wuebbles et al. 2017). Given these vulnerabilities, there is an urgent need for adaptation strategies that improve the resilience of WW systems. For the purposes of this paper, we define resilience as the capacity of a WW system to prepare for, cope with, recover from, and change to reduce vulnerability to stress, especially the impacts from extreme events and future climate change (IPCC 2007; Francis and Bekera 2014).

Paper No. JAWRA-18-0050-P of the *Journal of the American Water Resources Association* (JAWRA). Received March 23, 2018; accepted November 2, 2018. **Discussions are open until six months from issue publication**.

Department of Civil and Environmental Engineering (Mullin, Kirchhoff), University of Connecticut, Storrs, Connecticut, USA (Correspondence to Mullin: cristina.mullin@uconn.edu).

Citation: Mullin, C.A., and C.J. Kirchhoff. 2018. "Marshaling Adaptive Capacities within an Adaptive Management Framework to Enhance the Resiliency of Wastewater Systems." *Journal of the American Water Resources Association* 1–14. https://doi.org/10.1111/1752-1688.12709.

Over the past several decades, scholars have increasingly focused on infrastructure resiliency including water (Falco and Webb 2015; Mugume et al. 2015; Shin et al. 2018), transportation (Eisenack et al. 2012; Bhamidipati 2015; Therrien et al. 2015; Mostafavi and Inman 2016; Donovan and Work 2017), and power (Reed et al. 2009; Ouyang et al. 2012; Lin and Bie 2016; Panteli and Mancarella 2017). Most studies of infrastructure adaptation efforts to build resilience focus on hard adaptation actions (e.g., digging impoundments, raising equipment). Recently, scholarship has embraced softer adaptations such as governance for adaptation to climate change and resiliency (Camacho 2009; Engle and Lemos 2010; May and Plummer 2011; Rijke et al. 2013; Boyd and Juhola 2015). Despite this focus on infrastructure resiliency broadly, WW system resiliency is largely unexamined in the literature. Moreover, related human adaptations (e.g., making changes to address behavioral, social, economic, and governance factors) that also influence WW system performance and resiliency are rarely considered (Juan-García et al. 2017). Of the studies that do exist, most are modeling-based or are literature reviews that provide frameworks or guidance on what WW systems should do to increase resilience (Schoen et al. 2015; Butler et al. 2016). To our knowledge, only one published empirical case study discusses what systems are actually doing in practice to increase resilience (Rudberg et al. 2012). We aim to fill this important gap in the literature by advancing understanding of what WW systems are doing to build resilience, especially how human systems help build (or not) resiliency.

We use the concepts of adaptive capacity and adaptive management as a means to assess WW system resiliency and how human dimensions influence the resiliency of WW systems. This builds on prior scholarship of measures of adaptive capacity, including both generic and specific adaptive capacities, and adaptive management (Folke et al. 2002; Yohe and Tol 2002; Brooks et al. 2005; Berkhout et al. 2006; Sharma and Patwardhan 2008; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014). Using data from 31 structured interviews with WW system managers (hereafter managers), we explore the following research questions: (1) How have WW systems been impacted by past storms and how do these impacts affect resilience? (2) What kinds of generic adaptive capacities improve resilience? (3) What kinds of specific adaptive capacities are managers implementing and how do these capacities influence resilience? And, (4) How do adaptive capacity and adaptive management interrelate to foster resilience?

In the following sections, we review the literature, describe the methodology, and present our results. Then, we explore how adaptive capacities and adaptive management influence WW system resiliency and the relationship between adaptive capacity, adaptive management, and resiliency more broadly. We briefly discuss what hinders or limits resiliency and conclude with future research suggestions.

LITERATURE REVIEW

Adaptive Capacity and WW System Resiliency

Our review of the literature suggests that only a small subset of resilience research directly addresses WW system resilience, and most are modeling-based or are literature reviews that provide frameworks or guidance on what WW systems should do to increase resilience (Schoen et al. 2015; Butler et al. 2016; Juan-García et al. 2017). Applying findings from the broader resiliency literature suggests that resilient infrastructure systems have high adaptive capacity and can reorganize, learn, and successfully adapt to stress or changing circumstances and maintain their desired state after significant disruption (Folke et al. 2005; Nelson et al. 2007; Pahl-Wostl 2007, 2009). Having high adaptive capacity increases resiliency by enhancing a system's ability to anticipate disturbances and reduce impacts, to take advantage of opportunities or cope with consequences, to recover more quickly, and to make adaptive changes (definition adapted from IPCC 2007). Building on prior scholarship, we use the concepts of generic and specific adaptive capacities (Folke et al. 2002; Yohe and Tol 2002; Brooks et al. 2005; Berkhout et al. 2006; Sharma and Patwardhan 2008; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014), and adaptive management as a means to assess the resilience of WW systems and how human dimensions influence WW system resilience.

Generic and Specific Adaptive Capacities. Eakin et al. (2014) explained there are two types of adaptive capacities: (1) those associated with basic human development needs (generic) and (2) those associated with managing, reducing, and responding to climatic threats (specific). Generic capacities including education, funding, knowledge, learning, information, skills, stability, and leadership (Berkhout et al. 2006; Pahl-Wostl 2009; Emerson and Gerlak 2014; Juan-García et al. 2017) provide the basic human capacity to respond to stress, and by extension the fundamental capacity of WW systems to respond to stress. Specific adaptive capacities are, "adaptation interventions and capacities," (Sharma and Patwardhan 2008, 820) such as climatic information use, adaptation funding, emergency planning, technology, human capital, and infrastructure (Eakin and Lemos 2006; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014) that are specifically geared to or that can be marshaled to reduce or cope with impacts from a particular hazard. Generic and specific adaptive capacities are interdependent. Being able to make adaptive decisions and enhance specific capacities effectively depends on the availability of generic capacities and vice versa (Haddad 2005; Eakin and Lemos 2006; Sharma and Patwardhan 2008). For instance, good leadership may compensate for low generic capacities such as insufficient funding, because good leaders establish helpful connections or they find creative funding solutions to manage problems when they arise (Moser and Ekstrom 2010). Generic and specific adaptive capacities also tradeoff (Eakin and Lemos 2006), especially in infrastructure systems. For example, because large and robust physical adaptations are costly and, as such, may not be socially or economically acceptable, less expensive investments in resiliency such as strengthening generic capacities may be more attractive than investing in new, expensive specific capacities (Dessai and Hulme 2007).

Few studies have examined adaptive capacity in WW systems. One study by Rudberg et al. (2012) found that increased knowledge on climate change and its impacts (generic capacity) helps WW systems justify spending money on adaptive actions (specific capacity) needed to improve resilience. Managers who were both aware of climate change and who understood the specific impacts climate change will likely have on their WW systems were better able to justify changing routines or investing in building specific capacities to adapt (Rudberg et al. 2012). Awareness and knowledge of climate change as well as funding (generic capacities) were the primary factors affecting managers' ability to build specific adaptive capacity and increase resiliency (Rudberg et al. 2012).

Adaptive Management. Classic adaptive management focuses on experimental learning by formally testing out different management techniques and carefully monitoring how they affect the resilience of ecological systems using controlled experiments (Holling 1978; Walters 1986; Allen et al. 2011; Westgate et al. 2013; Chaffin et al. 2016). In recent years, the term adaptive management has extended beyond ecological experiments to incorporate broader, more flexible learning-based approaches that improve the management and resilience of other types of systems including public health (Hess et al. 2012) and water resources management more broadly (Pahl-Wostl 2007; Kirchhoff and Dilling 2016). While adaptive management concepts have been applied more broadly in recent years, to our knowledge, adaptive management has not yet been applied to managing infrastructure systems to improve resilience.

Scholars suggest that rather than traditional, top-down management, managing infrastructure systems under changing conditions also requires a more adaptive approach (Pahl-Wostl 2007; Kirchhoff and Dilling 2016) that balances the short-term and long-term aspects of resilience. In this way, managing systems for resilience requires moving away from reactive, inflexible approaches that have led to complacency and inadequate attention to risk reduction and prevention (Baylis et al. 2016), to adaptive management approaches that foster ongoing learning, proactivity, and transformation especially in response to climate change (Hess et al. 2012).

METHODS

Data Collection

We use data from focused qualitative interviews with managers to understand impacts and responses from past storms and their implications for adapting to future climate change. The interviews addressed a range of topics and included questions about WW system characteristics (i.e., funding, size of system, location); the nature and severity of past storm impacts, what helped or hindered their emergency preparedness, response, and recovery; risk perceptions regarding climate change (i.e., future severe weather, sea level rise); the types of adaptive decisions and actions made (if any); what helped or hindered implementing adaptive decisions (e.g., availability of science, political support, leadership, adequate funding see, Moser and Ekstrom 2010); and what factors have the strongest impact on resiliency. The 31 interviewees were recruited from a random stratified (i.e., stratified by inland vs. coastal location, impacted vs. not impacted, and made changes vs. did not make changes) sample of 86 survey respondents (for more information on the survey, see Kirchhoff and Watson 2018). All interviewees are WW professionals comparable in age and education. The interview protocol was pilot tested with four managers not included in the final sample in July and August 2016, after which refinements were made to the protocol before initiating interviews for the study. Interviews were recorded and transcribed. See Supporting Information for the interview protocol.

Data Analysis

We sorted interview data into selective categories and themes (i.e., both predetermined and emergent) using a combination of both inductive (i.e., grounded theory) and deductive qualitative methodologies

(Creswell 2007). QSR International's NVivo 11 qualitative data analysis Software (QSR International Pty Ltd. Version 11, NVivo Pro edition, 2015; QSR International [Americas] Inc. United States, Canada and Latin America, Burlington, MA) was used to code interview transcripts for capacities (i.e., generic, specific, and adaptive management). The following adaptive capacities were coded: (1) skilled staff (i.e., flexible, dependable, knowledgeable, well trained, and resourceful); (2) good asset management (i.e., proactive and ongoing maintenance, repair, and replacement; monitoring and assessment; prevention of mechanical failures; and continual improvements); (3) good leadership (i.e., facilitates ongoing learning and change, proactivity, trust building, and useful connections); (4) sufficient funding (i.e., for both day-to-day and emergency operations); (5) soft adaptations: effective emergency preparedness, response, and recovery; (6) hard adaptations: temporary or permanent adaptations to increase resiliency; and (7) implementing adaptive management (i.e., continuous organizational learning, experimental adaptation, and transformation) to reduce vulnerability and increase resilience. In this study, we refer to 1–4 as generic adaptive capacities and 5–6 as specific adaptive capacities. Temporary storm resiliency interventions coded in Category 6 include hard adaptation actions implemented right before a storm hits aimed at increasing the WW system's ability to cope with and reduce impacts from that particular storm. These are typically removed after the event passes. Permanent resiliency interventions coded in Category 6 are permanent hard adaptations intended to reduce potential impacts and help the WW system cope with consequences and/or recover more quickly from future storm events. To explore how generic, specific, and adaptive management capacities relate to WW system resiliency, we controlled for the degree of historical impacts and tracked the amount and diversity of adaptations. We also considered WW system characteristics (i.e., funding availability, type and size of system, location) as potential drivers of WW system resilience.

PAST STORM IMPACTS AT WW SYSTEMS

Most (65%) managers said their systems were significantly impacted in some way by past storms such as Alfred, Irene, and Sandy; past impacts that managers attributed to the effects of severe weather are included in Table 1.

We found an association between location and the likelihood of storm impacts, particularly flooding. Most interviewees (81%) manage WW facilities located in a flood zone next to a river, tidal basin, or coastal area; most (76%) of those systems were impacted by storm surge, tidal, coastal, or river flooding in the past.

TABLE 1. Past storm impacts reported by WW systems.

Effects of severe weather	WW system impacts	# Systems
High winds, downed trees	Power loss	7/31
River, coastal, or tidal flooding, storm surge, sustained precipitation, high winds, hurricane	Power loss, water in and around facility, lost access to critical facilities, roads, or pump stations, bypassing,[1] broken equipment or controls, electrical system damage	19/31
Power loss	Bypassing, lost bacteria for treatment	5/31
Ice building up because of inflow and infiltration	Sewage backups, less flow	1/31
Trouble getting fuel or running out of fuel needed to power generators	Power loss	3/31

Note: Systems impacted by multiple effects of severe weather are included in the counts for each individual effect (i.e., double counted).
[1]WW systems with low flow capacities were forced to bypass large amounts of non-treated or partially treated sewage directly into nearby waterways.

GENERIC ADAPTIVE CAPACITIES

Skilled Staff

WW systems with skilled staff — these are staff who are experienced, knowledgeable, and involved and that can wear many hats — more effectively manage both day-to-day and emergency operations and have greater capacity to cope during and recover from emergencies. For example, one interviewee said, "… some of us have been here 15, 18 years, you know, I've got operators here with 25 years, so pretty much anything that goes on, whether it's flooding or a power pump or loss of power, you know, or toxic sludge coming in, somebody here has seen it and knows how to react" (W15). Having experienced staff is especially beneficial in reducing storm impacts. For example, regarding a 2012 storm, one interviewee said they experienced, "… torrential downpour for a couple of hours straight," (W13) that increased flow into their system from 10.3 million gallons per day to 25 million gallons per day. Without experienced staff, storm impacts would have been worse, "Yeah, if our staff had not known what to do. Our assistant plant manager is very hands on, really close to the training staff, and if he wasn't so hands on, if he wasn't so knowledgeable and then shared his knowledge with our staff, then it probably could have been terrible" (W13). Overall, having staff that can maintain and operate the system brings them closer to the equipment, and helps them understand what equipment is vulnerable. A manager said, "I like the idea of being involved and for our staff to be hands-on in these upgrades or these small incremental changes because it gives us real knowledge, some real knowledge of how did this go together" (W16). He also said, "If it fails, we're the ones who installed this so we're going to already have a leg up on how to fix it" (W16).

Good Asset Management

Resilient WW systems have managers who make continuous, incremental improvements to pump stations, plants, facilities, technology, generators, and pipes; both to make changes affordable, and to ensure equipment are dependable and work properly for day-to-day and emergency operations. One manager said, "... preventative maintenance can be an amazing thing" (S12). Proactive maintenance reduces vulnerability and increases a system's ability to cope during storms. For instance, one manager said they are better prepared to cope with disturbances because they proactively identify and fix their system's weaknesses — "[their town] ... is at least progressive in terms of looking out the future ... where other towns wait till something breaks before they even decide to fix it. We are being proactive and progressive looking. So that's a factor in our favor" (W31).

In addition to being proactive, managers are, "... chipping away at some of the infrastructure improvements on an ongoing basis" (W14). For example, "... instead of doing you know, a big upgrade every 20 years or so, you're doing small upgrades along the way" (W02). An interviewee said, we, "... continuously invest in our infrastructure here so it's an ongoing improvement process" (W10). Another manager said, "It's not good to you if it's not functionally operational" (W14). Ongoing maintenance, repair, and replacement of equipment is viewed as a necessity both to ensure good working order and affordability (see Sufficient Funding).

Additionally, because WW infrastructure is old, incremental maintenance is needed to reduce inflow and infiltration (I&I) in the collection systems. I&I and its impact on resiliency was a concern for most (74%) managers interviewed. I&I is problematic because when too much extra water enters the system, it overwhelms the plant and contributes to bypassing untreated or partially treated sewage, thereby lowering resilience. For example, one interviewee said, we bypass when, "... we get over an inch and a half of rain in less than 24 hours" (W19). Another said, "We're always concerned with I&I because a fact of the matter is that some of these old pipes ... we do know that for a fact, that they're leaking" (W14). Unfortunately, I&I is an ongoing maintenance issue for most WW systems — "You can't resist those roots. When you finish you have start all over again" (W07). To try and reduce I&I, a few managers are doing flow modeling and monitoring to try and identify problem areas (W19). A manager of a more resilient WW system said, "... to assist us in monitoring our collection system and pump stations we've developed a computer maintenance management system ... now we can readily identify areas in our system that need manhole inspections or line cleaning activities ... we finally have the resources at our fingertips that allow us to really keep a pulse on how efficient our collection system and pump stations are operating" (W31).

Good Leadership

Leaders who encourage staff to wear many hats, trust them to make decisions, and involve them widely in the design and installation of equipment help facilitate innovation and effective emergency management contributing to resilience. Having staff that wear many hats is important because, "... if somebody's out sick, there's enough cross-training that takes place so that anybody can step into any role and that facility will continue to run" (W06). Good leaders involve staff widely which helps build trust as indicated by the following interviewee, "They trust staff and the people they have working for them to make the best decisions for what's best for the facility or the city" (W15). For example, one manager said, "I think it's helpful to the employees where we can show some trust or faith in giving them some opportunity to make an imprint in the facility. Make a change" (W16). Building trust among the leadership and staff helps foster commitment, in turn committed staff care about the system's ability to withstand a storm and are willing to work long hours. A manager said, "probably half of the staff worked most of the hours through whatever, five, six, seven, eight, nine days" (W16). In addition, managers at more resilient systems are trusted by their funders (e.g., Water Pollution Control Authority) and are able to obtain needed resources — "If we need something, they know we're not lying about it" (W13).

Sufficient Funding

Having sufficient funds (i.e., budget for day-to-day, emergency reserve, and resiliency funding) increases managers' capacity to prepare for, recover from emergencies and make changes to increase WW system resilience. One interviewee said their, "... facility's plan spelled out 20 years of growth, capital projects, funding, sewer use fees, all that," which provides, "cash available if [they] need it in a pinch" (W12). Another manager said, "We have a reserve fund for treatment plant repairs or work that needs to be done ... [and] for the collection system repairs or work for capital improvement ... [while] ... emergency response would come out of [their] operation budget" (W08). Overall, managers that have funding for both day-to-day work and for emergencies are more resilient.

Generally, funding comes from the municipality — "... it's totally funded by the users of the sewer system," through sewer fees or from outside funding via state or federal grants and low interest loans (W24). For example, managers have used Environmental Protection Agency, "clean water funding," (W04) and, "USDA [U.S. Department of Agriculture] money" (W22, W24). Another system said they received a, "... 50% grant from the State of Connecticut," and paid, "... 50% from the facility" (W06). Some managers have taken advantage of these grant programs to make upgrades that increase the resiliency of their systems. Because they often lack, "... funds to maintain everything" (W20), making small incremental changes over a very long, extended period of time is the only way managers can afford to upgrade their WW systems. For example, a manager said, "... I guess they are small increments, but they're small increments over a very long, extended time. And that's the only way these small towns can afford these things" (W16).

While having sufficient funds helps increase resilience, lack of funding impedes many manager's ability to make changes to increase resilience. For example, a manager said, "I'd love to do all kinds of stuff but money's always the issue and how much can the ratepayer bear" (W25). Another interviewee said, "There are just aging infrastructures and old equipment everywhere, but no one's really stepping forward with the money to do it, so it stays how it is" (W13). Managers that struggle with their budget expressed that lack of public support for increasing sewer fees is a barrier to making changes to increase resiliency. For example, a manager said, "Nobody wants to spend millions of dollars on a sewer line that they never see" (W21).

SPECIFIC ADAPTIVE CAPACITIES

Soft Adaptations: Effective Emergency Preparedness, Response, and Recovery

Managers that have greater capacity to prepare their staff and equipment for issues that may arise during storms have more resilient WW systems. For example, "... once we find out these things are coming, we'll have conference calls with all our facilities with my area manager, and we'll go through planning, and what we're gonna have at the facility here, and who we're gonna have on staff, and make sure if it's a hurricane-type event or it's gonna be heavy rain, and winds, and stuff that everything's battened down" (W25). For other managers, keeping extra equipment on hand helps them weather the storm — "We have a few extra pumps, brand new, sitting on standby in case one burns, we can just plug in the next" (W09). Still others prepare equipment by fueling up and completing maintenance. For example, to prepare for a power outage, one manager said, "When we saw the storm coming we make sure the generators are operable. That fuel is filled up on them. Any maintenance that has been pending gets completed" (W02). Echoing this, another interviewee said, "... we make sure the generators, of course, are all full with fuel, especially in the winter time" (W11).

Managers with more staff available to work before, during, and after an emergency event are better able to prepare, cope, and recover from a storm or emergency event. For example, an interviewee said, "... staff definitely plays a big role in getting us going and making sure that everything is working properly ... we usually add one or two more personnel to the shifts so that they are available should we need them here" (W04). Another said, staff were available, "... to work extended hours by setting our own schedule up so that we could continuously monitor and take care of things as they occurred" (W05). When staff work through storms, they need to be prepared to potentially stay there for an extended period of time. For example, a manager said, we, "... have stuff available at the facility in case someone gets stuck here and they're working here by themselves or with a couple of guys by themselves, so we make sure we have food, and clothing, and stuff like that" (W25).

Effective emergency preparedness is also about establishing and maintaining lines of communication and relationships with the town, state, or other third parties (i.e., fuel providers, emergency contractors, and power companies) ahead of time to mitigate impacts and speed recovery. For example, one interviewee described how new communication pathways were established after a particularly harrowing event. In this case, miscommunication led to panic. To rectify this, he said his town hired a new emergency response leader. With the new Chief of Police, he said now, "We have a better chain of command for our emergency response ... we're going to get our information from that emergency control room at the police station from one man. We're not going to just be listening on the video or getting all this bad information that can cause us to panic" (W16). Lines of communication with the state help as well. One manager said that the state's online portal, "... where you could report what was happening each morning or afternoon or evening, or what you needed, or what you're experiencing through the storm," was helpful for coping with storm events (W02).

In addition to lines of communication with the town and state, resilient systems have established lines of communication and relationships with outside parties. An interviewee said, "As with any storm or single event ... establishing communication is the first goal, making sure the service provider is aware of the circumstances ... [and] fuel service providers also have to be contacted" (W03). Another said, "Reliance on third-party assistance is always part of the equation in meeting any weather-related event" (W03). Systems become more reliant on third-party assistance if the impacts from an event are long-lasting, meaning, "... any time the timeline of a storm impact reaches three, five, seven days or more the restoration is clearly determined by the third-party utility" (W03). More resilient systems have access to third-party assistance which helps them recover more quickly if they are impacted. For example, one interviewee said, "We do have emergency contractors so if there's a break or some kind of repair that needs to be made they're on board too" (W14). Another said they cannot always rely on emergency contractors because they are competing with other managers for assistance from the same resources — "Sometimes we do plan for that if something's coming and try to make arrangements, but everybody's vying for the same equipment when those type of events are on the way, so sometimes you need to make sure that you've planned ahead and you have that stuff in advance" (W25). Managers increase their WW systems resiliency by planning ahead and having additional options in mind in case they do not have access to assistance from third parties. Some managers seek assistance from other WW managers — for example, one manager said he has already agreed to help others by lending his equipment. Other managers ask, "... if we have an issue can we borrow your flusher truck so we can operate it? ... and we go okay fine, no problem" (W12).

Established lines of communication with power utilities are especially important to speed power restoration after an outage event. To improve power restoration rates, power companies may put WW systems on emergency power prioritization lists. For example, one manager said, "... they actually came to us and looked for priority sites throughout the community," (W14) and now, "... the stations are part of an overall list of facilities that are on a high priority with the utility provider" (W03). Another said, "We are priority facilities so we notify them and generally if we do lose power they get us fairly quickly" (W08). Finally, another said, "... we're considered a priority for them, so they're gonna make sure that we're back on primary commercial power as quickly as possible" (W20).

Hard Adaptations: Temporary or Permanent Adaptations to Increase Resiliency

Managers are making large or small, temporary or permanent infrastructure changes to increase WW system reliability and robustness. Regarding infrastructure changes, one manager said, "... we may have to try to do something intermittently and then something long term" (W14). Small or temporary changes can make a large difference in a system's ability to cope and recover from storms. For example, a manager with a WW system more resilient to storms said they mitigate I&I into their sewer system during storms by using, "... manhole structures [that] are built and secured with water tight covers" (W03). Another said they, "... have some manhole covers that have multiple holes in them ... [and they have] been changing those out as [they] can to manhole covers with no holes" (W02). He also said they are looking at using rubber stoppers to reduce inflow in the future instead of replacing covers because, "It is cheaper and easier to put in rubber stoppers ... [and replacing] the manhole covers [costs] over $100 apiece ... So it'd be cheaper to do quartz or rubber stoppers or something along those lines" (W02). Another system said they use plugs in a similar manner to prevent their pump stations from flooding — "... we did get plugs, and have them to this day, so we can plug those vent holes off, and it worked in some spots if the water didn't continue to rise and run in the cover in the top" (W05).

Being prepared to cope with power outages makes WW systems more resilient to severe storms where power loss is an issue. Generators are a good example of how managers reduce WW system impacts from power outages using either temporary or permanent backup power. In some cases, managers said they have permanent generators that can run their entire plant when they lose power — "We have a generator that runs the entire plant if something should happen" (W24). Another said, "... we're 100% generator-backed-up, so during Hurricane Irene and the October snowstorm [Alfred], we were off grid for about a week, running on backup generator. But it runs like a charm. You don't even notice any difference in the operation" (W18). Other managers said their WW systems and pump stations do not all have permanent backup power. These systems without permanent backup power cope with outages by moving temporary portable generators around as needed — "We have portable generators that we move out for the few small stations that don't have fixed standby generators" (W20). Another manager with a less resilient WW system said, "We don't have auxiliary power at every location. Although that would be the optimum condition, [but we] do have an auxiliary power facility now that we can take from place to place" (W14). If pump stations are located far away from each other, it is important for them to have their own generators, because road access may be limited during storms. For example, the manager of one less resilient system said, "We usually have backup power by a manual generator that we'd hook up to. But there was no access to it for a certain amount of time ... we actually got power back on before we had access to it" (W29). Many managers said the most important adaptive change they made to increase their capacity to cope was to get generators, or to increase the number of generators they have.

Managers tend to use temporary or small adaptations that are not cost intensive because they do not have sufficient funding to make large-scale changes — for example, one manager said, "... our major challenge is making sure that the electrical systems inside of the pump stations and the pumps themselves don't get flooded ... but short of raising them up which is not really an option in those locations, we take the approach that we will waterproof 'em ... basically we have large rubber mats that we put over the top of the Bilco doors ... it's surprising how effective a large rubber mat with a couple sandbags on it will make a Bilco door waterproof ..." (W01). When asked if more permanent adaptations were needed to ensure the pump stations do not get flooded, the same interviewee said, it is, "... gonna be a considerable expense that I don't know that I can justify because my methodology albeit some of my jury rigging, it works. So, if I could accomplish the same thing using duct tape and bailing wire do I really need to go out and have a whole new station rebuilt at considerable dollars for that rainy day?" (W01).

Permanent storm resiliency interventions tend to be large and expensive, and to increase resiliency, these must be completed before a storm hits. For example, a manager said, "... we're doing a lot of resiliency changes ... We're involved in a big project now, which will be taking our electrical distribution out of the basement and putting it on the first floor, well above the 100-year flood, probably closer to above the 500 flood. And then also we have a tunnel system underground, putting in the ability to have tunnel flooding protection" (W20). Another more resilient system said, they moved all of the electrical equipment way above the flood zone to increase their resilience to flooding — "All of the electrical rooms are above a 500-year flood. So even if this place were to have the dike overcame, we wouldn't really lose too much critical equipment" (W24). Pump stations and electrical equipment are vulnerable to flooding and during storms it may be difficult to access roads to drive to sites to monitor pump stations. Regarding a large change in technology that enhanced their resiliency, a manager said, "... what we learned from that is to incorporate remote sensing and basically be able to see the pump station from the comfort of the control room so we do not have to drive out there unless there truly is a problem" (W16).

While many managers are implementing hard adaptations, there may be limits to large-scale resiliency investments. A manager said, "... if we lifted the whole station, the whole area around it, four feet, then it would alleviate the problem totally. Right now, we just built a retainment around the whole thing ... I don't know if it's the best thing for it, but it works ... financially, it wouldn't be cost-effective to do that [lift the whole station]" (W29). Regarding investments to increase resiliency by reducing I&I, another manager said, "At some point, there is that law of diminishing return that we will start to identify and say that it's just not cost-effective for us to be throwing this kind of money into the system, if it's really not gonna make a significant difference" (W31). On the other hand, failing to invest in hard adaptations can also be costly, for instance, "For the amount of money we were doing on maintenance, [it] was cost-prohibitive. So, they decided to just put a whole new one in" (W18).

IMPLEMENTING ADAPTIVE MANAGEMENT

Managers of WW systems that have been impacted consistently or severely in the past are more likely to employ an adaptive management approach to understand, plan for, and mitigate anticipated risks than those who manage WW systems that have not been impacted, making their systems more resilient to future damage. By employing adaptive management, we mean these managers are promoting ongoing learning, experimentation, and innovation to enhance resilience. For example, regarding experimentation, one manager said, "Don't wait until it's going wrong and then try to figure it out. You're going to fail for sure. So the best time to make changes is when things are going pretty good. Not wholesale changes, but tinker around a little or, as I always tell people here if they want to try something, go ahead and monkey around with it and see what you can come up with. If it works, great. If not, we ditch it" (W16).

Regarding ongoing learning, he also said, "I try to mention to them all the time to make a list of all the things you've learned in the last six months that you didn't know," and, "Of course you don't want to have everybody at 65 years old, either. Sprinkle in some young people, too, so it can get passed on, that tribal knowledge. I think that gets missed sometimes, too" (W16). Managers who implement adaptive management are also able to learn from other WW systems' experiences. For example, after Hurricane Sandy hit Connecticut, one manager said, "We shared information after, kinda telling stories … how did you make out?" (W05). In addition, when a storm hits, managers learn additional information about their WW system's vulnerabilities. For example, a manager said, "… we learned a few things during that event. And that was that, you know the generators, even though we test them monthly and keep them up and maintain them, that we had one go down on low oil pressure" (W28). He also said, "… the Department of Public Works learned a lesson there too cause some of the creeks had some grading [i.e., changes made to the ground elevation and side slopes of the stream channel to increase flow] that was part of it. So those were filled with debris from the high water" (W28).

Implementing adaptive management also involves transformation, which may include taking advantage of new technologies. One manager mentioned that a potential barrier to implementing new technologies is that operators in Connecticut, "… are not required to get continuing education credits each year," and that, "Other New England states require 25 tracked hours every two years, which sort of forces you to attend conferences and seminars and pick up on new technologies" (W06). Other managers learn about new technologies from other systems — "We definitely look to see what others have done in order to get to the point that we got here" (W04).

In addition to employing adaptive management, these systems and their managers implement more adaptations to mitigate future damage than systems that have not been impacted (see Figure 1).

The increasing amount of adaptations can be traced to having high amounts and diversity of adaptive capacities coupled with learning from past impacts to make improvements. For example, an interviewee said, "… historically it's been reactionary … we had a storm event at that station … [and] after that first flooding event then we put in procedures … to address that particular flooding. So … we have been able to reduce flooding impacts at that particular station and that is the only station that's at a position where it actually has flooded" (W08). Similarly, another interviewee said, "We prepare for a storm coming, and of course we learn from everybody after a storm happens, and we all try to get better from there" (W26). Another said, "We do our after action reports on each event, which are part of the closing up of the EOC [Emergency Operations Center]. And we incorporate that into our training, or standard operating procedures" (W19). These managers are employing adaptive management by fostering ongoing learning and change and thus are better

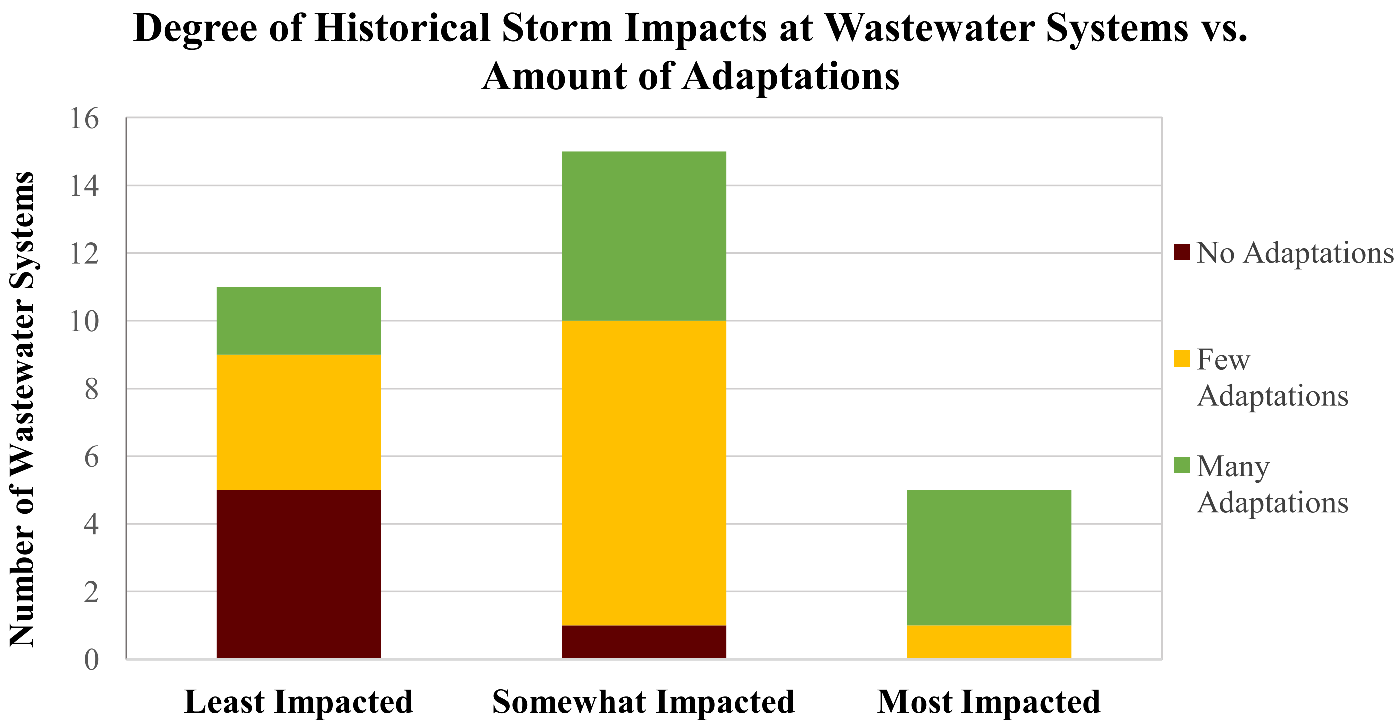

FIGURE 1. Chart showing the relationship between degree of historical storm impacts at wastewater (WW) systems and amount of adaptations. WW systems most impacted in the past have managers who are implementing the most adaptations to mitigate future storm damage.

able to understand and reduce vulnerabilities and increase their WW systems resilience to future storms. Adaptive management is especially important for enhancing and sustaining resiliency because it helps managers better understand their systems vulnerabilities, how those vulnerabilities change over time, and what specific countermeasures, if implemented, would reduce those vulnerabilities.

DISCUSSION AND CONCLUSION

Using data from 31 interviews with managers, we assessed WW system resiliency based on concepts of generic and specific adaptive capacities and adaptive management. This work builds on prior research on adaptive capacity measurement and extends our understanding of the influence of adaptive capacity and adaptive management on WW resilience in practice (Folke et al. 2002; Yohe and Tol 2002; Brooks et al. 2005; Berkhout et al. 2006; Sharma and Patwardhan 2008; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014).

Our results support previous findings that two of the most important generic adaptive capacities influencing a WW system's resilience is strengthening in-house staff expertise and good leadership (Rudberg et al. 2012). Staff that are reliable, flexible, knowledgeable, well trained, resourceful, and communicate effectively are able to do more work in-house and tend to build more resilient WW systems. Moreover, staff that are involved in the decision-making process are confident, committed, and trusted and work together well to make sense of complex situations, manage conflict, and build partnerships, knowledge, and support for change (Folke et al. 2005; Gunderson et al. 2006; Kenward et al. 2011; Pahl-Wostl et al. 2013; Emerson and Gerlak 2014). Good leadership helps foster staff that are more likely to engage in debates about the best adaptations to build resilience, more likely to care about the system's ability to withstand a storm, and more likely to be willing to work long hours. Additionally, we found good leaders build strong relationships with their customers, town, state, and/or other third parties, and thus are more likely to gain financial support for making changes to increase resilience. This is consistent with prior research that showed the importance of leadership for building trust, understanding, and communication pathways, increasing the ability to manage conflict, and facilitate adaptation to changing circumstances (Folke et al. 2005; Gunderson et al. 2006; Pahl-Wostl 2007; Pahl-Wostl et al. 2013; Emerson and Gerlak 2014; Peat et al. 2017).

Results also suggest WW systems with high generic adaptive capacities (i.e., skilled staff, good asset management, good leadership, and sufficient funding) are better able to understand what specific capacities or adaptation measures (e.g., soft and/or hard adaptations) should be implemented for a given context and time, and are more likely to have greater amounts and diversity of specific adaptive capacities making them more resilient. WW systems with high generic adaptive capacities and greater amounts and diversity of specific adaptive capacities also tend to have a better handle on the issues they face, the resiliency measures they can try out, and are better positioned to make investments over time. We also considered WW system characteristics (i.e., funding availability, type and size of system, location) as potential drivers of WW system resilience and found these factors do affect vulnerability and adaptive capacity, but do not affect the relationship between adaptive capacity and resiliency.

Managers that employed a "diversity of adaptations" strategy meaning building and deploying a mix of temporary and permanent, and a mix of hard and soft adaptations are on average more resilient. Building and deploying diverse specific capacities adds flexibility. Managers typically make small, temporary or intermittent changes to reduce WW system vulnerability first before shifting to larger, more expensive permanent changes. Similar to Hess et al. (2012), we found managers sometimes elect to rely on existing infrastructure and all-hazards preparedness rather than investing in innovations when increased risks have yet to materialize. Even for systems that have been impacted: at some point, the cost of storm resiliency interventions may outweigh the benefits, and, if a system manager does not have funds available and/or thinks that their temporary interventions are adequate for reducing storm impacts, larger permanent interventions are less likely to be done. Building on Dessai and Hulme (2007), this finding adds a new rationale for why managers may elect to forgo more expensive investments. Managers build resilience through smaller scale adaptations when managers know their system's vulnerabilities and whether or not and for how long these smaller temporary interventions will work.

While having high amounts of generic and specific adaptive capacities is necessary for resilience, they alone are not sufficient; more resilient WW systems also have high capacity for employing adaptive management to marshal those adaptive capacities and make informed adaptations. Having high capacity for adaptive management, including the capacity for ongoing learning, is needed to assess risks and make adaptive decisions. Prior studies found training and education form the basis for being able to understand risks and solve problems, and to make decisions and learn from them (Bruin et al. 2007) — all of which are crucial for adapting to climate change (Lutz and Muttarak 2017). Similarly, we found capacities to understand, learn, and make decisions (capacities for adaptive management) are fundamental to managers' abilities to make adaptive decisions and to build specific capacities that are critical for resilience. In addition, similar to Peat et al. (2017), we found that adaptive management is effective when WW systems have good leadership and that flexibility promotes experimentation. Finally, we found that WW systems that were impacted by storms consistently or severely in the past are more likely to employ adaptive management. This finding is consistent with prior research that found organizations learn, innovate, and change in response to outside pressures (Berkhout et al. 2006), and that strategies only begin to arise after systems have been impacted by extreme weather events (Berrang-Ford et al. 2011).

Adaptive management is helpful for resilience because it enables human systems to learn from disturbance (Holling 1996), recognize risks, and make continuous changes to improve resilience to climate variability and climate change. In addition, adaptive management provides a framework for continuing to build, evolve, and mobilize generic and specific adaptive capacities needed for resilience. Adaptive management's focus on continual learning, experimentation, and adjustment is critical for avoiding complacency and backsliding which undermines resilience gains. Despite these advantages, if climate change is abrupt and unexpected, incremental adaptive changes initiated in an adaptive management frame may be insufficient (Folke et al. 2004; Rudberg et al. 2012).

Finally, our results suggest that WW system resilience is more human-driven than the current literature suggests. Current literature on infrastructure resilience emphasizes structural resilience of the physical infrastructure including the ability of the WW treatment processes to withstand higher or lower temperatures and flows or the ability of WW system equipment and structures to withstand flooding (Juan-García et al. 2017). Our findings suggest that resilience of the physical infrastructure is only one aspect of resilience and that WW system resilience depends equally (or more so) on the capacity for resilience that the human systems that manage the physical system possess. That is, the most resilient WW systems are able to marshal, build, and deploy generic and specific adaptive capacities within an adaptive management framework to build resilience (see Figure 2).

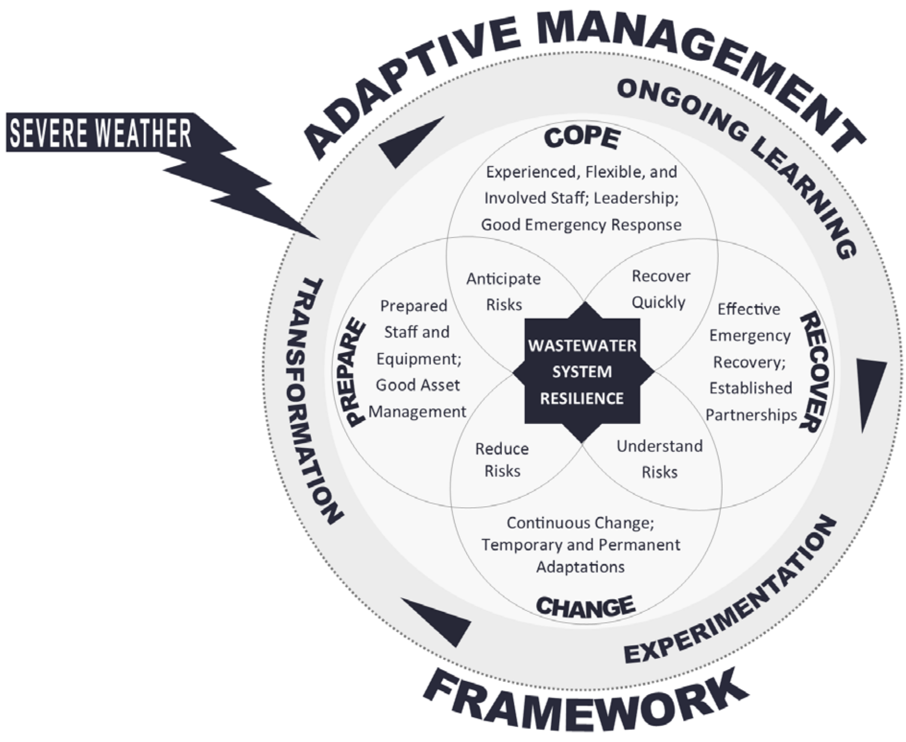

FIGURE 2. An adaptive management framework provides a means to learn from disturbances and to marshal adaptive capacities to make informed adaptations to reduce vulnerability. Adaptive management in turn depends on the amount and diversity of underlying adaptive capacities (i.e., generic and specific) needed for resilience, which is the capacity to prepare, cope, recover, and change.

Structural resilience remains an important contribution of overall WW system resilience, but it is embedded in and amplified by the adaptive capacities and adaptive decisions managers make as part of an adaptive management approach.

More work is needed to explore the limits of adaptive capacities and adaptive management for building resilience as well as to better understand what specific adaptive capacities help foster the kinds of transformations necessary to withstand more rapid climatic changes. In addition, more research is needed to better understand how generic and specific capacities interact leading to more or less desirable resiliency outcomes.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Interview protocol.

ACKNOWLEDGMENTS

This study was supported by funding from a municipal planning grant from the U.S. Department of Housing and Urban Development. The authors thank researchers and staff at the Connecticut Institute for Resilience & Climate Adaptation (CIRCA) and Stacy Pappano (CT DEEP), Carlos Esguerra (CT DEEP), Beth Doran (CT DEEP), Syed Bokhari (CT DEEP) for their assistance and support and Peter Watson for conducting the interviews. We also extend our sincere appreciation to all of our interview respondents.

LITERATURE CITED

Allen, C.R., J.J. Fontaine, K.L. Pope, and A.S. Garmestani. 2011. "Adaptive Management for a Turbulent Future." *Journal of Environmental Management* 92: 1339–45. https://doi.org/10.1016/j.jenvman.2010.11.019.

Baylis, J., A.J. Edmonds, M.E. Grayson, J.J. Murren, J. McDonald, and B. Scott. 2016. "National Infrastructure Advisory Council (NIAC) Water Sector Resilience Final Report and Recommendations." National Infrastructure Advisory Council.

Berkhout, F., J. Hertin, and D.M. Gann. 2006. "Learning to Adapt: Organisational Adaptation to Climate Change Impacts." *Climatic Change* 78 (1): 135–56. https://doi.org/10.1007/s10584-006-9089-3.

Berrang-Ford, L., J.D. Ford, and J. Paterson. 2011. "Are We Adapting to Climate Change?" *Global Environmental Change* 21 (1): 25–33. https://doi.org/10.1016/j.gloenvcha.2010.09.012.

Bhamidipati, S. 2015. "Simulation Framework for Asset Management in Climate-Change Adaptation of Transportation Infrastructure." *Transportation Research Procedia* 8: 17–28. https://doi.org/10.1016/j.trpro.2015.06.038.

Boyd, E., and S. Juhola. 2015. "Adaptive Climate Change Governance for Urban Resilience." *Urban Studies* 52 (7): 1234–64. https://doi.org/10.1177/0042098014527483.

Brooks, N., W. Neil Adger, and P. Mick Kelly. 2005. "The Determinants of Vulnerability and Adaptive Capacity at the National Level and the Implications for Adaptation." *Global Environmental Change* 15 (2): 151–63. https://doi.org/10.1016/j.gloenvcha.2004.12.006.

Bruin, W.B., A.M. De Parker, and B. Fischhoff. 2007. "Individual Differences in Adult Decision-Making Competence." *Journal of Personality and Social Psychology* 92 (5): 938–56. https://doi.org/10.1037/0022-3514.92.5.938.

Butler, D., S. Ward, C. Sweetapple, M. Astaraie-Imani, K. Diao, R. Farmani, and F. Guangtao. 2016. "Reliable, Resilient and Sustainable Water Management: The Safe & SuRe Approach." *Global Challenges* 1 (1): 63–77. https://doi.org/10.1002/gch2.1010.

Camacho, A.E. 2009. "Adapting Governance to Climate Change: Managing Uncertainty through a Learning Infrastructure." *Emory Law Journal* 59: 4–77. https://doi.org/10.2139/ssrn.1352693.

Chaffin, B.C., W.D. Shuster, A.S. Garmestani, B. Furio, S.L. Albro, M. Gardiner, M.L. Spring, and O.O. Green. 2016. "A Tale of Two Rain Gardens: Barriers and Bridges to Adaptive Management of Urban Stormwater in Cleveland, Ohio." *Journal of Environmental Management* 183: 431–41. https://doi.org/10.1016/j.jenvman.2016.06.025.

Creswell, J.W. 2007. *Research Design: Qualitative, Quantitative and Mixed Method Approaches*. Thousand Oaks, CA: SAGE Publications. https://doi.org/10.4135/9781849208956.

Dessai, S., and M. Hulme. 2007. "Assessing the Robustness of Adaptation Decisions to Climate Change Uncertainties: A Case Study on Water Resources Management in the East of England." *Global Environmental Change* 17 (1): 59–72. https://doi.org/10.1016/j.gloenvcha.2006.11.005.

Donovan, B., and D.B. Work. 2017. "Empirically Quantifying City-Scale Transportation System Resilience to Extreme Events." *Transportation Research Part C: Emerging Technologies* 79: 333–46. https://doi.org/10.1016/j.trc.2017.03.002.

Eakin, H., and M.C. Lemos. 2006. "Adaptation and the State: Latin America and the Challenge of Capacity-Building Under Globalization." *Global Environmental Change* 16 (1): 7–18. https://doi.org/10.1016/j.gloenvcha.2005.10.004.

Eakin, H.C., M. Lemos, and D. Nelson. 2014. "Differentiating Capacities as a Means to Sustainable Climate Change Adaptation." *Global Environmental Change* 27: 1–8. https://doi.org/10.1016/j.gloenvcha.2014.04.013.

Eisenack, K., R. Stecker, D. Reckien, and E. Hoffmann. 2012. "Adaptation to Climate Change in the Transport Sector: A Review of Actions and Actors." *Mitigation and Adaptation Strategies for Global Change* 17 (5): 451–69. https://doi.org/10.1007/s11027-011-9336-4.

Emerson, K., and A.K. Gerlak. 2014. "Adaptation in Collaborative Governance Regimes." *Environmental Management* 54 (4): 768–81. https://doi.org/10.1007/s00267-014-0334-7.

Engle, N.L., and M.C. Lemos. 2010. "Unpacking Governance: Building Adaptive Capacity to Climate Change of River Basins in Brazil." *Global Environmental Change* 20 (1): 4–13. https://doi.org/10.1016/j.gloenvcha.2009.07.001.

Falco, G.J., and W.R. Webb. 2015. "Water Microgrids: The Future of Water Infrastructure Resilience." *Procedia Engineering* 118: 50–57. https://doi.org/10.1016/j.proeng.2015.08.403.

Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling, and B. Walker. 2002. "Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations." *Ambio* 31 (5): 437–40. https://doi.org/10.1579/0044-7447-31.5.437.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling. 2004. "Regime Shifts, Resilience, and Biodiversity in Ecosystem Management." *Annual Review of Ecology, Evolution, and Systematics* 35: 557–81. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711.

Folke, C., T. Hahn, P. Olsson, and J. Norberg. 2005. "Adaptive Governance of Social-Ecological Systems." *Annual Review of Environment and Resources* 30 (1): 441–73. https://doi.org/10.1146/annurev.energy.30.050504.144511.

Francis, R., and B. Bekera. 2014. "A Metric and Frameworks for Resilience Analysis of Engineered and Infrastructure Systems." *Reliability Engineering and System Safety* 121: 90–103. https://doi.org/10.1016/j.ress.2013.07.004.

Guikema, S., L. Mclay, and J.H. Lambert. 2015. "Infrastructure Systems, Risk Analysis, and Resilience-Research Gaps and Opportunities." *Risk Analysis* 35 (4): 560–61. https://doi.org/10.1111/risa.12416.

Gunderson, L.H., C. Folke, and M. Janssen. 2006. "Generating and Fostering Novelty." *Ecology and Society* 11 (1): 50. https://doi.org/10.5751/ES-01811-110150.

Haddad, B.M. 2005. "Ranking the Adaptive Capacity of Nations to Climate Change When Socio-Political Goals Are Explicit." *Global Environmental Change* 15 (2): 165–76. https://doi.org/10.1016/j.gloenvcha.2004.10.002.

Hess, J.J., J.Z. McDowell, and G. Luber. 2012. "Integrating Climate Change Adaptation into Public Health Practice: Using Adaptive Management to Increase Adaptive Capacity and Build Resilience." *Environmental Health Perspectives* 120 (2): 171–79. https://doi.org/10.1289/ehp.1103515.

Holling, C.S. 1978. "Adaptive Environmental Assessment and Management." In *International Series on Applied Systems Analysis*, edited by C.S. Holling, 357–63. Chichester and New York: Wiley.

Holling, C.S. 1996. "Engineering Resilience Versus Ecological Resilience." *Engineering Within Ecological Constraints* 32: 31–44. https://doi.org/10.17226/4919.

Horton, R.M., G. Yohe, W. Easterling, R. Kates, M. Ruth, E. Sussman, A. Whelchel, D. Wolfe, and F. Lipschultz. 2014. "Ch. 16: Northeast. Climate Change Impacts in the United States: The Third National Climate Assessment." *U.S. Global Change Research Program*, 1–24. https://doi.org/10.7930/j0sf2t3p.

IPCC. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC Intergovernmental Panel on Climate Change*, edited by M. Parry, O. Canziani, J. Palutikof, P. van der Linden, and C. Hanson. Cambridge: Cambridge University Press.

Juan-García, P., D. Butler, J. Comas, G. Darch, C. Sweetapple, A. Thornton, and L. Corominas. 2017. "Resilience Theory Incorporated into Urban Wastewater Systems Management. State of the Art." *Water Research* 115: 149–61. https://doi.org/10.1016/j.watres.2017.02.047.

Kenward, R.E., M.J. Whittingham, S. Arampatzis, B.D. Manos, T. Hahn, A. Terry, R. Simoncini, J. Alcorn, O. Bastian, M. Donlan, K. Elowe, F. Franzén, Z. Karacsonyi, M. Larsson, D. Manou, I. Navodaru, O. Papadopoulou, J. Papathanasiou, A. von Raggamby, R.J.A. Sharp, T. Söderqvist, Å. Soutukorva, L. Vavrova, N.J. Aebischer, N. Leader-Williams, and C. Rutz. 2011. "Identifying Governance Strategies That Effectively Support Ecosystem Services, Resource Sustainability, and Biodiversity." *Proceedings of the National Academy of Sciences of the United States of America* 108 (13): 5308–12. https://doi.org/10.1073/pnas.1007933108.

Kirchhoff, C., and P. Watson. 2018. "Are Wastewater Systems Adapting to Climate Change? Drivers of Adaptation Action among Wastewater Systems." Manuscript in review.

Kirchhoff, C.J., and L. Dilling. 2016. "The Role of U.S. States in Facilitating Effective Water Governance under Stress and Change." *Water Resources Research* 52: 2951–64. https://doi.org/10.1002/2015WR018431.

Lin, Y., and Z. Bie. 2016. "Study on the Resilience of the Integrated Energy System." *Energy Procedia* 103: 171–76. https://doi.org/10.1016/j.egypro.2016.11.268.

Lutz, W., and R. Muttarak. 2017. "Forecasting Societies' Adaptive Capacities through a Demographic Metabolism Model." *Nature Climate Change* 7: 177–84. https://doi.org/10.1038/nclimate3222.

May, B., and R. Plummer. 2011. "Accommodating the Challenges of Climate Change Adaptation and Governance in Conventional Risk Management: Adaptive Collaborative Risk Management (ACRM)." *Ecology and Society* 16 (1): 47. https://doi.org/10.5751/ES-03924-160147.

Moser, S., and J. Ekstrom. 2010. "A Framework to Diagnose Barriers to Climate Change Adaptation." *Proceedings of the National Academy of Sciences of the United States of America* 107 (51): 22026–31. https://doi.org/10.1073/pnas.1007887107.

Mostafavi, A., and A. Inman. 2016. "Exploratory Analysis of the Pathway towards Operationalizing Resilience in Transportation Infrastructure Management." *Built Environment Project and Asset Management* 6 (1): 106–18. https://doi.org/10.1108/BEPAM-03-2015-0011.

Mugume, S.N., D.E. Gomez, F. Guangtao, R. Farmani, and D. Butler. 2015. "A Global Analysis Approach for Investigating Structural Resilience in Urban Drainage Systems." *Water Research* 81: 15–26. https://doi.org/10.1016/j.watres.2015.05.030.

Nelson, D.R., W. Neil Adger, and K. Brown. 2007. "Adaptation to Environmental Change: Contributions of a Resilience Framework." *Annual Review of Environment and Resources* 32: 395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348.

Ouyang, M., L. Dueñas-Osorio, and X. Min. 2012. "A Three-Stage Resilience Analysis Framework for Urban Infrastructure Systems." *Structural Safety* 36–37: 23–31. https://doi.org/10.1016/j.strusafe.2011.12.004.

Pahl-Wostl, C. 2007. "Transitions towards Adaptive Management of Water Facing Climate and Global Change." *Water Resources Management* 21 (1): 49–62. https://doi.org/10.1007/s11269-006-9040-4.

Pahl-Wostl, C. 2009. "A Conceptual Framework for Analysing Adaptive Capacity and Multi-Level Learning Processes in Resource Governance Regimes." *Global Environmental Change* 19 (3): 354–65. https://doi.org/10.1016/j.gloenvcha.2009.06.001.

Pahl-Wostl, C., M. Palmer, and K. Richards. 2013. "Enhancing Water Security for the Benefits of Humans and Nature — The Role of Governance." *Current Opinion in Environmental Sustainability* 5 (6): 676–84. https://doi.org/10.1016/j.cosust.2013.10.018.

Panteli, M., and P. Mancarella. 2017. "Modeling and Evaluating the Resilience of Critical Electrical Power Infrastructure to Extreme Weather Events." *IEEE Systems Journal* 11 (3): 1733–42. https://doi.org/10.1109/JSYST.2015.2389272.

Peat, M., K. Moon, F. Dyer, W. Johnson, and S.J. Nichols. 2017. "Creating Institutional Flexibility for Adaptive Water Management: Insights from Two Management Agencies." *Journal of Environmental Management* 202: 188–97. https://doi.org/10.1016/j.jenvman.2017.06.059.

Reed, D.A., K.C. Kapur, and R.D. Christie. 2009. "Methodology for Assessing the Resilience of Networked Infrastructure." *IEEE Systems Journal* 3 (2): 174–80. https://doi.org/10.1109/JSYST.2009.2017396.

Rijke, J., M. Farrelly, R. Brown, and C. Zevenbergen. 2013. "Configuring Transformative Governance to Enhance Resilient Urban Water Systems." *Environmental Science and Policy* 25: 62–72. https://doi.org/10.1016/j.envsci.2012.09.012.

Rudberg, P.M., O. Wallgren, and Å.G. Swartling. 2012. "Beyond Generic Adaptive Capacity: Exploring the Adaptation Space of the Water Supply and Wastewater Sector of the Stockholm

Region, Sweden." *Climatic Change* 114 (3–4): 707–21. https://doi.org/10.1007/s10584-012-0453-1.

Schoen, M., T. Hawkins, X. Xue, C. Ma, J. Garland, and N.J. Ashbolt. 2015. "Technologic Resilience Assessment of Coastal Community Water and Wastewater Service Options." *Sustainability of Water Quality and Ecology* 6: 75–87. https://doi.org/10.1016/j.swaqe.2015.05.001.

Sharma, U., and A. Patwardhan. 2008. "An Empirical Approach to Assessing Generic Adaptive Capacity to Tropical Cyclone Risk in Coastal Districts of India." *Mitigation Adaptation Strategies for Global Change* 13 (8): 819–31. https://doi.org/10.1007/s11027-008-9143-8.

Shin, S., S. Lee, D.R. Judi, M. Parvania, E. Goharian, T. McPherson, and S.J. Burian. 2018. "A Systematic Review of Quantitative Resilience Measures for Water Infrastructure Systems." *Water* 10 (2): 164. https://doi.org/10.3390/w10020164.

Therrien, M.C., S. Beauregard, and A. Valiquette-L'Heureux. 2015. "Iterative Factors Favoring Collaboration for Interorganizational Resilience: The Case of the Greater Montréal Transportation Infrastructure." *International Journal of Disaster Risk Science* 6 (1): 75–86. https://doi.org/10.1007/s13753-015-0044-7.

Walters, C. 1986. "Adaptive Management of Renewable Resources." *Bulletin of Marine Science*. New York: McMillan.

Westgate, M.J., G.E. Likens, and D.B. Lindenmayer. 2013. "Adaptive Management of Biological Systems: A Review." *Biological Conservation* 158: 128–39. https://doi.org/10.1016/j.biocon.2012.08.016.

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock. 2017. "Climate Science Special Report: Fourth National Climate Assessment." *U.S. Global Change Research Program* 1: 470. https://doi.org/10.7930/j0j964j6.

Yohe, G., and R.S.J. Tol. 2002. "Indicators for Social and Economic Coping Capacity: Moving toward a Working Definition of Adaptive Capacity." *Global Environmental Change* 12 (1): 25–40. https://doi.org/10.1016/S0959-3780(01)00026-7.